THE DEVELOPMENT OF PROTOCOLS TO RESTORE THE GLOBALLY AT-RISK LIMESTONE BARRENS ECOSYSTEM

by

© Corrina J Copp

A thesis submitted to the School of Graduate Studies

in partial fulfilment of the requirements for the degree of

Master of Science

Department of Biology

Memorial University of Newfoundland

October 2014

St. John's Newfoundland and Labrador

ABSTRACT

Restoring ecosystems and habitats in human-altered landscapes is challenging where reference sites to guide restoration can be limited or absent. The current shift in restoration theory to a dynamic reference alleviates some of this concern, acknowledging systems are not static. However, historical references are still useful as restoration targets when relatively intact. I applied this principle here, focusing on the limestone barrens of Newfoundland (Canada), an ecosystem that represents a biodiversity hotspot and hosts endemic plant species, e.g. the endangered *Braya longii*; human activities have degraded its critical habitat.

Historical aerial photographs were used to depict landscape topography prior to substrate removal, and identify intact reference sites. Identified reference sites were characterized in terms of substrate, nutrient and vegetation composition, and topography through field observations and measurements. To test protocols to restore the complex small-scale disturbance regime, substrate manipulation experiments were constructed and monitored for frost heave and cycles. Experiments were also seeded with native flora, including *B. longii* to determine an effective means of re-introduction following restoration.

Limestone barrens occur sparsely on the landscape atop ancient beach ridges. Low potential habitat (10%) was observed at the study site in 1948, of which slightly less than half was degraded by quarry activity and road construction by 1995. Remnant high quality habitat identified in aerial photos and described through field surveys is characterized by frost heave and sorting, high silt/clay and bare ground cover, and low organic content. Degraded sites and overburden material differed from the reference

site in terms of vegetation, substrate and nutrient composition. In addition, substrate treatments to restore small-scale disturbance that lacked added overburden material demonstrated similarities to the reference site in terms of the average number of frost cycles and duration suggesting partial recovery of cold-soil processes. The seeding experiments with native flora, including the endangered endemic *B. longii*, resulted in low percent emergence. However, more seeds are expected to germinate in subsequent years given germination syndromes.

This thesis emphasizes the need for human intervention, rather than a non-intervention expecting regeneration given the absence of vegetative and natural disturbance recovery towards limestone barrens. It also recommends that overburden material not be used to restore soil and substrate as it will hinder progression along the target limestone barrens trajectory. Overall, the recommendations provide a baseline methodology to restore limestone barrens habitat in degraded quarry sites, addressing the Federal Recovery Strategy's target to expand and restore critical habitat, natural freeze-thaw disturbance, and *B. longii* within its historical range.

ACKNOWLEDGEMENTS

I would like to thank everyone who has helped me along this rewarding journey beginning with my supervisory committee; Luise, thank you for the opportunity to be your graduate student. You are a great role model, field assistant, an incredibly intelligent and driven woman and have inspired me to achieve those things that are important for conservation and life. I would not have been able to complete this project without your guidance, support, knowledge and enthusiasm. Susan your passion and knowledge of the limestone barrens is contagious. Your insight, help both in and out of the field, and guidance is something I will always be grateful for. Steve, I am grateful to have had the opportunity to meet and work with you. Your feedback, knowledge, guidance and passion in the field of restoration have been incredibly helpful and inspire my continued involvement in the field.

I need to thank my family for their continued support; Cass, for the hours you spent proofreading my papers, your objective opinion and pep talks, support and honesty to keep me grounded and smiling; Mom and Dad, thank you for keeping me focused, giving me the opportunity to pursue my education and go after what I want.

I would like to thank everyone who helped me with fieldwork: my field assistants Garry Dart and Agnes Mason; Wildlife and Parks and Natural Areas Divisions, Department of Environment and Conservation employees Jeri Graham, Claudia Hanel, Jessica Humber, Tina Leonard, Erika Pittman, and Elizabeth Smith; Dulcie House and Jean Hoddinott from Limestone Barrens Habitat Stewardship Program; the members of the Sandy Cove Action Committee, Sandy Cove summer students, and the Flowers Cove's Green Teams; Lynn Dempster from the provincial government department of Innovation, Business, and Rural Development (IBRD); Ann Marceau and Michael Burzynski; Murray Whalen our heavy equipment operator; Maggie and Harold Chambers of French Island Bed and Breakfast for giving me a home away from home while in the field and Holland Nurseries for the pots that were kindly donated to the project. This research would not have been possible without everyone's help, guidance and support.

I also cannot forget to thank my lab mates, Louis Charron, Emilie and Tucker Kissler, Vanessa Mardones, Laura Seigwart Collier, Andrew Trant and Margie Wilkes for all their support and help both in the lab and field. It was a joy and honour to work with you all! Also, thank you to Dr. Trevor Bell (Memorial University) and his lab, and Dr. Martin Batterson (Dept. of Natural Resources, NL Government). Your guidance in the interpretation of aerial photographs and substrate analysis, and use of your resources allowed me to successfully complete my research. Lastly, thanks to those who helped me with GIS including Dr. Shawn Leroux and Robert Way, and Dr. David Schneider for your endless help with statistics.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

1 GENERAL INTRODUCTION

A decade ago, historical landscapes were considered the ideal reference condition for the assisted rehabilitation and recovery of ecological and ecosystem function (Bradshaw, 1987; SER, 2004; Clewell & Arson, 2013). Now, these references no longer seem applicable and are considered impractical and unrealistic under rapidly changing environmental conditions instigated by anthropogenic activity (Hobbs et al., 2006, 2013). Recreating the past is no longer the target in restoration, rather it is the attempt to re-establish the system within the range of the original historical trajectory prior to human activities (Clewell and Aronson, 2013; Balaguer et al., 2014). In many cases this requires blending historical information with knowledge predicting environmental change due to climate and increased presence of exotic weed species (Zedler et al., 2012; Balaguer et al. 2014) creating the idea of a “dynamic” reference (Hiers et al., 2012; see Appendix I for key term definitions).

In highly degraded habitats with altered structural compositions and functional components, such as mines and quarries, the creation of functional and diverse novel or analogous ecosystems are proposed rather than restoring the historical reference given thresholds have been irreversibly crossed (Hobbs et al., 2009; Lundholm and Richardson, 2010; Zedler et al., 2012; Figure 1). Restoring historical site characteristics within highly altered systems is considered unrealistic and often unsuccessful given the rigorous manipulation and management resources required to maintain the desired system (Hobbs et al. 2009). However, habitats not irreversibly altered to a novel state, and retaining intact historical biotic/abiotic characteristics in combination with novel components, are considered hybrid (Hallet et al., 2013; Hobbs et al., 2009; Figure 1). Such hybrid systems have been restored within the range of their historical trajectory (Koch, 2007), and highlight the continued use of historical states to guide restoration (Balaguer et al., 2014). In particular, the application of historical states to guide restoration in globally rare ecosystems impacted by quarry and mining activities.

Approximately two billion hectares of soil resources (~15% of the Earth's land surface) have been degraded by anthropogenic activities (Jie et al., 2002). In particular, such activities have threatened approximately 88% of endemic species' habitats globally (Myers et al., 2000). Quarry and mining practices contribute to this degradation in Canada and around the world, degrading approximately 1% of the world's land surface (Tropek et al., 2012). Both these practices alter the landscape geomorphology leading to habitat loss, erosion, and disruption of the normal disturbance and hydrological regimes (Langer, 2001). Limestone quarrying and gravel extraction are considered one of the primary threats to limestone restricted species and are challenging sites to restore given their unique geological history and geomorphology (BirdLife/FFI/IUCN/WWF, 2014).

In many cases quarry and mining sites are not rehabilitated following closure, leaving derelict and uninhabitable sites lacking vital ecological components such as soil and substrate (Bradshaw, 1987; Clemente et al. 2004). For example, lack of fine-grained material in quarried areas reduces soil moisture, rooting potential, nutrient retention, and alters the timing of heat influencing life history traits of native plant species (Firlotte and Staniforth, 1996; Noel, 2000; Greene, 2002). Identifying those missing ecological components is a priority for the development of restoration protocols and recovery of habitat structure and function in these at-risk degraded sites.

Development of restoration protocols should utilize historical properties of an ecosystem as available to determine structural and functional attributes that can be re-established, setting the system along the historical trajectory while also allowing for the introduction of novel characteristics to assure achievable outcomes (Zedler et al., 2012; Balaguer et al. 2014). This approach acknowledges past ecological attributes, and the site's current and future limitations (Zedler et al., 2012; Balaguer et al. 2014). Furthermore, accepting that the reference model is not constraining but serves as a guide, gives restoration a starting point with an open endpoint within the natural range of variation for that ecosystem (Clewell and Aronson, 2013; Balaguer et al., 2014) thus is flexible to the dynamic nature of ecosystems.

The hybrid system approach was attempted on the Great Northern Peninsula of Newfoundland (Canada), where the patchy distribution of aggregate and gravel deposits ideal for road development resulted in a large number of small borrow pits (Ricketts and Vatcher, 1996). Degraded sections of limestone barrens exist in a hybrid state given the loss of substrate and vegetation in quarried areas, presence of adjacent intact remnant areas and absence of invasive species (Hallet et al., 2013; Figure 1). Incorporating historical information in protocol development, in conjunction with defining site limitations will assist in the recovery of functional and structural components to reduce physical fragmentation and increase critical habitat in this globally at-risk limestone barrens ecosystem.

Limestone pavements are unique ecosystems globally, nationally, and provincially (The Wildlife Trusts, n.d.). They have a mosaic composition, consisting of open limestone outcrops to areas of vegetated cover including heath, grasslands or scrublands (Cumbria Wildlife Trust, 2000; Wilson and Fernandez, 2013). Limestone pavements encompass subclasses of limestone habitats including the alvars of southern Ontario (Canada) (Catling and Brownell, 1995), the limestone pavements of the Burin Peninsula (Ireland) (Limestone Pavement Conservation, n.d.; Wilson and Fernandez, 2013), and the limestone barrens of Newfoundland (Canada) (Environment Canada, 2012). These limestone ecosystems are similarly characterized by exposed limestone bedrock with minimal soil or substrate over bedrock, high pH, low nutrient availability, are home to endemic floral species and have been impacted by quarrying and/or gravel extraction. This thesis focuses on the latter habitat - the limestone barrens of Newfoundland which has been degraded by gravel quarrying.

In Newfoundland, the limestone barrens are located within the Strait of Belle Isle Ecoregion on the north western coast of the Great Northern Peninsula, making up less than 1% of the island's area (Damman, 1983). Over the last 50 years, only 10% of limestone barrens within the distribution of the endangered *Braya longii*, a limestone barrens endemic (described below), has remained intact (Janes, 1999; Hermanutz et al., 2009), highlighting the low predicted natural occurrence of *Braya longii* on the landscape. Of this 10%, 16% is considered high quality limestone barrens habitat

(Greene, 2002). The limestone barrens is a biodiversity hotspot possessing unique geology, climate, disturbance regime and native flora (Sutton et al., 2006). The only endemic plants on the island of Newfoundland are found here.

Open limestone barrens are patchily distributed atop plateaus and ancient beach ridges below an elevation of 50-70 m and across three bedrock formations: Eddies Cove (oldest); St. George's; and Table Head (Grant, 1992; Greene, 2002) within the West Coast Lowland physiography. Substrates are carbonate-rich, and characterized by bare limestone bedrock, dolomite, frost shattered rock, limestone heath, and small localized patches of glacial and marine sediment derived from glacial melt water and marine sediment deposited during the inundation by sea water (Roberts, 1983; Grant, 1992). Such coarse and fine calcareous surficial geologies have been shown to possess many endemic species relative to other surficial geologies (Anderson and Ferree, 2010). The unique geology of the limestone barrens is an important consideration in the development of restoration protocols; especially when considering the influence on complex small-scale disturbance regimes, and threatened and endangered inhabitant with narrow habitat requirements.

The limestone barrens fall within the Northern Peninsula Climatic Zone of Newfoundland, primarily influenced by the Labrador Current (Banfield, 1983). The area experiences short cool summers, long cold winters, approximately 120 frost-free days, and reduced growing degree days (Roberts, 1983). This region of Newfoundland is expected to see an increase in the number of frost free days with the changing climate (Slater, 2005; Hjort and Luoto, 2009; Finnis, 2013). Yearly precipitation ranging between 760 – 900 mm, with approximately 300 cm falling as snow (Banfield, 1983), is also predicted to change, with an increase of 20-200mm of rain expected during the summer and fall (Slater, 2005). Current ambient conditions directly influence weathering regimes, and further minimize nutrient release, decay of organic material and biological activity, thus slowing the process of soil development (Billings, 1973; Campbell and Claridge, 1992). How the predicted increase of 4°C within the next 65 years (Slater, 2005) will influence the future trajectory of the limestone barrens, its unique flora and cold soil processes, is largely unknown, though predictions can be made. For example, the frequency of freeze-thaw cycling is predicted to increase (Hjort and Luoto, 2009), and ecosystem and biome ranges are predicted to shift (Slater, 2005; Grimm et al., 2013). Determining the influence of climate change on cold soil processes will assist in understanding its affect on the limestone barren's small-scale disturbance regime.

Naturally occurring disturbances generally provide heterogeneity across the landscape at both a micro- and macro-scale, creating patches of low and high biodiversity (Thorpe and Stanley, 2011). Freeze-thaw cycling and frost sorting are both characterized by the movement of stones and particles within the substrate during ice lens formation and the expansion of water horizontally and vertically (Bergsten et al., 2001; Greene, 2002; Matsuoka et al., 2003). They are influenced by several abiotic variables including substrate texture (~12-19% fine-grained material has been identified to effectively allow for needle ice development as finer material will hold more water) (Meentemeyer and Zippin, 1981; Bergsten et al., 2001); vegetation and snow cover (insulated areas tend to experience fewer frost cycles) (Firlotte and

Staniforth, 1996); soil water chemistry (presence of dissolved solids can suppress freezing points) (Chantal et al., 2006); temperature (fluctuations above and below 0°C); and topography and aspect (north facing slopes experience cooler temperatures than south slopes) (Hjort and Luoto, 2009). Annually, the limestone barrens have approximately 245 days of frost (Banfield, 1983). Freeze-thaw cycling and frost sorting are critical aspect of the natural disturbance regime of the limestone barrens of Newfoundland, maintaining open, non-vegetated areas across the landscape (Anderson, 1988; Figure 2), and creating hotspots for arctic-alpine seedling recruitment (Sutton et al., 2006). These areas create open regions of low competition for opportunistic species and primary colonizers (Sutton et al., 2006). This complex, small-scale disturbance is critical in providing sufficient disturbance to pioneering species yet inhibits competitors (Jonasson,1986; Noel, 2000; Greene, 2002; Hermanutz et al., 2002). Understanding the development of small-scale disturbance will promote its incorporation into protocols to restore habitat function.

The interaction and cumulative effects of climate, geology and substrate characteristics of the limestone barrens influence the native flora adapted to this area. The limestone barrens ecosystem is dynamic, consisting of vegetated crowberry (*Empetrum nigrum* L.) barrens and open limestone barrens habitats. The plant communities inhabiting the region include the limestone heath *Empetretum-Salicestosum reticulatae* and *Potentilletum-Dryadetosum integrifoliae* (Meades, 1997). These plants possess climatically adapted traits including low growth forms or cushions to avoid desiccation, tolerate nutrient poor conditions, and have structural adaptations to natural disturbance such as robust taproots (Bliss, 1971). For example *B.*

longii is an endangered (G1, N1, S1; see Appendix I for abbreviations), endemic plant species well adapted to the limestone barrens and occurs within the area of the study site in Sandy Cove (Figure 3). Ranging in size from 1 – 10 cm, *B. longii* is a primary colonizer possessing a stout contractile taproot, adapted for anchorage in well drained, open, and non-vegetated sites with frost susceptible substrates (Meades, 1997; Hermanutz et al., 2002). Outlining and restoring habitat characteristics key to supporting native flora will influence ecosystem development towards the desired target trajectory.

Following the suggestion of Zedler et al. (2012), this research takes a bottom up approach to develop restoration protocols addressing the recovery of at-risk and degraded limestone ecosystems. More specifically, this thesis focuses on the limestone barrens of Newfoundland. Using the historical landscape to guide restoration targets within a hybrid context, this research determines what has been degraded and lost, and what remains in terms of reference sites on the landscape. The main objectives of this thesis are to: 1) develop methods regarding how to restore historical landscape topography and slope using aerial photographs and intact references sites; 2) using this methodology characterize reference sites identified in aerial photographs in terms of substrate, nutrient and vegetation composition, and topography through field observations and measurements; 3) test protocols to restore the complex small-scale disturbance regime via the construction of substrate manipulation experiments and monitoring of frost heave and cycles; and 4) determine an effective and efficient means to re-introduce native flora, including *B. longii* and other native limestone barrens flora, following restoration.

Currently, no protocols have been developed to restore degraded sections of the limestone barrens ecosystem within Newfoundland. Recommendations to inform the implementation of sustainable restoration protocols are necessary to increase the amount of critical habitat for *B. longii*, as this is a key target identified in the Long's braya (*B. longii*) and Fernald's braya (*B. fernaldii*) Federal Recovery Strategy (Environment Canada, 2012), underscoring the importance of this research.

1.1 REFERENCES

Anderson, S. (1988). The upfreezing process: Experiments with a single clast. *Geological Society of America Bulletin*, **100**, 609–621.

Anderson, M.G. & Ferree, C.E. (2010). Conserving the stage: climate change and the geophysical underpinnings of species diversity. *PLoS ONE*, **5**, e11554.

Balaguer, L., Escudero, A., Martín-Duque, J.F., Mola, I. & Aronson, J. (2014). The historical reference in restoration ecology: Re-defining a cornerstone concept. *Biological Conservation*, **176**, 12–20.

Banfield, C.E. (1983). Chapter 3: Climate. *Biogeography and Ecology of the Island of Newfoundland* pp. 37–106. Dr. W. Junk Publishers, The Hague, The Netherlands.

Bergsten, U., Goulet, F., Lundmark, T. & Löfvenius, M.O. (2001). Frost heaving in a boreal soil in relation to soil scarification and snow cover. *Canadian Journal of Forest Research*, **31**, 1084–1092.

Billings, W.D. (1973). Arctic and alpine vegetations: Similarities, differences, and susceptibility to disturbance. *BioScience*, **23**, 697–704.

BirdLife/FFI/IUCN/WWF. (2014). *Joint Briefing Paper on Extraction and Biodiversity in Limestone Areas'*. Cambridge, UK.

Bliss, L.C. (1971). Arctic and alpine plant life cycles. *Annual Review of Ecology and Systematics*, **2**, 405–438.

Bradshaw, A.D. (1987). The reclamation of derelict land and ecology of ecosystems. *Restoration ecology: A Synthetic Approach to Ecological Restoration* pp. 53–74. Cambridge University Press, Cambridge-New York, NY-Melbourne.

Campbell, I.B. & Claridge, G.G.C. (1992). Soils of cold climate regions. *Weathering, Soils and Paleosols* pp. 183–201. Elsevier, Amsterdam.

Catling, P.M. & Brownell, V.R. (1995). A review of the alvars of the Great Lakes region: Distribution, floristic composition, biogeography and protection. *The Canadian Field-Naturalist*, **109**, 143–165.

Chantal, M. de, Rita, H., Bergsten, U., Löfvenius, M.O. & Grip, H. (2006). Effect of soil properties and soil disturbance on frost heaving of mineral soil: a laboratory experiment. *Canadian Journal of Forest Research*, **36**, 2885–2893.

Clewell, A.F. & Aronson, J. (2013). *Ecological Restoration : Principles, Values, and Structure of an Emerging Profession (2nd Edition)*. Island Press, Covelo, CA, USA.

Cumbria Wildlife Trust. (2000). *Limestone Pavement Action Plan*. THE CUMBRIA BIODIVERSITY ACTION PLAN, Sergents Barn, Lowther, Penrith, Cumbria.

Damman, A.W.H. (1983). Chapter 5: An ecological subdivision of the land of Newfoundland. *Biogeography and Ecology of the Island of Newfoundland* pp. 163-206. Dr. W. Junk Publishers, The Hague, The Netherlands.

Environment Canada. (2012). *Recovery Strategy for the Long's Braya (*Braya Longii*) and the Fernald's Braya (*Braya Fernaldii*) in Canada*. Environment Canada, Ottawa.

Finnis, J., (2013). *Projected impacts of climate change for the province of Newfoundland & Labrador*. Provincial Government of Newfoundland & Labrador, The Office of Climate Change, Energy Efficiency & Emissions Trading.

Firlotte, N. & Staniforth, R.J. (1996). Strategies for revegetation of disturbed gravel areas in climate stressed subarctic environments with special reference to Churchill, Manitoba, Canada: a literature review. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **33**, 49–52.

Grant, D.R. (1992). *Quaternary Geology of St. Anthony-Blanc Sablon Area, Newfoundland and Quebec*. Memoir, Geological Survey of Canada.

Greene, S. (2002). *Substrate Characteristics of Braya Habitat on the Limestone Barrens, Great Northern Peninsula, Newfoundland*. B.Sc. Honours thesis, Memorial University, Department of Geography, St. John's, NL.

Grimm, N.B., Chapin, F.S., Bierwagen, B., Gonzalez, P., Groffman, P.M., Luo, Y., Melton, F., Nadelhoffer, K., Pairis, A., Raymond, P.A., Schimel, J., Williamson, C.E., (2013). The impacts of climate change on ecosystem structure and function. Frontiers in Ecology and the Environment, **11**, 474–482.

Hallet, L.M., Standish, R.J., Hulvey, K.B., Gardener, M.R., Suding, K.N., Starzomski, B.M., Murphy, S.D. & Harris, J.A. (2013). Towards a conceptual framework for novel ecosystems. *Novel Ecosystems: Intervening in the New World Order*, First Edition pp. 16–28. John Wiley & Sons, Ltd, Southern Gate, Chichester, West Sussex, UK.

Hermanutz, L.A., Mann, H., Anions, M.F.E., Ballam, D., Bell, T., Brazil, J., Djan-Chékar, N., Gibbons, G., Maunder, J., Meades, S.J., Nicholls, W., Smith, N. & Yetman, G. (2002). *National Recovery Plan for Long's Braya (*Braya Longii *Fernald) and Fernald's Braya (*Braya Fernaldii *Abbe)*. National Recovery Plan, Canadian Wildlife Service, Ottawa, Ontario.

Hermanutz, L., Squires, S. & Pelley, D. (2009). *2008 Limestone Barrens Research Report*. Wildlife Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, Comer Brook, Canada.

Hiers, J.K., Mitchell, R.J., Barnett, A., Walters, J.R., Mack, M., Williams, B. & Sutter, R. (2012). The dynamic reference concept: Measuring restoration success in a rapidly changing no-analogue future. *Ecological Restoration*, **30**, 27–36.

Hjort, J. & Luoto, M. (2009). Interaction of geomorphic and ecologic features across altitudinal zones in a subarctic landscape. *Geomorphology*, **112**, 324–333.

Hobbs, R.J., Arico, S., Aronson, J., Baron, J.S., Bridgewater, P., Cramer, V.A., Epstein, P.R., Ewel, J.J., Klink, C.A., Lugo, A.E., Norton, D., Ojima, D., Richardson, D.M., Sanderson, E.W., Valladares, F., Vilà, M., Zamora, R. &

Zobel, M. (2006). Novel ecosystems: theoretical and management aspects of the new ecological world order. *Global Ecology and Biogeography*, **15**, 1–7.

Hobbs, R.J., Higgs, E.S. & Hall, C. (2013). *Novel Ecosystems: Intervening in the New* Ecological *World Order*. John Wiley & Sons.

Hobbs, R.J., Higgs, E. & Harris, J.A. (2009). Novel ecosystems: implications for conservation and restoration. *Trends in Ecology & Evolution*, **24**, 599–605.

Janes, H. (1999). Braya Longii *(Long's Braya),* Braya Fernaldii *(Fernald's Braya), and Disturbance on Newfoundland's Great Northern Peninsula*. B.Sc. Honours thesis, Memorial University, Department of Geography, St. John's, NL.

Jie, C., Jing-zhang, C., Man-zhi, T. & Zi-tong, G. (2002). Soil degradation: a global problem endangering sustainable development. *Journal of Geographical Sciences*, 12, 243–252.

Jonasson, S. (1986). Influence of frost heaving on soil chemistry and on the distribution of plant growth forms. *Geografiska Annaler. Series A, Physical Geography*, **68**, 185–195

Koch, J.M. (2007). Alcoa's mining and restoration process in South Western Australia. *Restoration Ecology*, **15**, S11–S16.

Langer, W.H. (2001). *Potential Environmental Impacts of Quarrying Stone in Karst - A Literature Review*. Open-File, U.S. Geological Survey, U.S. Department of the Interior.

Limestone Pavement Conservation (n.d.). Introduction. URL http://www.limestone-pavements.org.uk/introduction.html [accessed 28 July 2014]

Lundholm, J.T. & Richardson, P.J. (2010). Mini-review: Habitat analogues for reconciliation ecology in urban and industrial environments. *Journal of Applied Ecology*, **47**, 966–975.

Matsuoka, N., Abe, M. & Ijiri, M. (2003). Differential frost heave and sorted patterned ground: field measurements and a laboratory experiment. *Geomorphology*, **52**, 73–85.

Meades, S.J. (1997). *COSEWIC Status Report on the Long's Braya,* Braya Longii *in* Canada. Ottawa, Ontario.

Meentemeyer, V. & Zippin, J. (1981). Soil moisture and texture controls of selected parameters of needle ice growth. *Earth Surface Processes and Landforms*, **6**, 113–125.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B. & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, **403**, 853–858.

Noel, L. (2000). *The Effect of Disturbance on the Seedling Recruitment and Persistence of* Braya Longii *and* Braya Fernadii. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

NRCAN. (2012). CanVec-012P07-Flower's Cove.

Ricketts, M.J. & Vatcher, S.V. (1996). *Granular Aggregate-Resource Mapping in the Roddickton-Main Brook Area, Great Northern Peninsula, Newfoundland*. Geological Survey, Newfoundland Department of Natural Resources.

Roberts, B.A. (1983). Chapter 4: Soils. *Biogeography and Ecology of the Island of Newfoundland* pp. 107–162. Dr. W. Junk Publishers, The Hague, The Netherlands.

Slater, J., (2005). *Statistical downscaling of temperature and precipitation for climate change impact assessment of rare plants on the limestone barrens of northwestern Newfoundland*. B.Sc Joint Honours, Memorial University, Department of Geography, St. John's, NL.

Sutton, J.T., Hermanutz, L. & Jacobs, J.D. (2006). Are frost boils important for the recruitment of arctic-alpine plants? *Arctic, Antarctic, and Alpine Research*, **38**, 273–275.

Society for Ecological Restoration International Science & Policy Working Group. (2004). *The SER International Primer on Ecological Restoration*. www.ser.org & Tucson: Society for Ecological Restoration International.

The Wildlife Trusts. (n.d.). Limestone pavement. URL http://www.wildlifetrusts.org/wildlife/habitats/limestone-pavement [accessed 31 July 2014]

Thorpe, A.S. & Stanley, A.G. (2011). Determining appropriate goals for restoration of imperilled communities and species. *Journal of Applied Ecology*, **48**, 275–279.

Tropek, R., Kadlec, T., Hejda, M., Kocarek, P., Skuhrovec, J., Malenovsky, I., Vodka, S., Spitzer, L., Banar, P. & Konvicka, M. (2012). Technical reclamations are wasting the conservation potential of post-mining sites. A case study of black coal spoil dumps. *Ecological Engineering*, **43**, 13–18.

Wilson, S. & Fernandez, F. (2013). *National Survey of Limestone Pavement and Associated Habitats in Ireland*. Department of Arts, National Parks and Wildlife Service, Heritage and the Gaeltacht, Ireland.

Zedler, J.B., Doherty, J.M. & Miller, N.A. (2012). Shifting restoration policy to address landscape change, novel ecosystems, and monitoring. *Ecology and Society*, **17**.

Figure 1. The current state of an ecosystem depending on level of human-disturbance and alteration of functional and structural components. The star indicates the classification of the degraded limestone barrens ecosystem. Figure modified from Hobbs et al. (2009).

Figure 2. Sorted frost polygon with fine centre and coarse border in bottom right hand corner of 1 x 1m quadrat. Photo taken at the Sandy Cove Ecological Reserve.

Figure 3. Sandy Cove study site, within current *B. longii* habitat. Map constructed using ESRI® ArcMAP™ version 10.1. Map of Newfoundland modified from Environment Canada (2012) and water bodies extracted from NRCAN (2012).

Figure 1.

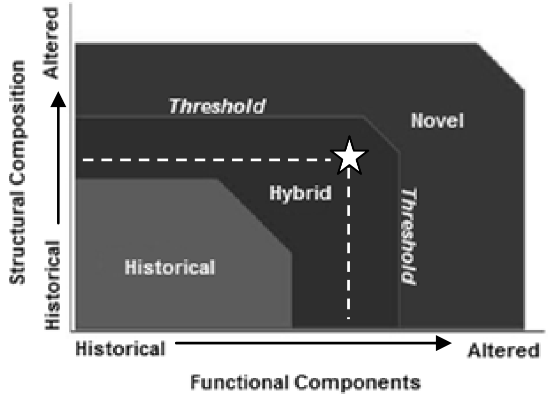
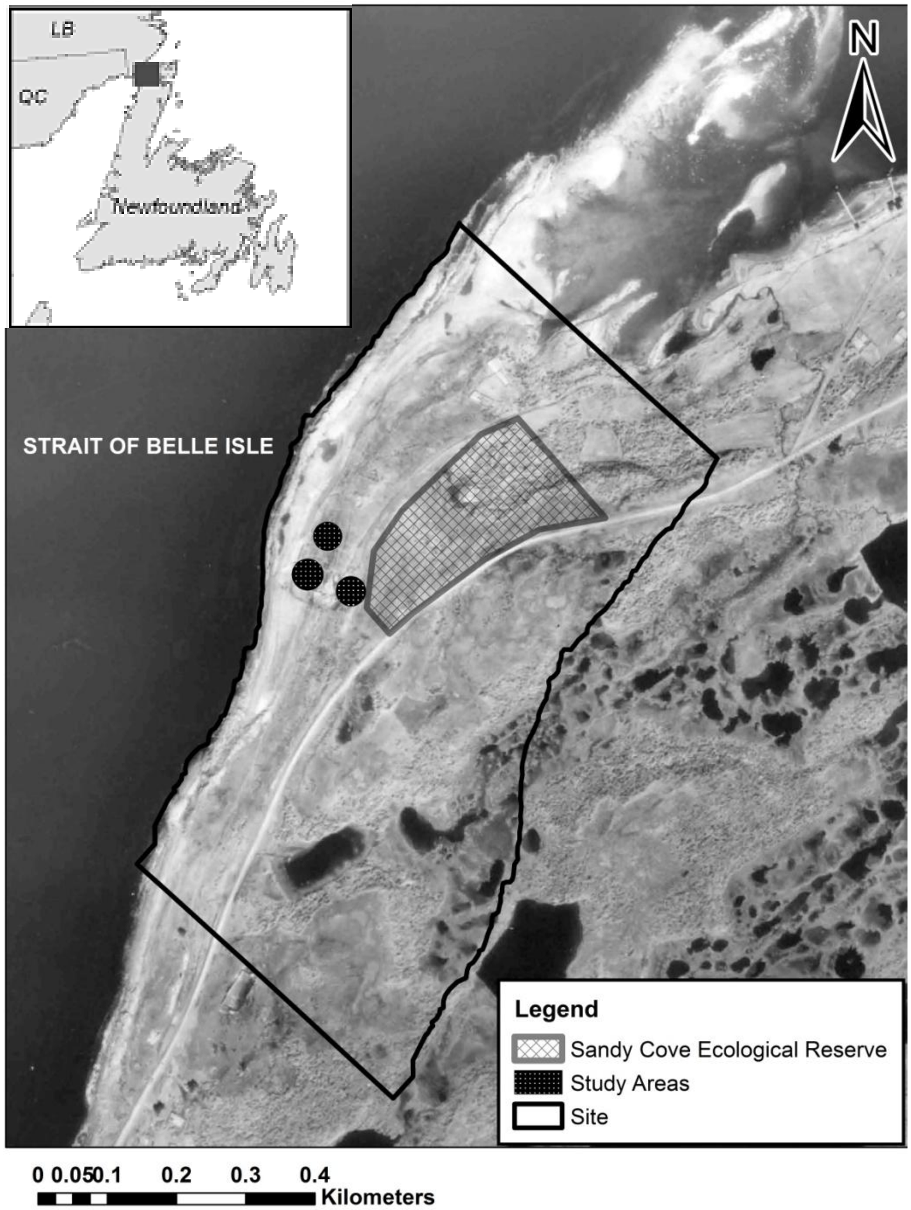

Altered
Structural Composition
Historical
Threshold
Novel
Hybrid
Threshold
Historical
Historical
Altered
Functional Components

Figure 2.

Figure 3.


LB
QC
Newfoundland
N
STRAIT OF BELLE ISLE
Legend
Sandy Cove Ecological Reserve
Study Areas
Site
0 0.050.1 0.2 0.3 0.4
Kilometers

CO-AUTHORSHIP STATEMENT

All manuscripts in this thesis were co-authored with Drs. Luise Hermanutz and Susan Squires. Chapter 2 has additionally been co-authored with Dr. Trevor Bell. Both chapters 2 and 3 have been written and formatted for submission to journals of choice. In all instances I was the principal contributor to project design and proposal, implementation of the field research component, gathering and analysis of the data, and manuscript preparation.

CHAPTER 2

2 RECONSTRUCTING ECOLOGICAL MEMORY IN AN AT-RISK ECOSYSTEM

2.1 Abstract

75% of Earth's ice-free surface has been degraded by human urbanization. In restoring these sites, extent of degradation, invasive species and climate change have challenged the use of historical references in favour of a novel ecosystem approach. However, in natural and semi-natural ecosystems where structural and functional thresholds have not been irreversibly crossed, historic aerial photographs provide a novel means to recreate the historical topography, differing from the use of the surrounding landscape to inform site reconstruction, identify remnant reference sites, and provide baseline targets. The limestone barrens of Newfoundland (Canada), a globally threatened ecosystem with many rare plants, provide such an example. Here, remnant reference patches guide the restoration of pre-human modified landscape topography to mimic historical beach ridge geomorphology key to habitat function.

Historical aerial photographs pre- (1948) and post-highway (1968-1995) construction and associated quarrying were assessed to develop restoration protocols for limestone quarries. Topography, land use change, limestone barrens loss, and reference sites were identified to inform restoration. Reference sites and human-degraded areas (quarry floor and overburden) were characterized using vegetation transects (n=20), and soil and nutrient sampling (n=172). Additionally, to restore landscape topography pre-human degradation, remnant natural area elevation points were collected (n=336).

Historical aerial photographs suggest that 4.9ha of the 50ha study site contained potential limestone barrens. After 47 years, slightly more than half (2.8ha) remains following road construction and quarrying. Further, only 1.9ha is actually high quality limestone barrens habitat; open, non-vegetated, and exhibiting complex small-scale disturbance. Low natural occurrence on the landscape underscores conservation need, and provides a restoration target.

Remnant open limestone barrens substrates have low organic content, high percent fine particles (silt/clay) and bare ground cover, and high manganese (ppm), and low phosphorus (ppm) concentrations. These areas are colonized predominately by *Juniperus horizontalis*, and *Erigeron hyssopifolius*, differing from human-degraded areas which display dissimilar vegetation communities suggested by NMDS ordination, though species are predominately native.

Defining reference sites for restoration projects is challenging, however we provide a broadly applicable approach using a historical context to develop restoration protocols in hybrid ecosystems not irreversible altered using: i) remnant habitat characteristics to define a baseline; and ii) historical aerial photographs to define relevant reference habitat, historical landscape topography, and land use change. In combination these steps fill a currently acknowledged gap, and assist in defining a starting point, and providing a suitable foundation for further restoration.

Keywords: quarrying, Newfoundland, biodiversity, freeze-thaw disturbance, beach-ridge geomorphology, limestone barrens, aerial photographs

2.2 Introduction

Globally, anthropogenic activities have degraded approximately 75% of the Earth's ice free land area (Ellis et al., 2010), quarrying and mining having modified approximately 0.3-1% (Hooke and Martín-Duque, 2012; Tropek et al., 2012), making restoration a more frequently used approached. Limestone extraction in the form of hard-rock quarries and gravel pits is a dominant industry globally, and is currently a primary threat to restricted limestone species (BirdLife/FFI/IUCN/WWF 2014). Mines and quarries can remain un-rehabilitated following closure, leaving a derelict and uninhabitable landscape, lacking vital ecological and functional components (Bradshaw 1987; Clemente et al. 2004). To improve ecological function of such landscapes, restoration ecology strives to mitigate anthropogenic impacts on the natural systems and habitats (Society for Ecological Restoration International Science & Policy Working Group, 2004). Restoring these areas triggers the need to learn about the past landscape, understanding the historical derivation from the regional geology, hydrology, topography, climate and geography (Balaguer et al., 2014).

However, in many cases these aspects, which are encompassed within the term "ecological memory", are overlooked and is identified as a gap in the literature (Balaguer et al., 2014). Ecological memory refers to past environmental events, such as glaciation, that have shaped and/or restricted the existing habitat, ecosystem or landscape characteristics, and remain a part of the landscape (Thompson et al., 2001). With rapidly changing environments and climates, urbanization, and introduction of non-native and invasive species, the idea of using a historical reference as a target for restoration has come under scrutiny; its validity and applicability recently debated

(Seastedt et al., 2008; Hobbs et al., 2009; Reinhardt et al., 2010; Hiers et al., 2012). Rather, novel targets incorporating projected climate change and current invasive species to provide analogous functional and structural attributes, are proposed in systems irreversibly beyond inherent thresholds (Hobbs et al., 2013). Despite this shift in thought, latent and active ecological memory stored in the landscape are considered a fundamental component pivotal to redefining the historical reference concept and restoring an ecosystem within its historical trajectory (Balaguer et al., 2014). Widely available and frequently utilized aerial photographs (Bierman et al., 2005), in combination with ground collected elevation points provide topographical information, historical and current, to guide future landscape restoration and best practice strategies not readily utilized.

Quarry and mine sites provide an opportunity to incorporate the idea of ecological memory, maintaining the historical reference as a guidepost to study habitat and species recovery, incorporate historical topography which is often lacking (Balaguer et al., 2014), and explore the interacting facets of geomorphology and ecology (Reinhardt et al., 2010; Raab et al., 2012). Studies have incorporated the surrounding topography to guide landscape design of abandoned quarries, stressing the importance of restoring land topography and morphology to recover structure and function (Martín-Duque et al., 2010; Balaguer et al., 2014). In these systems, historical references still represent a baseline for restoration targets and efforts to guide the system within a range of the original stable state (Jackson & Hobbs 2009; Balaguer et al. 2014). The use of historically-derived targets to guide ecosystem and habitat recovery is important as these targets define restoration practice, separating it from others such as ecosystem design and engineering (Balaguer et al. 2014). Here, latent ecological memory in terms of historic beach ridge geomorphology is explored for its use in the development of protocols to restore at-risk ecosystems and species at-risk critical habitat.

For at-risk ecosystems, threatened species, habitat protection and restoration are identified as fundamental components essential to the recovery process (Carroll et al., 1996; Noss, 2000). With rapidly changing biotic and abiotic conditions, literature identifying realistic targets to restore at-risk habitats and species is very limited. Systems are not static, and shifting restoration perspectives to incorporate current and future changes in biotic and abiotic conditions will be pivotal to project success (Choi, 2007; Hobbs et al., 2009). However, the use of creative and novel approaches to maintain desired systems, such as globally at-risk habitats pushed into a hybrid state and outside the historical range of variability should be considered (Seastedt, Hobbs & Suding 2008). Landscapes surrounding quarries or mines can provide a baseline to restore an analogous stable topography mimicking geomorphic characteristics (Hancock, Loch & Willgoose 2003; Martín-Duque *et al.* 2010; Balaguer et al. 2014), mitigate human impact in environmentally sensitive areas, improve aesthetics and restore natural habitat (Koch, 2007). This has been applied in particular to hard rock quarries and quarries with steep walls (Yundt and Lowe, 2002). Incorporating knowledge on historical, current and future change and novel approaches, innovative restoration protocols can be developed for recovery and conservation efforts targeting rare at-risk habitats and species at-risk (SER, 2009).

The limestone barrens of Newfoundland are part of a globally rare ecosystem defined by distinct geomorphology, complex small-scale freeze-thaw disturbance regime, and high plant biodiversity (Environment Canada 2012; Figure 4). It is a biodiversity hotspot for calciphiles and arctic-alpine like plant communities, is home to the only endemic plant species on the island of Newfoundland, and makes up less than 1% of NL's land area (Meades, 1997). However, over the past 50 years the ecosystem has been degraded by road construction, gravel quarry activity, and housing development. Degrading activities such as surface quarrying historically occurred frequently within critical limestone barrens habitat of endangered endemics such as *Braya longii* (Brassicaceae) (Environment Canada, 2012). Currently, <10% of the limestone barrens habitat occurring within the habitat range of *B. longii* (18 km narrow coastal span) is considered suitable habitat with open, non-vegetated areas exhibiting natural small-scale substrate disturbance (Hermanutz, 2001; Greene, 2002). Need for habitat restoration protocol development in this at-risk ecosystem, and for its endangered endemics is explicitly outlined in Species at Risk Federal Recovery Strategies (Environment Canada, 2012).

The goal of this research is to outline globally applicable recommendations to inform protocols that acknowledge ecological memory to restore regional topography and ecosystem function in degraded systems using the at-risk limestone barrens ecosystem and its species at-risk as a case study. To address habitat restoration and recovery targets for this at-risk ecosystem and its endemic flora including *B. longii* as outlined in the Federal Recovery Strategy (Environment Canada, 2012), historical, current, and future factors such as geomorphology, disturbance regime, sources of degradation, and climate need to be integrated to ensure reestablishment of natural properties.

Using aerial photographs from an era prior to, and after, large-scale limestone barrens change (i.e. 1948), the historic landscape topography was reconstructed to define a historically-derived target and provide insight into an appropriate structural foundation for subsequent restoration efforts. Study objectives included: 1) the use of historical aerial photograph interpretation to depict limestone barrens habitat loss and landscape change through time to set restoration targets; 2) characterizing high quality limestone barrens habitat to define a reference model and guide restoration efforts in terms of local topography, vegetative community, and nutrient and substrate composition; and 3) create a surface interpolation model using historical aerial photographs and remnant habitat patches to inform restoration of site topography. We predict that readily available aerial photographs will provide important historical information, outlining land use change, critical habitat loss, and reference sites, which will enable us to define baseline restoration targets to expand critical habitat and conserve at-risk habitats and species.

2.3 Methods

2.3.1 Site Description

The study site is located in the small community of Sandy Cove, Newfoundland (Canada; 51°21'17.43"N, 56°39'41.96"W; Figure 3), on the northwestern coast of the Great Northern Peninsula within the Strait of Belle Isle Ecoregion. The site occurs adjacent to the Sandy Cove Ecological Reserve (http://www.env.gov.nl.ca/env/parks/wer/r_sce/index.html). Climatic characteristics include 760-900mm of precipitations per year, approximately 120 frost-free days, and daily average temperatures ranging from -0.4° – 5.0°C (Banfield, 1983; Roberts, 1983; Environment Canada, 2013). The study site is approximately 50ha and, consists of overburden piles and pits resulting from quarrying, human exposed and naturally occurring limestone bedrock, and limestone and crowberry barrens. Overburden piles are vegetated by non-native and opportunistic native weedy species, while pits and quarry-exposed bedrock areas remain non-vegetated. Natural limestone and crowberry barrens are patchy amongst human-degraded areas. All research was conducted under appropriate government permits.

2.3.2 Aerial Photograph Interpretation and Surface Model Construction

A preliminary site assessment was conducted using historical aerial photographs pre- (i.e. 1948) and post- (i.e. 1968, 1979, 1989, and 1995) road development using a stereoscope to assess landscape change (Janes, 1999; Greene, 2002). Identified landscape features included: human-degradation including dwellings, roads, overburden piles, and quarry pits; natural areas including potential limestone barrens habitat (i.e. open, non-vegetated areas characterized by high albedo; see Greene (2002)); and geological features including historic beach ridges. Features were traced onto transparency paper for each year to determine temporal land use change. Human-degraded and natural areas were differentiated using change over time, interpreting elements such as texture (i.e. rough vs. smooth), tone (i.e. light vs. dark), linear features, and hollows and peaks visualized by vertical and slope exaggeration. The latter term occurs when the vertical scale becomes greater than the horizontal scale allowing one to discern small topographic changes on a landscape (Sabins, 1978). Perceived exaggeration is converted to real elevation values using flight height and focal length of the lens (Rosas, 2011). All aerial photographs and their respective transparencies were orthorectified using PCI Geomatica 2012 Orthoengine® version 4.7.1. Transparencies were heads-up digitized using ESRI® ArcMAP™ version 10.1 (Appendix II; ESRI (2011)).

The historical geomorphology was modeled using regularly sampled geomorphology points. Model creation, depicting the historical geomorphology, used regularly sampled elevation points taken within remnant natural areas and not within degraded areas between June and August 2013. Points were sampled at 20m Universal Transverse Mercator (UTM) grid intersections predetermined in ESRI® ArcMAP™ version 10.1. Predetermined points within the outlined 50ha study site were subsampled to include every other point from south to north to maximize the area sampled within the study period. Given the small amount of available remnant natural area and grid points falling within these areas, opportunistic sampling occurred along transects to increase the number of natural points collected and minimize gap size in the surface model. A total of 463 points were collected using a Trimble® GeoXH handheld GPS with antennae unit and Trimble® Terrasync™ software to ensure sub-metre accuracy following post-processing of data (see Appendix II). Points were ground-truthed between June and August 2013 to confirm aerial interpretation.

The surface model recreated the study site using remnant natural patches. The existence of remnant patches allowed for interpolation, providing coarse topographical information where human-degraded gaps currently exist on the study site. Uncertainty with interpolation is acknowledged given increasing gap size increases error despite sampling density (Doucette and Beard, 2000). Also, factors such as terrain complexity influence this uncertainty where more complex terrains demonstrate greater error at smaller gap sizes (Doucette and Beard, 2000), the limestone barrens having a low-moderate complexity. Aside from evaluating mean absolute error associated with interpolated values, results can be further verified using advanced photogrammetry techniques (Butler et al., 1998).

Geostatistical and deterministic interpolations were used to model historical landscape elevation and slope at the study site, prior to substrate removal, using collected points from remnant natural patches. All elevation points occurring on human-degraded areas were removed, with 336 of the 463 points occurring within remnant limestone barrens patches (i.e. crowberry barrens, limestone barrens or bedrock). Surface interpolation is a common approach in predicting elevation values across a landscape (Chaplot et al., 2006) though does have inherent drawbacks depending on sample density and gap size as mentioned above. The purpose of this step was not to create a high resolution surface, but rather to coarsely depict the sites historical topography to guide the construction of a similar historical configuration. Two surface interpolators were selected - ordinary kriging and inverse distance weighting (IDW) (Chaplot et al., 2006). The former method was selected to attain a measure of error around the elevation predictions (ESRI, 2004) and given its ability to work well on data points that are spatially clustered and sparse (Doucette & Beard, 2000). The deterministic surface interpolator IDW was used for comparison to the geostatistical method of kriging. The Geostatistical Wizard in ESRI® ArcMAP™ version 10.1 was used to run interpolations.

2.3.2.1 Statistical Analysis

Collected point data were assessed using exploratory spatial data analysis (ESDA) for normality, spatial autocorrelation and trends (ESRI, 2004). ESRI (2004) 'model training' protocols were then followed to validate model protocol selection. This required random point selection to create a test subset (n=34) and training subset (n=302). The latter subset was used to construct four ordinary kriging surface models using the Exponential, Guassian, Quartic and Constant kernel functions, and one deterministic model (IDW). The empirical semivariogram was modeled using the two most common, Spherical and Exponential models (ESRI, 2004). Optimized model parameters (i.e. nugget, range, and sill) were selected in all cases; instrument error was set to 97.5% given that 2.5% of the post-processed points using Trimble® GPS Pathfinder® Office software (Version 4.10) were above 1 m accuracy; given the historical beach ridge geomorphology, anisotropy was selected to accommodate the unequal rate of change between the north-south and east-west directions. The test subset was used to validate the five predicted surfaces. The surface with unbiased predictions, minimal difference between measured and predicted values, and a valid assessment of uncertainty and variability was then selected (ESRI, 2004). To determine if measured elevation values differed significantly from predicted model values a non-parametric Kruskal Wallis test was used given non-normal data.

2.3.3 Defining reference limestone barrens patches and current site characteristics

Reference sites provide baseline targets, important structural and functional habitat information, and benchmarks for project success. Current site features, including natural and human-degraded, were defined using vegetation transects, and substrate and nutrient sampling. A total of 20 transects (N=7 overburden; N=2 crowberry; N=3 limestone barrens; N=6 quarry floor (Dart, 2013)), with equally spaced 1m x 1m quadrats (n=3-5) along varying lengths were conducted mid to late July of 2012 and 2013, given most native species flower early to midsummer. Total percent cover and cover of individual species were estimated in each quadrat to the nearest 5%. Plant species covering <5%, were recorded as 1% (i.e. trace). Two observers conducted side-by-side surveys on alternating plots (one observer per plot) to reduce observer bias. Photos and voucher specimens were collected for unknown species for later identification.

Substrate samples were collected in the same areas as the vegetation plots from Sandy Cove (n=148) in June 2012, which occurs within habitat identified as limestone barrens (Environment Canada, 2012), for substrate and nutrient analysis. Substrate samples (74 - 5 x 5 x 10 cm) were collected from overburden piles, classified as

Young (Y, ~15yrs; n=12), Mid (M, ~25yrs; n=12), and Old (O, ~45yrs; n=18) predetermined from aerial photographs, natural crowberry heath (n=6), limestone barrens (n=8), and the quarry floor (n=18; Dart, 2013). Samples were air dried and then 50g were wet and dry sieved with 0.5g/mL of Epsom salts to determine gravel, sand and silt/clay percent composition (Allen, 1975; Greene, 2002). Nutrient samples were analysed by the Newfoundland and Labrador (NL) Natural Resources Geochemical laboratory (St. John's, NL) using loss-on-ignition at 550°C for organic material and total multi-acid digestion, ICP determination (Finch, 1998). Substrate samples were additionally sorted to remove the >2mm fraction and assessed for pH. A subsample of 10g was mixed with 25mL of distilled water and stirred for 0.5hrs (Hendershot et al., 2008). A Fisher Scientific ™ accumet™ AB15 Plus Basic™ pH/mV/°C Meter was used to measure pH, and was calibrated with three buffers (pH=4, 7, 10) every 12 samples to maintain accuracy (Hendershot et al., 2008).

Potential limestone barrens patches interpreted from aerial photographs were assessed for optimal habitat quality defined by Greene (2002). The 14 observed remnant limestone barrens patches were visually assessed for human or natural disturbance level (i.e. high, medium, low), and coarse percent cover of substrate and vegetation. The former was determined using a pre-constructed dichotomous key (see Appendix II, Table AII.1), informed by previous studies (Janes, 1999; Greene, 2002; Rafuse, 2005). The key categorized patches as: human-degraded (low, medium, high), naturally disturbed (low, medium, high), or other (beach, crowberry barrens, overburden). In addition, remnant habitat patches were assessed for substrate and vegetation percent cover using 10 regularly sampled 0.5 x 0.5m quadrats along transects (n=1-5) running parallel to the ocean and ranging in length (10-150m) depending on patch shape and area (70-8000m^2). In contrast to previous vegetation transects, percent cover of individual species was not recorded in the field, but rather a digital photograph (Nikon CoolPix AW100) of each quadrat was taken given the main interest in substrate cover. Also, these images will serve as a permanent record for baseline monitoring of reference habitat patches. Using Adobe® Photoshop Elements 12, percent cover was visually assessed from photos and rounded to the nearest 5% for each class. Bare ground was subdivided into: soil (dark organic material); fines (particles <2mm; silt/clay, sands), gravels (2mm<256mm; granules, pebbles, cobbles); boulders (256mm<4096mm); and bedrock (Wentworth, 1922) similar to Robinson (2010).

2.3.3.1 Statistical Analyses

Dissimilarity in species compositions across the study area (i.e. quarry floor, vegetated and non-vegetated overburden piles, and crowberry and limestone barrens) was determined using unconstrained non-metric multidimensional scaling (NMDS) using the “metaMDS” function in the Vegan package (Oksanen, 2000). This method was used given the interest in species compositions across the study site, non-linearity, and the large number of zeros in the data (Zuur et al., 2007). To ensure a global minimum was reached and did not stalled at a local minimum, a loop with 1000 iterations was run using the “previous.best” function in the “metaMDS” wrapper. A second matrix containing explanatory abiotic variables was fit to the species ordination using Vegan’s “envfit” function. To avoid collinearity in abiotic variables, variation inflation factors (VIF), and forward selection using Vegan’s “ordistep” function was used to remove redundancy (Zuur et al., 2009). VIF values obtained were below three, similar to Zuur *et al.* (2009) as higher values suggest collinearity or variation in one variable that is well explained by another. The Bray-Curtis semi-metric distance was used to rank species percent cover data as the data violated the triangulation assumption (McCune et al., 2002).

Variability in identified remnant limestone barrens patches in terms of coarse percent vegetation and substrate cover was assessed using the nonparametric permutation based multivariate analysis of variance (PERMANOVA) adonis test. This test is analogous to the parametric MANOVA to compare multiple response variables (Oksanen, 2000), in this case cover classes, and was used given violation of normality. Percent cover of each group (i.e. moss, other, fines, gravel, boulder, and bedrock) was the response variable, while the explanatory variable 'disturbance' was ranked in accordance with the dichotomous key and on a scale from high human disturbance (-3) to high natural disturbance (3) with crowberry barrens (0) acting as the midpoint. The assumption of homogenous group beta dispersion between 'disturbance' levels was assessed using Vegan's "betadisp" function. All analyses were conducted using R Software version 3.0.2.

2.4 Results

2.4.1 Historical aerial photograph interpretation depicts limestone barrens habitat loss and landscape change through time setting restoration targets

Identifying remnant habitat patches is important for the selection of reference sites, and the development of restoration protocols and targets. Historical aerial photographs provided a time lapsed series of the study site from 1948 to 1995, depicting how human activity has affected the area, and the portion of at-risk potential limestone barrens lost. Patches were identified as having high albedo, and low vegetation cover (Greene 2002). In 1948, Sandy Cove had minimal human-degradation; a few trails, cleared forest patches and community dwellings. Dwellings are situated within a bay between two halves of the Sandy Cove Ecological Reserve (Figure 4B). No potential limestone barrens were observed here, though presence prior to inhabitation is unknown. Open limestone barrens are patchy within the study area (Figure 4B), historically occurring on ancient beach ridges, in close proximity to the coast, and intermittent amongst the vegetation (i.e. crowberry barrens). Beach ridges were a characteristic feature of the surrounding landscape given glacial retreat, submergence and re-emergence history (Grant, 1992); creating a heterogeneous landscape where beach ridges are separated by low lying bogs and ponds. The 50ha study site, in 1948 consisted of 9.8% potential limestone barrens and 90.2% vegetation and water (eg. ponds and bogs) (Figure 5A). These historical aerial photographs outline that open potential limestone barrens are likely rare within the bigger landscape.

The main source of habitat degradation and fragmentation at the study site was a main highway (Viking Trail Highway, Route 430) constructed in the early 1950s; first observed in the 1967/68 aerial photographs. The selected route for the highway was along the coast, more specifically on the ancient beach ridges. Additionally, quarry operations began around this time; road operations utilizing the easily accessible material at the surface or just below the crowberry barrens, targeting limestone barrens patches given their degradation and loss observed in sequential photographs. The aerial photographs provide evidence of linear features flanking the road suggesting material was removed to build the highway. This activity at the study site resulted in a 2.3% loss of the outlined 9.8% potential limestone barrens. Replacing open limestone barrens within the historical landscape are road and quarry land uses. Road construction was a precursor to subsequent degradation and loss of local site topography and at-risk limestone barrens.

Road construction and quarry activity degraded and destroyed potential limestone barrens on the landscape, while the latter also altered landscape geomorphology and topography. In 1979, quarry activity was the most pronounced. From its first occurrence in 1967/8, activity had expanded northward. Overburden is piled on site and limestone substrates have been removed to bedrock in some areas. This pit and piling disrupted the uniform topography observed in 1948 and 1967/8. The amount of quarry activity coincides with highway upgrades and rerouting approximately 75m southeast of the study site. After 1979, further quarry expansion and change in potential limestone barrens was minimal. From 1979 to 1995, quarry expansion and road upgrades led to an additional 1.9% loss of the remaining 7.5%

potential limestone barrens observed in 1967/68 within the study site (Figure 5B). Collectively, road and quarry activity degraded 43% of the original 9.8% potential limestone barrens and 23ha or 39% of the study site in total. Remnant potential limestone barrens patches are now more isolated among the altered site's matrix of open quarry floor, overburden piles, and highway (Figure 5B), highlighting the sites hybrid state. What type of limestone habitat existed in those now degraded areas, whether high or low quality, is unknown. However, those outlined areas that still remain provide reference sites likely possessing similar characteristics given the proximity, allowing for their use in setting baseline restoration targets.

2.4.2 Surface interpolation model allows for original site topography reconstruction and landscape restoration using remnant reference habitat

Historical aerial photograph interpretation and collected elevation data inform protocols to restore landscape topography, including elevation and slope, aimed towards mimicking pre-road and -quarry degradation using surface interpolation. Using the test and training method, ordinary kriging with an exponential kernel and stable function had the smallest mean difference between measured and predicted values (0.0014m), which should be close to zero (ESRI, 2004). Using this pre-determined protocol, the final interpolation had an average mean difference between measured and predicted values of -0.0038m, and a lower RMSE and variation between predicted and measured values (RMSE=0.58m; Average SE=0.59) relative to the validated model (see Appendix III). The model slightly overestimated measured values (0.97m). In addition, prediction errors are highest in areas with no associated point data (i.e. degraded locations) and have an increased distance from the nearest neighbour, which was expected. The interpolated surface produced a 3-dimensional model coarsely depicting the site's historical beach ridge topography (Figure AIII.3), which will guide the future restoration of site topography.

2.4.3 Characterizing optimal limestone barrens to define a reference model to guide restoration efforts

The percent cover and species composition of human-degraded and natural areas is dissimilar. Limestone barrens and vegetated overburden piles differed with the latter dominated by species not native to the limestone barrens including *Leymus mollis* (Trin.) (Poaceae; 28-57±1-5%), *Taraxacum spp.* (Asteraceae; 3-9±1-2%), *Vicia cracca* L. (Fabaceae; 4±2%) and *Equisetum sp.* (Equisetaceae; 1-3±1-2%). The non-vegetated overburden and the quarry floor overlap and are both dominated by native limestone barrens species including sedge spp., *P. maritima* L. subsp. *juncoides* (Lam.) Hultén (Plantaginaceae), moss spp., *Rhodiola rosea* L. (Crassulaceae) and *Achillea millefolium* L. subsp. *lanulosa* (Nutt.) Piper (Asteraceae) (Figure 6). In contrast, natural limestone barrens are dominated by bare ground (64±2%) and the native species *Dryas integrifolia* Vahl. subsp. *integrifolia* (Rosaceae; 20±1%). In terms of species composition and percent cover, the NMDS suggests open limestone barrens are more similar to crowberry barrens which is dominated by *Empetrum nigrum* L. (Empetraceae; 20±2%), *D. integrifolia* (18±2%), *Salix reticulata* L. subsp. *reticulata* (Salicaceae; 18±3%) and *Betula pumila* var. *glandulifera* (Betulaceae; 13±3%) (Figure 6). Additionally, the variability in species found inhabiting human-degraded areas relative to natural areas was greater given the spread of points in space suggesting species assemblages are random, and opportunistic colonization by those species arriving first.

Variation in species compositions across the study site are in part attributed to substrate particle size, bare cover and four geochemical properties. Vegetated overburden (Treatments=Young, Mid and Old) and limestone barrens are polarized along the first axis, the former being positively correlated with organic material (LOI) and the latter with bare ground cover (Figure 6). On the second axis, vegetated overburden is positively correlated with phosphorus, while both limestone and crowberry barrens are negatively correlated with phosphorus and positively correlated with percent silt/clay and manganese (Figure 6). Both the quarry floor and limestone barrens are positively correlated with bare ground, the latter on average demonstrating a higher percentage. These results suggest that human alteration of limestone barrens substrate and geochemical properties, particularly the increase in phosphorus and organic material, has led to the observed dissimilarities in species composition.

Remnant limestone barrens patches identified from aerial photographs are visually heterogeneous in terms of disturbance level and ground cover. Human-modified site cover was dominated by bedrock (10-35±0-5%) and gravel (30-50±5%) (Figure 7). In contrast, naturally-disturbed remnants had high percent covers of gravel (50-65±0-5%) and vegetation (30±0-5%) including *D. integrifolia* and *J. horizontalis* (Figure 7). In terms of percent cover of soils, fines, gravel and boulders, human-modified and natural-disturbed sites were found to differ significantly (pseudo-F=5.07; r^2=0.13; p=0.001). Further, variability among intact remnant patches suggests not all potential habitat sites identified in aerial photographs are high quality reference habitat (open, non-vegetated and heterogeneous substrate exhibiting natural substrate disturbance), rather sites range on a scale from low to high quality (Table AIII.4). However, the low r^2 value suggests another variable(s) aside from the scaled level of disturbance remains unexplained. Those classified as high quality make up approximately 67.8% (~3.8% of the study site) of the potential limestone barrens habitat patches identified in aerial photographs.

2.5 Discussion

This study provides a series of readily available tools to support restoration efforts that utilize a region's pre-existing framework and existing ecological memory. The approach outlined here using a series of historical aerial photographs creates a foundation for subsequent restoration steps. It acknowledges historical geomorphic structure which is key to the recovery of habitat function in a hybrid system, and facilitates threatened and at-risk ecosystems such as global limestone barrens with intact reference sites along the target historical trajectory. Despite loss of pre-existing site features due to gravel quarrying and road construction, the interpretation of historical aerial photographs pre- and post-road construction provided a means to identify and describe local topography and relevant remnant open limestone barrens reference habitat.

More importantly, it necessitates the critical assessment comparing the degraded quarry floor and stockpiled overburden material to natural sites in terms of absent or abundant abiotic (e.g. geochemical, substrate) or biotic (e.g. vegetation) components. The previously smooth landscape depicted in historical aerial photographs and remnant natural areas supports the removal or leveling of overburden to restore topography. However, the overburden's dissimilarity to reference sites opposes its use in the restoration of open limestone barrens habitat as it would hinder the recovery of habitat function. This is in contrast with many projects where available overburden is a source of organic material or fill (Strohmayer, 1999). Characterizing reference sites and the historical landscape, and the continued incorporation into restoration planning is critical (Clewell and Aronson, 2013; Balaguer et al., 2014).

Characterizing reference habitat in terms of topography, and geochemical, substrate, and vegetative composition is important for determining the extent to which habitats are degraded, whether it exists in a historical, hybrid or novel state (Hallet et al., 2013), to defining restoration targets, and setting benchmarks for restoration success (Society for Ecological Restoration International Science & Policy Working Group, 2004; Clewell and Aronson, 2013). The method outlined here using historical aerial photographs, surface interpolation and intact reference sites identifies and allows for the incorporation of topography into restoration protocols to mimic aspects such as beach ridge geomorphology, providing the foundation to revive dormant ecological memory and initiate site development towards the reference trajectory (Balaguer et al., 2014) in terms of functional and structural components.

Geochemical and physical soil properties, and geomorphology can constrain vegetation colonization and recolonization (Palik, 2000; Raab et al., 2012), and influence disturbance regimes (Jonasson, 1986). For example, the only endemic plants on the island of Newfoundland are found on the limestone barrens, which may in part be due to the calcareous geology in combination with fine to coarse sediment properties that are associated with higher incidences of endemic species (Anderson and Ferree, 2010). The high silt/clay fraction of intact remnant limestone barrens areas have been similarly observed in other studies (Greene 2002), while the low concentrations of phosphorus and percent organic material are conducive to the frost sorted substrates of the limestone barrens (PNAD, 1990) and arctic-alpine regions (Jonasson, 1986). Observed discrepancies in these properties between reference sites, and overburden and quarry floors support the shift in historical habitat function to the current hybrid state. However, this baseline information also sets targets for monitoring and properties that need to be restored for colonization of native flora.

Previous studies have suggested the lack of observed fine-grained silt/clay material in human-modified limestone barrens substrate limits moisture retention and frost susceptibility (Greene, 2002). Further, lack of gravel pit recolonization within northern climates has been attributed to low moisture retention and nutrient availability given lack of organic and fine material (Firlotte and Staniforth, 1996). The quarry floor within this study remained largely non-vegetated (~67% bare ground cover), and has demonstrated minimal native species re-colonization within the last 45 years (Mason, 2014), similar to other limestone quarries (Hopper and Bonner, 2003), negating the benefit of spontaneous regeneration despite its effectiveness observed in other ecosystems (Tomlinson et al., 2008). However, the lack of colonization by invasive species, and species not native to the limestone barrens on the quarry floors suggests a structural threshold has not yet been crossed. Rather the current state is reversible as those species that are recolonizing are native (Mason, 2014).

To supplement quarry floors, adding organic and fine material utilizing existing overburden has been suggested (Firlotte and Staniforth, 1996). However, increasing organic material can negatively affect habitat development, including a reduction in frost susceptibility, freeze-thaw cycling (Chantal et al., 2006), and promotion of woody and rhizomatous plant species colonization (Jonasson, 1986). Such plants can also indirectly affect freeze-thaw cycling and natural substrate disturbance (Peterson et al., 2003; Hjort and Luoto, 2009). Acknowledging how degraded sites such as quarry floors should be supplemented to improve native species recolonization and habitat function will be key to development along the target trajectory (Heneghan et al., 2008).

The importance of incorporating soil and substrate knowledge into restoration to improve substrate properties and habitat development has been emphasized in a number of studies such as Heneghan et al. (2008). For example, Ballantyne (1996) demonstrated the recovery of frost sorting in transplanted frost susceptible substrate in Scotland, suggesting substrate properties rather than location are important for this small-scale disturbance. This also supports the idea of ecological memory that remained within this previously frost sorted substrate. Thus, manipulating these properties in human-disturbed sites (Heneghan et al., 2008) to revive latent ecological memory and mimic the natural limestone barrens reference as suggested by Greene (2002) will be important to restore composition, geochemical properties, frost susceptibility and native calciphile re-colonization and persistence. Further it will assist hybrid systems such as the quarries observed within the limestone barrens ecosystems towards their historical trajectory.

Overburden piles on site demonstrate dissimilar characteristics to reference sites including a reduced percent silt/clay, calcium and magnesium, increased organic material and the non-native rhizomatous species *Leymus mollis* and *Vicia cracca*. The presence of these species suggest a lack of frost disturbance as they tend to be absent from frost sorted grounds (Jonasson, 1986). The colonization of ruderal and non-native species on overburden is not uncommon and has been similarly observed in other limestone quarries (Hopper and Bonner, 2003) and coal mines (Dos Santos et al., 2008). The benefit of using stored overburden material in restoration is dependent on the restoration target. Its use is apparent, though it can hinder the system's recovery along the target trajectory, perhaps even pushing an ecosystem past a structural or functional threshold. Acknowledging these differences allows for its appropriate use or lack thereof in restoration as suggested here.

Historical aerial photographs are an important tool readily used to identify landscape change through time (Bierman et al., 2005). In Estonia, patches of alvar grasslands were identified using detailed maps outlining vegetation cover (Helm et al., 2006) and historical aerial photographs (Pärtel et al., 1999). These authors depicted the reduction in their distribution and area over time due to human activities. Here, a similar means was used for pre- and post-road to identify habitat loss and landscape change, but also to outline the distribution of remnant limestone barrens reference sites to assist in setting restoration targets. Aerial photographs depicted a scattered yet connected distribution of limestone barrens patches within the study site, making up approximately 10% of the study area pre-human degradation, and supporting its inherently low prevalence on the landscape. Similar to the study in Estonia, the fragmentation of original patches lead to the observation of more smaller disconnected patches over time.

A key point in the conservation of many ecosystems including the limestone barrens, and emphasized by Helm, Hanski & Pärtel (2006), is connectivity between these fragmented patches for the trajectory of future community composition. Patch size and distribution on the landscape are well known to contribute to species persistence, where isolation can lead to a genetic isolation and inbreeding depression (Turner, 1989). Though *B. longii* may not be hindered by the latter given it is self-fertilized (Parsons and Hermanutz, 2006; Environment Canada, 2012), the fragmented habitat may impede its ability to move with the changing climate given low dispersal capabilities (<50 cm) (Tilley, 2003) and naturally sparse distribution of high quality habitat (Greene, 2002). Acknowledging the historical and current extent and distribution of habitat patches on the landscape will be important for reconnecting patches, restoring species-at-risk into their historic habitat range as outlined in Federal Recovery Strategies (Environment Canada, 2012) and prioritizing areas for restoration to create stepping stone habitats (Jump and Peñuelas, 2005).

In this study, surface interpolation was used to recreate the historical landscape that existed prior to substrate removal, providing a coarse model for historical landscape restoration to be applied in high priority areas. Data deficient or quarried regions had high prediction errors on the study site, though the presence of remnant natural areas allowed for the surface to be created. Chaplot *et al*., (2006) showed that ordinary kriging using high point spacing on a relatively smooth landscape in France was an appropriate and accurate method. In cases where LIDAR data are available, it would provide more accurate microhabitat information (Questad et al., 2013) not provided in ground collected data and aerial photographs. Despite areas for improvement, the approach developed here is simple, flexible and can accommodate for differences in landscape topography if aerial photographs pre-human modification and remnant patches are present, making it applicable to the broader field of restoration.

Merging historic and current site information will guide the restoration of topography, historical geomorphology, and critical habitat in hybrid systems with intact reference sites that lack non-native and invasive colonization and retain historical characteristics. It is important to note that this is a proposed method to guide the system along the historical trajectory. However, like many restored systems the end result is open-ended as systems are constantly evolving, especially under conditions of environmental change. We can only incorporate what is known or best predicted to assist in restoring a system to within its historical range, implementing adaptive management strategies in the future to maintain the favoured trajectory.

2.6 Recommendations

Identifying reference limestone barrens patches sets a baseline and benchmark for the quantity and distribution of habitat on the landscape, vegetation recovery, and for monitoring habitat restoration. Within the study area, a minimum of 10% (5.0ha) should be restored to limestone barrens given the existence of ~9.8% prior to human modification of the study site. The reduced amount of habitat remaining, and dissimilarity of human-modified locations from reference sites emphasizes the ecosystems hybrid state. It should be acknowledged that the ecosystem can be guided within the historical range, however the endpoint along this trajectory is unknown and will likely still possess hybrid characteristics.

These recommendations should be implemented in high priority areas to improve the landscape matrix, creating ‘stepping stone habitats’ between remnant patches, theoretically allowing the adaptation and expansion of native and endangered species in the face of a changing climate (Jump and Peñuelas, 2005; SER, 2009). High priority areas will require geochemical and substrate modifications if dissimilar from the reference site to allow for re-establishment of the native disturbance regime and floral community. Furthermore, overburden piles with high quantities of organic material and phosphorus should be removed from the site to reduce non-native limestone barrens species colonization and seed input, allow for freeze-thaw cycling, and restore site topography. Restoring the abiotic foundation in terms of landscape topography, its latent ecological memory, and morphology will be critical in guiding ecosystems toward their target trajectory. This study outlines such an approach to achieve this foundation, combining the use of historical, current, and future site information for hybrid ecosystems such as Newfoundland’s limestone barrens.

2.7 Acknowledgements

This study was funded by the Natural Sciences and Engineering Research Council of Canada (CGS to CC), Departments of Environment and Conservation (Wildlife Division and Parks and Natural Areas Division) and Natural Resources (Mines and Energy), Limestone Barrens Habitat Stewardship Program (LBHSP), and Memorial University. We are grateful to those who helped collect the data, including field assistants G. Dart and A. Mason, D. House (LBHSP), community members and summer students, the local Green Teams, and Provincial Government employees. Thank you to Dr. T. Bell and his lab for helping with photo interpretation and mapping, Dr. S. Leroux for his guidance with GIS, and Dr. M. Batterson for his guidance with the analysis of nutrient samples. Also, we would like to thank Dr. S. Murphy for reviewing and providing feedback.

2.8 References

Allen, T., (1975). *Particle size measurement*, 2nd ed. Chapman and Hall, London, England.

Anderson, M.G. & Ferree, C.E. (2010). Conserving the stage: climate change and the geophysical underpinnings of species diversity. *PLoS ONE*, **5**, e11554.

Balaguer, L., Escudero, A., Martín-Duque, J.F., Mola, I., Aronson, J., 2014. The historical reference in restoration ecology: Re-defining a cornerstone concept. *Biological Conservation*, **176**, 12–20.

Ballantyne, C.K., (1996). Formation of miniature sorted patterns by shallow ground freezing: A field experiment. *Permafrost and Periglacial Processes*, **7**, 409–424.

Banfield, C.E. (1983). Chapter 3: Climate. *Biogeography and Ecology of the Island of Newfoundland* pp. 37–106. Dr. W. Junk Publishers, The Hague, The Netherlands.

Bierman, P.R., Howe, J., Stanley-Mann, E., Peabody, M., Hilke, J., Massey, C.A., (2005). Old images record landscape change through time. *GSA Today*, **15**, 4–10.

Bradshaw, A.D. (1987). The reclamation of derelict land and ecology of ecosystems. *Restoration ecology: A synthetic approach to ecological restoration* pp. 53–74. Cambridge University Press, Cambridge-New York, NY-Melbourne.

Butler, J.B., Lane, S.N., Chandler, J.H., 1998. Assessment of dem quality for characterizing surface roughness using close range digital photogrammetry. *Photogrammetric. Record*, **16**, 271–291.

Carroll, R., Augspurger, C., Dobson, A., Franklin, J., Orians, G., Reid, W., Tracy, R., Wilcove, D. & Wilson, J. (1996). Strengthening the Use of Science In Achieving the Goals of the Endangered Species Act: An Assessment By the Ecological Society of America. *Ecological Applications*, **6**, 1–11.

Chantal, M. de, Rita, H., Bergsten, U., Löfvenius, M.O. & Grip, H. (2006). Effect of soil properties and soil disturbance on frost heaving of mineral soil: a laboratory experiment. *Canadian Journal of Forest Research*, **36**, 2885–2893.

Chaplot, V., Darboux, F., Bourennane, H., Leguédois, S., Silvera, N. & Phachomphon, K. (2006). Accuracy of interpolation techniques for the derivation of digital elevation models in relation to landform types and data density. *Geomorphology*, **77**, 126–141.

Choi, Y.D. (2007). Restoration ecology to the future: A call for new paradigm. *Restoration Ecology*, **15**, 351–353.

Clewell, A.F., Aronson, J., (2013). *Ecological Restoration : Principles, Values, and Structure of an Emerging Profession* (2nd Edition). Island Press, Covelo, CA, USA.

Dart, G. (2013) *Factors Affecting Plant Re-Colonization on Quarried Limestone Barrens Habitat on the Great Northern Peninsula, Newfoundland*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Department of Natural Resources (1948a). *Sandy Cove*. 1:40000. NFL-2-71. Newfoundland and Labrador Government Services and Lands, Air Photo and Map Library; St. John's, NL.

Department of Natural Resources (1948b). *Sandy Cove*. 1:40000. NFL-2-70. Newfoundland and Labrador Government Services and Lands, Air Photo and Map Library, St. John's, NL.

Department of Natural Resources (1968a). *Sandy Cove*. 1:15840. 20531-60. Newfoundland and Labrador Government Services and Lands, Air Photo and Map Library, St. John's, NL.

Department of Natural Resources (1968b). *Sandy Cove*. 1:15840. 20531-61. Newfoundland and Labrador Government Services and Lands, Air Photo and Map Library, St. John's, NL.

Dos Santos, R., Citadini-Zanette, V., Leal-Filho, L.S., Hennies, W.T., 2008. Spontaneous vegetation on overburden piles in the coal basin of Santa Catarina, Brazil. *Restoration Ecology*, **16**, 444–452.

Doucette, P., Beard, K., (2000). Exploring the capability of some gis surface interpolators for dem gap fill. *Photogrammetric Engineering & Remote Sensing*, **66**, 881–888.

Ellis, E.C., Klein Goldewijk, K., Siebert, S., Lightman, D. & Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, **19**, 589–606.

Environment Canada. (2012). *Recovery Strategy for the Long's Braya (*Braya Longii*) and the Fernald's Braya (*Braya Fernaldii*) in Canada*. Environment Canada, Ottawa.

Environment Canada. (2013). *Daniels Harbour Newfoundland Daily Data Report for November 2013*. Environment Canada.

ESRI. (2004). *ArcGIS 9: Using ArcGIS Spatial Analyst*. ESRI Press, Redlands, CA.

ESRI. (2011). What is editing? ESRI Press, Redlands, CA.

Faber-Langendoen, D., Nichols, J., Master, L., Snow, K., Tomaino, A., Bittman, R., Hammerson, G., Heidel, B., Ramsay, L., Teucher, A., & Young, B. 2012. NatureServe conservation status assessment: Methodology for assigning ranks. NatureServe, Arlington, VA.

Finch, C.J. (1998). *Inductively Coupled Plasma-Emission Spectrometry (ICP-ES) at the Geochemical Laboratory*. Current Research, Newfoundland Department of Mines and Energy: Geological Survey, St. John's, NL.

Finley, A. O. & Banerjee, S. (2010). Mba: Multilevel b-spline approximation. R package version 0.0-7. Retrieved from: http://CRAN.Rproject.org/package=MBA.

Firlotte, N. & Staniforth, R.J. (1996). Strategies for revegetation of disturbed gravel areas in climate stressed subarctic environments with special reference to Churchill, Manitoba, Canada: a literature review. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **33**, 49–52.

Grant, D.R. (1992). *Quaternary Geology of St. Anthony-Blanc Sablon Area, Newfoundland and Quebec*. Memoir, Geological Survey of Canada.

Greene, S. (2002). *Substrate Characteristics of Braya Habitat on the Limestone Barrens, Great Northern Peninsula, Newfoundland*. B.Sc. Honours thesis, Memorial University, Department of Geography, St. John's, NL.

Hallet, L.M., Standish, R.J., Hulvey, K.B., Gardener, M.R., Suding, K.N., Starzomski, B.M., Murphy, S.D., Harris, J.A., (2013). Towards a conceptual framework for novel ecosystems, in: *Novel Ecosystems: Intervening in the New World Order* pp. 16–28. John Wiley & Sons, Ltd, Southern Gate, Chichester, West Sussex, UK.

Hancock, G.R., Loch, R.J. & Willgoose, G.R. (2003). The design of post-mining landscapes using geomorphic principles. *Earth Surface Processes and Landforms*, **28**, 1097–1110.

Helm, A., Hanski, I. & Pärtel, M. (2006). Slow response of plant species richness to habitat loss and fragmentation. *Ecology Letters*, **9**, 72–77.

Hendershot, W.H., Lalanda, H. & Duquette, M. (2008). Chapter 16: Soil reaction and exchangeable acidity. *Soil Sampling and Methods of Analysis*, 2nd ed CRC Press and Taylor & Francis Group, Boca Raton, FL.

Heneghan, L., Miller, S.P., Baer, S., Callaham, M.A., Montgomery, J., Pavao-Zuckerman, M., Rhoades, C.C., Richardson, S., (2008). Integrating soil ecological knowledge into restoration management. *Restoration Ecology*, **16**, 608-617.

Hermanutz, L. (2001). *Conservation of Rare Plant Species on the Limestone Barrens of Newfoundland*. Endangered Species Recovery Fund.

Hiers, J.K., Mitchell, R.J., Barnett, A., Walters, J.R., Mack, M., Williams, B. & Sutter, R. (2012). The dynamic reference concept: Measuring restoration success in a rapidly changing no-analogue future. *Ecological Restoration*, **30**, 27–36.

Hjort, J. & Luoto, M. (2009). Interaction of geomorphic and ecologic features across altitudinal zones in a subarctic landscape. *Geomorphology*, **112**, 324–333.

Hobbs, R.J., Higgs, E.S. & Hall, C.M. (eds). (2013). *Novel Ecosystems*: *Intervening in the New Ecological World Order*. John Wiley & Sons, Ltd., Chichester, West Sussex.

Hobbs, R.J., Higgs, E. & Harris, J.A. (2009). Novel ecosystems: implications for conservation and restoration. *Trends in Ecology & Evolution*, **24**, 599–605.

Hooke, R.L. & Martín-Duque, J.F. (2012). Land transformation by humans: A review. *GSA Today*, **12**, 4–10.

Hopper, D.B., Bonner, F.J., 2003. *Reclamation of the Irish Cove Limestone Quarry (NTS 11F/15)*, Richmond County (Report of Activities No. 2004-1). Nova Scotia Department of Natural Resources, Mineral Resources Branch.

Jackson, S.T. & Hobbs, R.J. (2009). Ecological restoration in the light of ecological history. *Science*, **325**, 567–569.

Janes, H. (1999). Braya Longii *(Long's Braya),* Braya Fernaldii *(Fernald's Braya), and Disturbance on Newfoundland's Great Northern Peninsula*. B.Sc. Honours thesis, Memorial University, Department of Geography, St. John's, NL.

Jonasson, S. (1986). Influence of frost heaving on soil chemistry and on the distribution of plant growth forms. *Geografiska Annaler. Series A, Physical Geography*, **68**, 185–195.

Jump, A.S. & Peñuelas, J. (2005). Running to stand still: adaptation and the response of plants to rapid climate change. *Ecology Letters*, **8**, 1010–1020.

Koch, J.M. (2007). Alcoa's mining and restoration process in South Western Australia. *Restoration Ecology*, **15**, S11–S16.

Martín-Duque, J. f., Sanz, M. a., Bodoque, J. m., Lucía, A. & Martín-Moreno, C. (2010). Restoring earth surface processes through landform design. A 13-year monitoring of a geomorphic reclamation model for quarries on slopes. *Earth Surface Processes and Landforms*, **35**, 531–548.

Mason, A. (2014). *Temporal Patterns of Plant Recolonization on Limestone Quarries*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

McCune, B., Grace, J.B. & Urban, D.L. (2002). *Analysis of Ecological Communities*. MjM Software Design.

Meades, S.J. (1997). *COSEWIC Status Report on the Long's Braya,* Braya Longii *in Canada*. Ottawa, Ontario.

Noss, R.F. (2000). High-risk ecosystems as foci for considering biodiversity and ecological integrity in ecological risk assessments. *Environmental Science & Policy*, **3**, 321–332.

NRCAN. (2012) CanVec-012P07-Flower's Cove.

Oksanen, J. (2000). Vegan: Community ecology package. R package version 2.0-9. Retrieved from: http://CRAN.R-project.org/package=vegan.

Palik, B.J.; G. (2000). Using landscape hierarchies to guide restoration of disturbed ecosystems. *Ecological Applications*, **10**, 189–202.

Parsons, K., Hermanutz, L., (2006). Conservation of rare, endemic braya species (Brassicaceae): Breeding system variation, potential hybridization and human disturbance. Biological Conservation, **128**, 201–214.

Pärtel, M., Mändla, R., Zobel, M., (1999). Landscape history of a calcareous (alvar) grassland in Hanila, western Estonia, during the last three hundred years. Landscape Ecology. **14**, 187–196.

Peterson, R.A., Walker, D.A., Romanovsky, V.E., Knudson, J.A., Raynolds, M.K. & Krantz, W.B. (2003). A differential frost heave model: cryoturbation-vegetation interactions. *Proceedings of the Eighth International Conference on Permafrost* pp. 885–890.

PNAD, (1990). *Watts point ecological reserve (Management Plan)*. Government of Newfoundland and Labrador, Department of Environment and Conservation.

Questad, E.J., Kellner, J.R., Kinney, K., Cordell, S., Asner, G.P., Thaxton, J., Diep, J., Uowolo, A., Brooks, S., Inman-Narahari, N., Evans, S.A. & Tucker, B. (2013). Mapping habitat suitability for at-risk plant species and its implications for restoration and reintroduction. *Ecological Applications*, **24**, 385–395.

Raab, T., Krümmelbein, J., Schneider, A., Gerwin, W., Maurer, T. & Naeth, M.A. (2012). Initial ecosystem processes as key factors of landscape development—a review. *Physical Geography*, **33**, 305–343.

Rafuse, G. (2005). *The Impact of off-Road Vehicles on the Limestone Barrens Habitat and Resident Plants Endemic to the Great Northern Peninsula, NL, Canada*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Reinhardt, L., Jerolmack, D., Cardinale, B.J., Vanacker, V. & Wright, J. (2010). Dynamic interactions of life and its landscape: feedbacks at the interface of geomorphology and ecology. *Earth Surface Processes and Landforms*, **35**, 78–101.

Roberts, B.A. (1983). Chapter 4: Soils. *Biogeography and Ecology of the Island of Newfoundland* pp. 107–162. Dr. W. Junk Publishers, The Hague, The Netherlands.

Robinson, J.L. (2010). *Conservation of the Endangered Limestone Endemic Salix Jejuna; Effects of Anthropogenic Disturbance on Habitat and Life History*. M.Sc thesis, Memorial University, Department of Biology, St. John's, NL.

Rosas, H. (2011). Perception and reality in stereo vision: Technological applications. *Advances in Stereo Vision* (ed J.R.A. Torreao), InTech.

Sabins, F.F. (1978). *Remote Sensing: Principles and Interpretation*, 2nd ed. W. H. Freeman and Company, New York.

Seastedt, T.R., Hobbs, R.J. & Suding, K.N. (2008). Management of novel ecosystems: are novel approaches required? *Frontiers in Ecology and the Environment*, **6**, 547–553.

SER. (2009). *Ecological Restoration and Rare Species Management in Response to Climate Change*. Policy Position Statement.

Society for Ecological Restoration International Science & Policy Working Group, 2004. *The SER International Primer on Ecological Restoration*. Society for Ecological Restoration International.

Strohmayer, P., 1999. Soil stockpiling for reclamation and restoration activities after mining and construction. Restor. Reclam. Rev., StudentOn-Line Journal 4, 1–6.

Thompson, J.N., Reichman, O.J., Morin, P.J., Polis, G.A., Power, M.E., Sterner, R.W., Couch, C.A., Gough, L., Holt, R., Hooper, D.U., Keesing, F., Lovell, C.R., Milne, B.T., Molles, M.C., Roberts, D.W., Strauss, S.Y., 2001. Frontiers of Ecology. *BioScience*, **51**, 15–24.

Tilley, S. (2003). *The Factors Governing the Distribution of the Rare Plants* <u>Braya Longii</u> *and* <u>Braya Fernaldii</u> *(Brassicaceae) in Natural Habitats*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Tomlinson, S., Matthes, U., Richardson, P.J., Larson, D.W., 2008. The ecological equivalence of quarry floors to alvars. *Applied Vegetation Science*, **11**, 73–82.

Tropek, R., Kadlec, T., Hejda, M., Kocarek, P., Skuhrovec, J., Malenovsky, I., Vodka, S., Spitzer, L., Banar, P. & Konvicka, M. (2012). Technical reclamations are wasting the conservation potential of post-mining sites. A case study of black coal spoil dumps. *Ecological Engineering*, **43**, 13–18.

Turner, M.G. (1989). Landscape ecology: The effect of pattern on process. *Annual Review of Ecology and Systematics*, **20**, 171–197.

Wentworth, C.K. (1922). A scale of grade and class terms for clastic sediments. *The Journal of Geology*, **30**, 377–392.

Yundt, S.E., Lowe, B., (2002). Quarry rehabilitation - Cliffs, landforms and ecology, in: *Proceedings of the 26th Annual British Columbia Mone Reclamation Symposium*. Dawson Creek, B. C., 129–139.

Zuur, A.F., Ieno, E.N. & Smith, G.M. (2007). *Analysing Ecological Data*. Springer, New York, NY.

Zuur, A.F., Ieno, E.N., Walker, N.A., Saveliew, A.A. & Smith, G.M. (2009). *Mixed Effects Models and Extensions in Ecology with R*. Springer Science+Business Media, New York, NY.

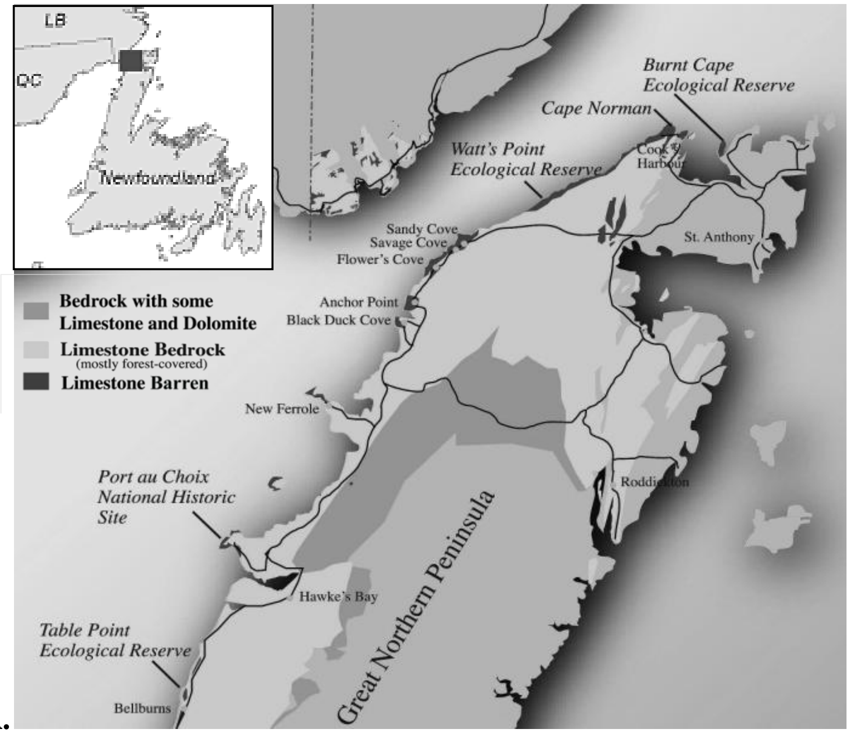
Figure 4. Limestone barrens (i.e. Limestone habitat - Black) of the Great Northern Peninsula, Newfoundland (Canada). A) Locations of limestone barrens on the Great Northern Peninsula. Figure modified from Maunder (2010) and Environment Canada (2012); B) 1948 Aerial photograph (Department of Natural Resources, 1948a, 1948b) of Sandy Cove Ecological Reserve and open limestone barrens present in 1948. Map created using ESRI® ArcMAP™ version 10.

Figure 5. Aerial photograph time series depicting limestone habitat (grey polygons) loss in the outlined study site. Note that polygons are overlain on a 1967 aerial image (Department of Natural Resources, 1968a, 1968b) given the poor resolution of the 1948 image. A) 1948; B) 1995. Map created using ESRI® ArcMAP™ version 10.1.

Figure 6. NMDS ordination displaying species compositions across the Sandy Cove study site. Stress is 0.16 after 8294 tries using previous.best. Abiotic factors with VIF less than three are fit to the species ordination. The Vegan package's metaMDS and envfit functions in R software version 3.0.2 were used to run analysis and create plot. Abbreviations: NV=Non-vegetated.

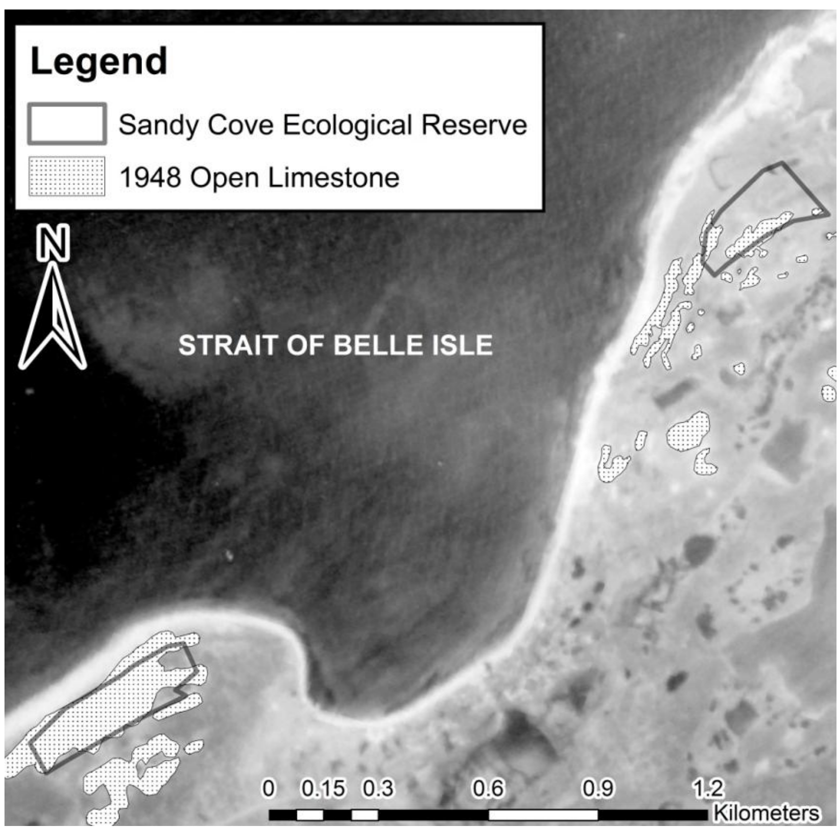
Figure 7. Average percent cover of moss, other vegetation including woody and herbaceous cover, soil, fines, gravel, boulders and bedrock across human-modified and natural sites. Both sites range in level of disturbance from low to high.

Figure 4.



LB
QC
Newfoundland
Bedrock with some Limestone and Dolomite
Limestone Bedrock (mostly forest-covered)
Limestone Barren
Burnt Cape Ecological Reserve
Cape Norman
Cook's Harbour
Watt's Point Ecological Reserve
Sandy Cove
Savage Cove
Flower's Cove
St. Anthony
Anchor Point
Black Duck Cove
New Ferrole
Port au Choix National Historic Site
Roddickton
Hawke's Bay
Great Northern Peninsula
Table Point Ecological Reserve
Bellburns

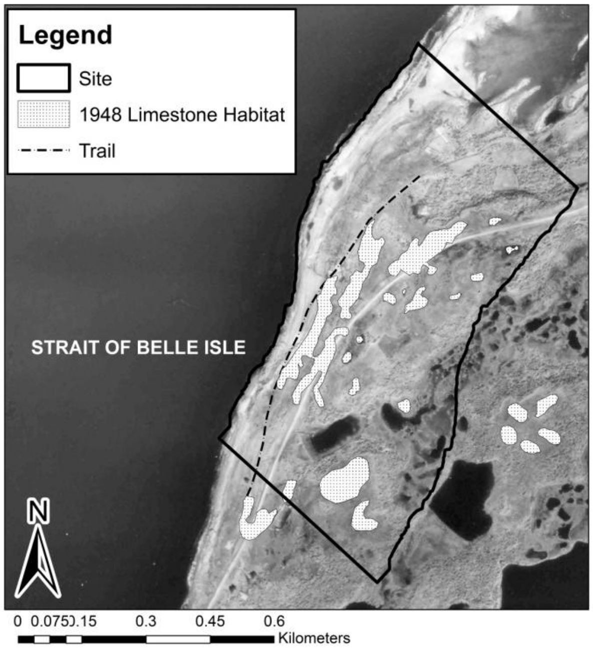
A.



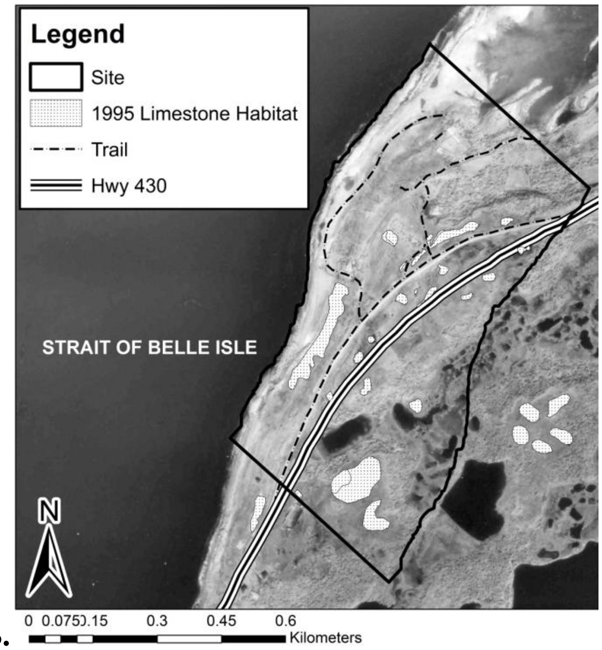
Legend
Sandy Cove Ecological Reserve
1948 Open Limestone
N
STRAIT OF BELLE ISLE
0 0.15 0.3 0.6 0.9 1.2
Kilometers

B.

Figure 5.

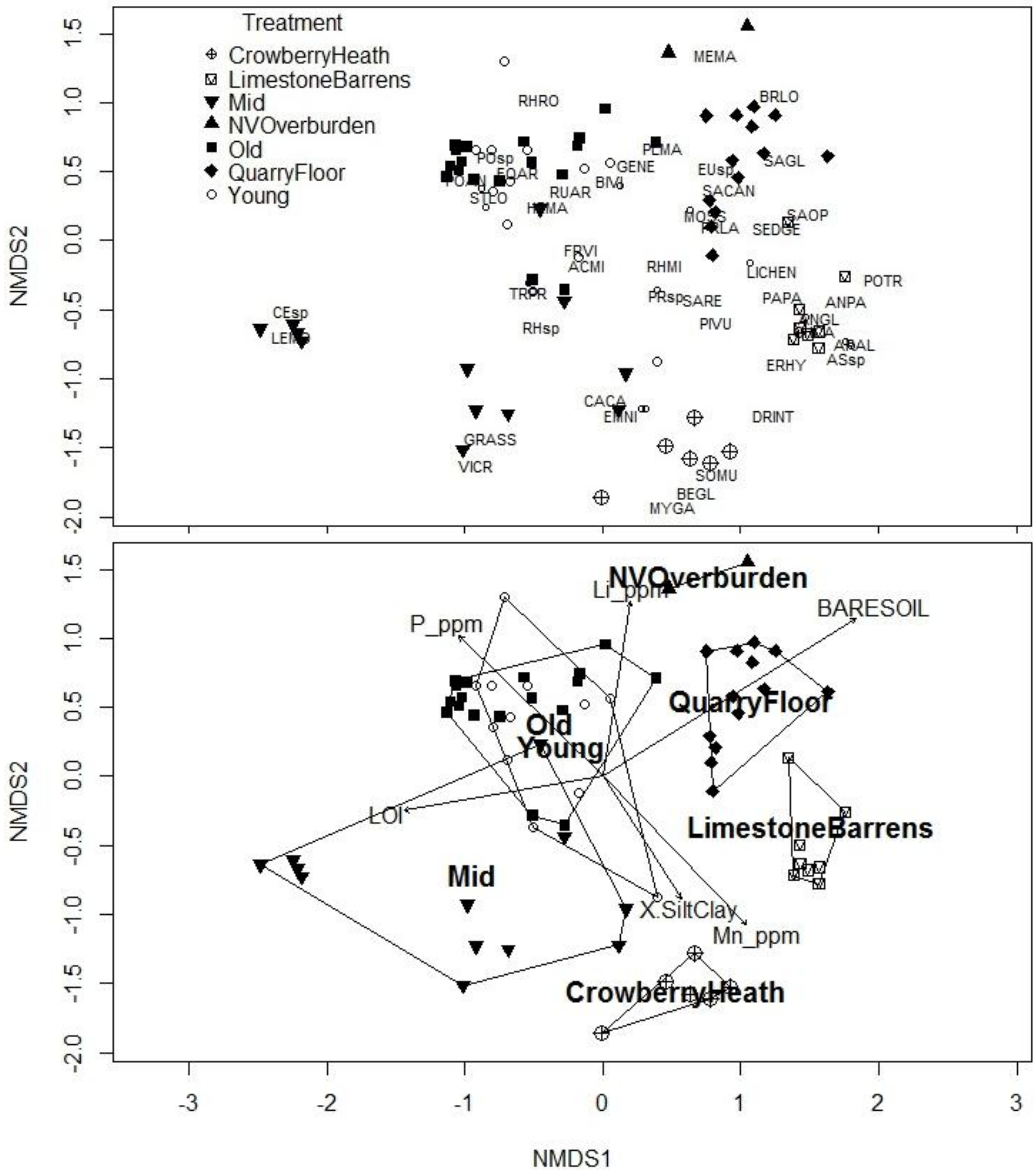

Legend
Site
1948 Limestone Habitat
Trail
STRAIT OF BELLE ISLE
N
0 0.075 0.15 0.3 0.45 0.6
Kilometers

A.


Legend
Site
1995 Limestone Habitat
Trail
Hwy 430
STRAIT OF BELLE ISLE
N
0 0.075 0.15 0.3 0.45 0.6
Kilometers

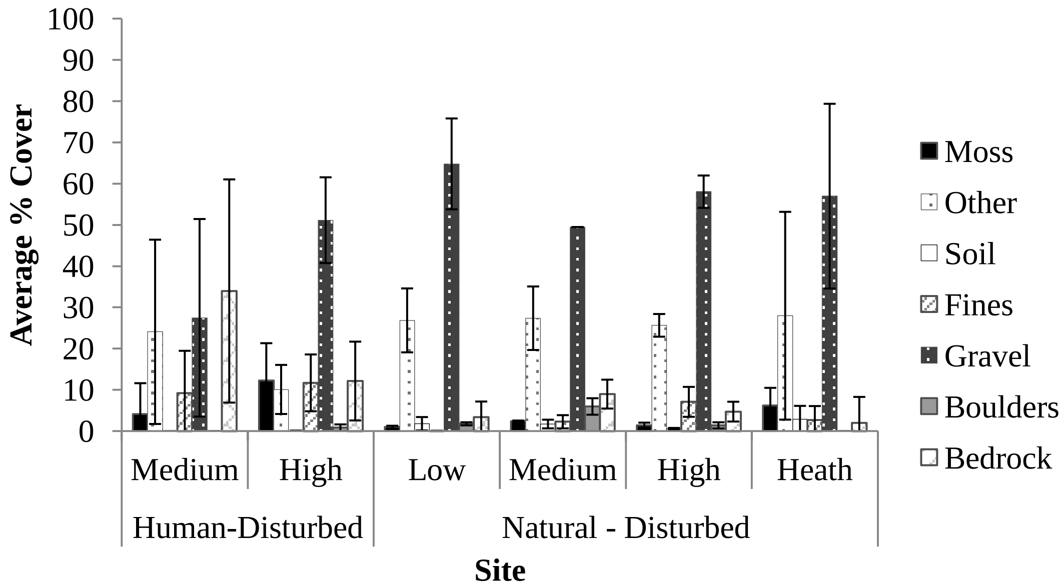
B.

Figure 6.



Treatment
CrowberryHeath
LimestoneBarrens
Mid
NVOverburden
Old
QuarryFloor
Young
NMDS2
NMDS1
NVOverburden
QuarryFloor
Old
Young
LimestoneBarrens
Mid
CrowberryHeath
Li_ppm
P_ppm
BARESOIL
LOI
X.SiltClay
Mn_ppm

Figure 7.


100
90
80
70
60
50
40
30
20
10
0
Average % Cover
Medium
High
Low
Medium
High
Heath
Human-Disturbed
Natural - Disturbed
Site
Moss
Other
Soil
Fines
Gravel
Boulders
Bedrock

CHAPTER 3

3 INTEGRATING SMALL-SCALE DISTURBANCE INTO ECOSYSTEM RESTORATION

3.1 Abstract

Restoring the functional and structural characteristics of degraded habitats is challenging given rapidly changing landscapes and predicted changes in climate. The restoration of small-scale disturbance, though less frequently acknowledged, can be an important functional component in a landscape, creating biodiversity hotspots and allowing rare elements such as endemic flora to recolonize. This study attempts to restore small-scale freeze-thaw disturbance within a globally at-risk habitat, the limestone barrens of Newfoundland (Canada). This habitat is home to the endangered endemic *Braya longii* among other unique plant species, which rely on small-scale disturbance for long-term persistence.

A before-after control-impact (BACI) and randomized block (n=3) design was used to experimentally recover small-scale disturbance with substrate treatments differing in overburden material, large limestone, and fine silt/clay substrate composition (n=6). Treatments were established in October 2012, and freeze-thaw cycling was monitored from October 2012 to August 2013 using heave devices (n=6) and soil temperature loggers (n=14). All experimental plots were additionally sown in May 2013 with *B. longii* (n=540), and the common natives *Primula laurentiana* (n=648), *Draba incana* (n=648) and *Rhodiola rosea* (n=648).

Substrate treatments lacking added organic material demonstrated similarities to the natural limestone barrens reference site. The latter demonstrated a maximum frost heave of 6.4±0.8cm, and 7.7±1.9 freeze-thaw cycles/month with an average duration of 1±2.2 h in April to 694.0±7.0 h in February. Substrate composition between treatments and reference site were significantly different. A mix of 10.9±1.4% organic, 27.6±7.2% large limestone gravel, 24.8±2.7% sand, and 47.6±4.7% silt/clay is recommended to mimic naturally freeze-thaw disturbed limestone barrens. The emergence of sown seeds *in situ* was low, *B. longii* (4.1%), *P. laurentiana* (0.6%), *R. rosea* (1.7%) and *D. incana* (0.6%), with no significant difference among treatments. Given the germination syndromes of these plant species, treatments should be monitored for at least five years.

This research outlines the importance of assisted restoration of degraded limestone habitats experiencing harsh climatic conditions, focusing on the restoration of native substrate compositions and characteristics to allow for the successful re-establishment of small-scale disturbance important for native community structure and the re-establishment of endemic and rare flora.

Keywords: Long’s braya, restoration, critical habitat, frost sorting, Recovery Strategy, limestone barrens, freeze-thaw, Newfoundland

3.2 Introduction

Many restoration projects strive to restore natural disturbance regimes as they are acknowledged functional ecosystem components, creating both spatial and temporal heterogeneity in community structure (Denslow, 1985). Natural disturbance regimes represent both environmental change (e.g. freezing-cycles) and re-cycling events (e.g. fire), scaled to the applicable spatial and temporal extent of the study system (White and Pickett, 1985). Restoration practice focuses primarily on the recovery of large-scale (e.g. fire) rather than small-scale (e.g. forest gap openings) regimes, despite the body of literature outlining the latter’s importance (Sigafoos, 1952; Levin and Paine, 1974; Platt, 1975; White and Pickett, 1985). Small scale disturbance provides heterogeneity at both a micro- and macro-scale, creating patches of low and high biodiversity (Thorpe and Stanley, 2011).

Small-scale disturbance plays an important role in the structuring of communities, and how communities change (Levin and Paine, 1974; White and Pickett, 1985). For example, it can provide a filter in the establishment of adapted pioneering flora in areas prone to frequent small-scale disturbance and impede the growth and development of maladaptive plants species, creating patches that fail to move along a defined successional trajectory (Sigafoos, 1952; Platt, 1975). Further, it assists in the maintenance of open, non-vegetated areas within fully vegetated landscapes (Jonasson, 1986; Anderson, 1988).This is a key characteristic of limestone barrens habitat of Newfoundland (Canada) which is regularly disturbed by seasonal and diurnal small-scale freeze-thaw cycling and frost sorting of areas <3m in size. This disturbance creates biodiversity hotspots (Sutton et al., 2006), and maintains high quality habitat for rare pioneer flora such as *Braya longii* (Hermanutz, 2001). Few studies have focused on restoring small-scale disturbance such as freeze-thaw cycling, which influences ~25% of Earth's land surface (French, 2007), and frost sorting in arctic-alpine, subarctic, and periglacial environments. On the contrary, studies have assessed methods to limit freeze-thaw processes in roadbed construction (Viklander, 1998), and boreal forest plantations and seedbed construction (Chantal et al., 2006).

The natural small-scale freeze-thaw cycling of arctic and alpine region substrates are characterized by the movement of stones and particles during ice lens formation, and the expansion of water horizontally and vertically (Washburn, 1956; Anderson, 1988; Greene, 2002; Peterson et al., 2003). Like many other natural disturbance regimes, freeze-thaw cycling can contribute to nutrient cycling, slowly releasing nutrients to the habitat (Jonasson, 1986; Walker et al., 2004). The development and persistence of freeze-thaw cycling and frost sorting are influenced by several abiotic and biotic variables such as climate, topography, substrate heterogeneity, and vegetation (French, 2007; Hjort and Luoto, 2009). The interaction between these variables is usually an important and complex component of moderating ecosystem function, such as small-scale disturbance and in the restoration of degraded lands such as quarries (Callaham et al., 2008).

On the limestone barrens, small-scale natural disturbance creates high quality habitat for endemic and endangered flora, such as *B. longii*, and common native flora. Such flora are physically adapted to this disturbance, the former possessing a contractile taproot for better anchorage (Meades, 1997; Hermanutz, 2001). Common native species, such as *Dryas integrifolia* Vahl. subsp. *integrifolia* (Rosaceae), are low growing, and well adapted to the frequently disturbed substrates and harsh climatic conditions. Associated vegetated areas include crowberry (*Empetrum nigrum* L. subsp. *nigrum* (Ericaceae)) barrens which are characterized by a thick and complete vegetative ground cover (Meades, 1997). Restoration and maintenance of the natural disturbance regime will be important for the persistence of the limestone barrens plant community as cessation of small-scale disturbance will lead to the displacement of rare species in favour of later successional community assemblages (Platt, 1975; Jonasson, 1986; Haugland and Beatty, 2005) such as the observed crowberry barrens.

Human alteration of limestone habitats is prevalent globally, leading to subsequent soil and substrate loss, and dysfunction in habitat structure and function such as hydrology and disturbance regimes (Tropek et al., 2012). Within the Newfoundland limestone barrens, native substrate particle composition has been significantly altered over the past decades due to road construction and gravel quarrying (Greene, 2002), leading to a reduced fine fraction and disrupting freeze-thaw cycling. Even in substrates where adequate fine material is present, heave potential may be hindered by compaction, from heavy machinery or off-road vehicles, due to pore space loss which is needed for stable ice nuclei formation (Rafuse, 2005; Torrance and Schellekens, 2006). Identifying substrate properties that have been lost outlines what is needed to restore appropriate substrate characteristics and those geophysical characteristics emphasized by Anderson *et al.* (2014), to revive the native small-scale disturbance regime, and restore high quality habitat for the native species assemblages and endangered endemics such as *B. longii* (Greene, 2002).

Determining how to restore small-scale disturbance regimes in at-risk ecosystems will assist development towards and along the target trajectory. Given the lack of incorporation into restoration projects, the goal of this research is to develop protocols addressing the re-establishment of habitat function in terms of the small-scale disturbance regime and structure within a rare and at-risk ecosystem. Here, the small-scale freeze-thaw disturbance regime is required for the maintenance of rare species' habitat. To address this goal, this study outlines protocols via 1) the construction and monitoring of experimental substrate treatments to mimic natural limestone barrens in terms of maximum heave, and number and duration of freeze-thaw cycling; and 2) the reintroduction of native vegetation including the endangered endemic *B. longii* to determine the effectiveness of sowing restoration sites. It is predicted that treatments lacking a high fraction of organic material and possessing more fine material, more closely mimic native limestone barrens, exhibiting a similar number of freeze-thaw cycles, amount of maximum frost-heave, duration of freeze-thaw cycles and a greater proportion of surviving and persistent emergent native seedlings.

3.3 Methods

The study site is located in the small community of Sandy Cove, Newfoundland (Canada; 51°21'17.43"N, 56°39'41.96"W; Figure 3), on the northwestern coast of the Great Northern Peninsula to the east of the Strait of Belle Isle; within the Strait of Belle Isle Ecoregion. It is adjacent to the Sandy Cove Ecological Reserve, a provincial protected area established to protect *B. longii*. The climatic characteristics include 760-900 mm of precipitation per year, approximately 120 frost-free days and daily average temperatures ranging from -0.4° – 5.0° (Banfield, 1983; Roberts, 1983; Environment Canada, 2013). The site has been heavily modified by limestone gravel quarrying and road construction (Janes, 1999; Greene, 2002). The study site is comprised of overburden piles and pits (both legacies of the quarrying), bedrock, limestone pavement and crowberry heath, the latter two being natural vegetation types of the site. All necessary government permits to work within the critical habitat range and handle the seeds of *B. longii* were acquired prior to commencing the study.

3.3.1 Experimental substrate treatments

Experimental substrate treatment plots were constructed in order to establish a protocol to restore substrate characteristics mimicking natural limestone barrens. To achieve this, a randomized complete block design was used to reduce variation attributed to unknown site factors (NCSS, 2012). A total of three blocks (each consisting of six treatments) were established creating three replicates of each treatment. To construct substrate treatment plots, the top layer of the selected overburden piles was removed as it was comprised of undesirable organic material and non-native and invasive vegetation. The remaining material was graded to mimic the historical slope and elevation (Chapter 2) (Firlotte and Staniforth, 1996). The removed material was stored in a contained location, for later removal.

Once the site was graded, three blocks were placed adjacent to the Sandy Cove Provisional Ecological Reserve boundary at the same elevation and slope. Within each block, six randomized 2 x 2m experimental treatment plots were constructed. Two of these six treatments were controls utilizing the quarry floor and overburden material. The remaining four treatments involved manipulation of the control substrate with fine and large limestone material, and combinations thereof to mimic natural limestone barrens. This plot size was selected to permit the development of frost polygons as mean diameters are generally <2m (Greene, 2002). The experimental substrate treatments included: 1) overburden material (O; control); 2) overburden material with large limestone and fine (i.e. silt/clays) material (O+L+F); 3) overburden with large limestone (O+L); 4) large limestone with fine material (L+F); 5) large limestone (L); and 6) no treatment (i.e. existing quarry floor control; QF) (see Appendix VI, Table AVI.1). Overburden and large limestone material was utilized from the study site while fine material was brought from a nearby quarry location (Yankee Point; 5km south) which falls within limestone barrens and the range of *B. longii* (Environment Canada, 2012). Approximately 75kg of fine material was added to those specified substrate treatment plots. The target substrate composition determined from natural reference sites (see Chapter 2) was 10.9±1.4% organic material, 47.6±4.7% fine material, 24.8±2.7% sand, and 27.6±7.2% gravel. Each treatment was raised ~30cm to distinguish from the surface and to control for substrate differences surrounding each treatment which may influence the recovery of the natural disturbance regime such as soil moisture. Fractions were layered using an excavator, and then the tines of the bucket were used to mix the fractions together, and finally tamped lightly with the bucket. Given variability in climate and the complex nature in the development of frost sorted circles, these plots will be preserved for long-term monitoring studies in the recovery of the native disturbance regime.

3.3.2 Monitoring of small-scale disturbance regime for each substrate treatment

Treatments were monitored for maximum frost heave using devices designed after Walker *et al.* (2004) and Romanovsky et al. (2008). One of the three blocks was installed with heave devices, in addition to one in each of adjacent natural limestone pavement and natural crowberry heath (n=8). Each device spanned plots with a transect possessing six associated measuring rods, also known as feet, with 1cm increments (n=6). A blue marker present below the crossbar was used to monitor the amount of maximum heave (see Appendix VI, Figure AVI.1). Given that outer structural rods could not be bolted to the bedrock (Walker *et al.* 2004), measurements at the center and outer posts were taken to ensure the device itself was not being heaved due to frost. Measurements were taken from each of the six rods within each treatment in October 2012, and then again in March, May, June, and July of 2013. Measurements in July 2013 were taken to determine whether wind was affecting the movement of the rods, as maximum heave was not expected to occur at this time of year.

Hobo tidbit® temperature loggers were inserted into the centre of experimental treatment plots to monitor the number and average duration of freeze-thaw cycles, which were defined as a temperature drop below and subsequent rise above 0°C. The length of a cycle was determined as the number of hours the temperature remained below 0°C. As few as eight cycles are required to the development of sorted frost polygons in frost-susceptible regolith (Ballantyne 1996). Both primary (i.e. short cycles in fall and spring) and secondary (i.e. long cycles during winter months) cycles were monitored; secondary cycles are considered to be more important for frost sorting (Perfect et al., 1988). Two of the three blocks were installed with temperature loggers (n=12), including the block installed with the heave devices. Two temperature loggers were also inserted into natural limestone barrens reference habitat to attain a baseline (n=2). Temperature loggers were set to monitor hourly temperatures between October 2012 and May 2013. These dates were selected given that frost cycling within this area begins in late September and continues until June (Banfield, 1983).

3.3.2.1 Statistical Analyses

Two-way ANOVAs and a generalized linear negative binomial model were used to determine if differences existed between experimental substrate treatments in terms of the amount of maximum frost heave, number of freeze-thaw cycles and duration (number of hours) of freeze-thaw cycles. The explanatory variable included treatment, while controlling for the effect of block and month. The Type I ANOVA error structure was used, ordering ‘Block’, ‘Month’ (if applicable), ‘Foot’ (if applicable’), and then ‘Treatment’ to control for the former three terms (Anderson, 2008). ‘Treatment’ was also ordered based on predicted similarity to the limestone barrens reference. To ensure assumptions of error homogeneity, error independence, and normality were not violated, residual and fitted values were examined. The negative binomial distribution, with a log identity, was used to assess the number of freeze-thaw cycles and duration given count data and no set number of trials (Zuur et al., 2007). In addition to testing for the above assumption, data were assessed for overdispersion. All analyses were conducted using R version 3.0.2.

3.3.3 Emergence and survival of native seeds sown in experimental substrate treatments

3.3.3.1 Field experiments with native species

Native seeds were sown within each experimental treatment plot to compare emergence and survival among the substrate treatments. All 18 of the experimental substrate treatments were seeded with *B. longii* (n=540), and *R. rosea*, *D. incana*, and *P. laurentiana* (total for all species, n=648). *B. longii* seeds were obtained from Memorial University's Botanical Garden's *ex situ* collection, while the latter three species were harvested from the study site under permit the previous fall (2012). All seeds were sourced from the study area to maintain local provenance (Bischoff et al., 2006), which has been shown as important for *B. longii* (Noel, 2000). Seeds were cold stratified at 1-3°C for one week prior to scarification. To scarify seeds, fine sandpaper (100-120grit) lining a small container was used similar to Tilley (2003). None of the three other species were scarified as previous studies show germination without scarification (Bliss, 1971). Scarification occurred the day before travelling to the study site for planting. All seeds were maintained under ambient conditions until planting was completed May 2013. Each experimental treatment plot (n=16) was subdivided into nine 50 x 50cm subplots. Within three of these subplots, 10 *B. longii* seeds were sown into each (n=30) using a gridded system to remove confounding effects such as slope, microclimate variability, and position. Three additional subplots were seeded with 12 *R. rosea*, *D. incana,* and *P. laurentiana* seeds each (see Appendix V, Figure AV.2). The three remaining subplots were left unseeded and acted as controls for monitoring of natural seed bank emergence.

Sown seeds were placed on the surface of the soil/substrate and lightly tamped down to ensure adherence to the soil/substrate, without burying the seed. Plots were assessed for seedling emergence in June, July, and August 2013 to determine if the number of emergents differed between experimental treatments. Control plots not seeded were monitored for native and non-native seedling emergence.

3.3.3.2 Laboratory seed germination experiments

To estimate seed viability and germination of samples used in the field experiment, 30 seeds of *B. longii, R. rosea*, *D. incana,* and *P. laurentiana* each were germinated under laboratory conditions. All seeds were cold stratified, while *B. longii* was also scarified similar to above. Seeds were placed on Whatman No.4 paper in sterilized Petri dishes and kept moist with distilled water. Dishes were sealed with Parafilm® and kept in the lab under ambient conditions (~25°C). Three replicates of 10 seeds were used for each species. Dishes were checked daily for germination, and room temperature was recorded. All germinates were transferred to pots containing a standard potting medium and watered regularly. *B. longii* seedlings surviving the transplant were relocated to the Botanical Gardens for further cultivation. Photos of all germinates were taken regularly for use in field identification.

3.3.3.3 Statistical Analysis

The collected count data, and proportion of emergent seedlings was assessed using a generalized linear model. The error structure was modeled using a binomial distribution as a known number of seeds/trials (*B. longii*, n=30; *R. rosea*, *P. laurentiana*, *D. incana*, n=36) were planted. The proportion of seedling emergence within each treatment, was treated as the response. ‘Treatment’ was set as the explanatory variable, controlling for ‘Block’ as a random factor. ‘Block’ was ordered first to control for its effect as outlined by Anderson (2008). The binomial model was assessed for overdispersion, and assumptions of error homogeneity, error independence, and normality. *P. laurentiana* and *D. incana* were not assessed using statistical analysis given the low proportion of emergent seedlings (0.62% for both). All analyses were conducted in R version 3.0.2, using the MASS package (Venable and Ripley, 2002).

3.4 Results

3.4.1 Construction and descriptive properties of experimental substrate treatments

The constructed treatments differed from the reference site in terms of percent gravel (F_5=8.8; p=4.6x10^{-4}), sand (F_5=5.0; p=6.8x10^{-3}), and organic (F_5=15.5; p=1.8x10^{-5}) (see Chapter 2) composition mimicking the onsite variability of available material after quarrying. A post-hoc Tukey test indicated that differences in treatments were between those treatments having added organic material and those lacking the addition (Figure 8.A). Relative to the limestone barrens reference site, a statistical difference was noted for all treatments in terms of organic content (10.9±1.4%), having a greater proportion relative to those treatments lacking added organic material (6.5-7.9±1.3-2.5%), and a lower organic fraction relative to those with added organic material (31.4-41.3±1.9-3.6%; Figure 8.A).

3.4.2 Monitoring of small-scale disturbance regime for each substrate treatment

Overall, significant differences among experimental substrate treatment plots in terms of the number and duration of freeze thaw cycles, and maximum frost heave were not observed, although similarities to the reference site were observed. In particular, treatments lacking added overburden material demonstrated a similar number of freeze-thaw cycles and average duration of these cycles each month compared to natural limestone barrens as predicted.

The re-initiation of a key process in small-scale disturbance, freeze-thaw cycling, was observed in all treatments. The greatest number of cycles was found to occur during the spring months of March and April; the number of cycles ranging across treatments from 7-16/ and 6-17/month, respectively (Figure **9**A). The number of freeze thaw cycles occurring from November 2012 to April 2013 across all treatments was found to significantly differ between months (df=5; p=<0.001), suggesting that some months demonstrate higher cycle frequency. The treatment with the greatest number of freeze-thaw cycles per month on average was the large limestone with fine material (6±2cycles/month), while the treatments with overburden material (4±1cycles/month) and overburden material with large limestone and fine treatment (4±1cycles/month) exhibited the lowest monthly average (Figure **9**A; Table 1). In comparison, the limestone barrens reference site demonstrated an average 8±1cycles/month (Figure **9**A; Table 1). A significant difference was found when comparing treatment to the reference site (df =6; p=<0.001), with the exception of the quarry floor and large limestone with fine material treatments which did not show a significant difference.

The duration of cycles was assessed to determine similarity to natural limestone barrens and the average length of primary and secondary freeze-thaw cycles. Primary freeze-thaw cycles (short spring/fall duration) appear to be occurring in November, March and April, while the secondary cycles (long winter duration) are occurring between December and February (Figure **9**B; Table 2). A significant difference in the duration of cycles was noted for ‘Month’ (df=5; p=<0.001) suggesting that primary and secondary cycles were occurring. Only large limestone with fine material and quarry floor treatments and the limestone barrens exhibited a freeze-thaw cycle in the month of January, while only overburden with large limestone, large limestone with fine material and quarry floor treatments and limestone barrens exhibited a cycle in

February (Figure **9**A & B). All other treatments remained below 0°C from December to March (Figure **9**A & B). This suggests that the treatments lacking fine material and containing a high fraction of organic material may hinder the occurrence of secondary frost heave. Relative to the limestone barrens reference site, large limestone with fine material and quarry floor treatments were most similar in terms of average duration for each cycle occurring within the specified month (Figure **9**B). However, no significant difference among treatments was found (df=6; p=0.07). A difference in 'Block' (df=1; p=<0.001) was noted suggesting high variability in cycle duration between blocks. In general, the limestone barrens demonstrated less variability in average hourly cycle duration per month relative to all treatments, with the large limestone and fines and quarry floor treatments demonstrating a similar pattern in cycle duration (Figure **9**B; Table 2).

All treatments exhibited a significantly lower maximum frost heave (F_6=10.6; p=<0.001; Figure 9.C) relative to the reference site. Differences observed occurred between large limestone with fine material and large limestone (Tukey HSD; p=0.032), and overburden with large limestone and large limestone (Tukey HSD; p=0.016). This difference suggests the presence of fine material or organic material is important in re-establishing frost heave. As anticipated, the target reference limestone barrens demonstrated approximately 6cm of maximum frost heave from October 2012 to June 2013 (Figure **9**C). Experimental treatments lacking organic material demonstrated more frost heave in comparison to those containing organic material supporting what was predicted (Figure **9**C); but the difference was not significant. Unexpectedly, the crowberry barrens demonstrated more frost heave than treatments containing overburden material and large limestone with and without added fine material, and large limestone with added fine material. However, the frost heave demonstrated by the crowberry barrens was comparable to the overburden material treatment.

3.4.3 Emergence and survival of native seeds

Laboratory trials demonstrated a high percent germination for *B. longii* (87%) and *P. laurentiana* (70%). In contrast, *R. rosea* had a low percent germination (23%) and *D. incana* did not germinate in laboratory trials. The number of planted seeds emerging for each species in all field treatments was lower than observed in the laboratory germination trials: *B. longii* (4.1%), *P. laurentiana* (0.6%), *R. rosea* (1.7%) with the exception of *D. incana* (0.6%) which had a higher success in field treatments. Overall, *B. longii*, *P. laurentiana*, and *R. rosea* showed a 90-99% reduction in observed emergence when comparing laboratory to field studies, while *D. incana* demonstrated field emergence not similarly observed in laboratory trials. For *B. longii* and *R. rosea*, no statistical difference was noted between field treatments (Table 3), while the emergence was too low in the other two species to statistically test differences.

3.5 Discussion

This study emphasizes the complex yet important relationship between climate, substrate, geographic location, small-scale disturbance, and vegetation within a globally rare limestone habitat, home to endangered endemic species. It found that small-scale disturbance, an often overlooked functional component, can be incorporated into restoration protocols with relative ease given an understanding of the ecosystem. Like many limestone ecosystems, the limestone barrens have been degraded by human activities such as quarrying and gravel extraction. Limestone areas in general are a challenge to restore (BirdLife/FFI/IUCN/WWF, 2014), however the unique arctic-alpine like climate, extreme environment, substrate properties, and cold-soil processes make the limestone barrens that much more challenging.

Given a large portion of the limestone barrens have been degraded by human activities, 10% of *Braya longii* habitat remains intact (Hermanutz et al., 2009), restoring quarried areas to increase critical habitat for native and endemic flora is a conservation priority. More importantly, restoring functional components such as small-scale disturbance is key to maintaining and restoring current plant communities. Here, partial recovery of the small-scale freeze-thaw disturbance regime was noted after one year, treatments lacking overburden material displaying similarities to the reference site in terms of the number and duration of freeze-thaw cycles. However, given potential recovery, this study proposes a substrate mix to be used in future quarry restoration projects that will allow for small-scale disturbance development and recolonization of native and endemic floral species. Further, this baseline information provides targets for restoration and a measure of restoration success in terms of the small-scale disturbance regime and native species colonization in restored quarry sites globally.

The limestone barrens rely on several climatic characteristics such as cold temperatures, high winds, and precipitation to maintain its small-scale disturbance regime, and the resultant open, non-vegetated areas. Climate change is predicted to influence frost activity regionally (Finnis, 2013) and globally (Jefferies et al., 2010), increasing freeze-thaw frequency and frost-free days which may hinder frost sorting creating relict polygons as observed in Mingan Archipelago National Park Reserve, Canada (Hjort and Luoto, 2009). This may also have negative impacts on the recruitment of endemic species, potentially killing seedlings germinating in the spring, more frequent freeze-thaw cycles ejecting seedling from the substrate (Hermanutz, pers. comm.). This would be a serious issue for the persistence of species such as *B. longii* that require a freeze-thaw induced scarification process for germination (Noel, 2000; Tilley, 2003; Squires, 2010).

Increased frequency of freeze-thaw cycles will also likely reduce the duration of the secondary heave cycle, which is important for frost sorting and has the most impact on ejecting adult plants from the substrate (Perfect et al., 1988), as observed at this study site. This may increase competition and the development of later successional stages that favour vegetative species (Perfect et al., 1988), such as *E. nigrum, D. integrifolia*, and *Salix spp*., and allow the habitat to develop towards *E. nigrum* barrens. Such progression occurs in tall-grass prairies, where small-scale mound creation by badgers (*Taxidea taxus*) are colonized by rare pioneering species initially and displaced by later stage species given the absence of further disturbance (Platt, 1975). The loss or change in small-scale disturbance may alter limestone barrens species distribution, reducing the openness of the habitat, increasing competition, and eliminating those shade-intolerant, disturbance-adapted species and primary colonizers such as *B. longii*. This study's collected baseline data on freeze-thaw cycles allows for continued monitoring and future trend analysis of increasing or decreasing cycle frequency in response to the changing climate and will inform the implementation of adaptive management strategies. Further it will allow for the development of a dynamic reference model as outlined by Hiers et al. (2012) to update baseline data and inform how restoration success of small-scale disturbance is defined at various points through time.

Vegetation surrounding bare and naturally disturbed substrates can positively or negatively impact the development of sorted frost polygons, moisture and nutrient availability, active freeze layer depth, depth of sorting, and rate of freezing (Walker et al., 2004; Hjort and Luoto, 2009). The bordering vegetation associated with limestone barrens is dynamic, and similar to other freeze-thaw disturbed habitats, where the faster freezing bare substrates draw moisture from the surrounding unfrozen vegetated areas, allowing the bare substrates to heave more than vegetated areas (Ping, 2013). Within arctic, alpine, and subarctic environments, sorted frost features generally range between 0.1-10m (Washburn, 1956) while limestone barrens features are <3m in diameter (Greene, 2002) making them more susceptible to the effects of surrounding vegetation.

The absence of vegetation, which moderates soil thermal regime (Hjort and Luoto, 2009), likely allowed all treatments to respond similarly in terms of active layer depth and time/duration of freezing observed in this study. The observed maximum frost heave in natural limestone barrens, however, was expected as a previous study demonstrated similar vertical displacement (Greene, 2002). In contrast, the encroachment and shading by vegetation may hinder sorted polygon development, acting as a stabilizing factor resulting in relict polygons and periglacial features (Peterson et al., 2003; Hjort and Luoto, 2009). Smaller features, including those on the limestone barrens, are likely more susceptible to the encroachment and shading of vegetation given their small area but also shallower sorting depth (Ray et al., 1983; Daanen et al., 2008). The complex relationship between bare substrates and vegetation is evident, and is a key component to ecosystem function. Continued monitoring of this relationship in the treatment plots and constructed nucleation sites, consisting of rescued vegetation incorporated into the restoration site, is needed to fully determine its influence on restoration.

Site revegetation is an important aspect of most restoration projects, especially those recovering rare plant species such as *B. longii*. Some studies argue that spontaneous regeneration and minimal human intervention is an effective approach to maintain rare habitats, biodiversity, and endemic flora in old quarry sites (Tomlinson et al., 2008; Prach et al., 2011). However, in arctic- and alpine-like regions where organic and nutrient content is low, the growing season is short, climate conditions are harsh, and recolonization is slow (Billings, 1973; Firlotte and Staniforth, 1996; Mason, 2014), the assisted recovery of native vegetation is fundamental to restoration success.

For example, after ~45 years, native limestone barrens species recolonization within old quarry sites is slow, species compositions relative to reference sites are dissimilar (Mason, 2014), and frost-sorting has not recovered likely given the lack of substrate heterogeneity (Greene, 2002). High salt concentrations in degraded substrates due to the coastal location of the limestone barrens and rapid evaporation on the bare quarry floor may also hinder species such as *D. integrifolia* from colonizing (Walker et al., 2004). A combination of elements are likely influencing the lack of recolonization, determining those missing components will be important for restoring the foundation needed for further habitat development.

Substrate manipulations in this study demonstrated that sown seeds were able to germinate in the treatments. Here, a low seedling emergence (<5%) was similar to that observed by Müller et al. (2011), who found low field germination success (<10%) for most arctic-alpine species, which they attributed to temperature and moisture. Previous studies sowing *B. longii* into natural limestone barrens habitat demonstrated 26-50% emergence (Tilley, 2003; Pelley, 2011). The higher emergence of *B. longii* observed in previous studies may be due to year to year climate variability, different lengths of stratification, and the sowing of seeds into existing natural high quality habitat. Additionally, low emergence and death of *B. longii* may have resulted from seeds germinating below the surface in the pore spaces between the gravel, which has previously been noted in human-modified substrates (Hermanutz, pers. comm.). Survival of those observed emergent seedling will be important as seedling monitoring in previous studies demonstrated persistence following the first year (Squires, pers. comm.). Despite the observed emergence, *B. longii* has long-lived seeds (Hermanutz et al., 2002) and continued monitoring may result in the detection of emergence in subsequent years when conditions are optimal, freeze-thaw cycles bring them closer to the surface, and seed coats have been further scarified (Hermanutz, pers. comm.).

The re-establishment of key habitat functions, such as the disturbance regime, along the target trajectory may take years to centuries (SER and IUCN, 2004), frost sorting in particular can take years to millennia (Hallet, 2013). It should be emphasized that the substrate treatments in this study are at the initial stages of development and are expected to develop towards the currently observed reference areas over time. The small amount of variability in number of freeze-thaw cycles and their duration observed in the natural reference site relative to the substrate treatments suggest that the substrate treatments are within the early stages of development and in theory could shift towards various trajectories. Allowing the treatments to settle for more than a year given the recent disturbance will likely reduce observed variability among blocks. However, an increase in the number of blocks in future studies may be needed.

Despite the predicted time scale for recovery, the limestone barrens are located at the southern edge of frost-features and may recover within a shorter time period given appropriate conditions. Ballantyne (1996), for example, noted re-establishment of frost sorting after two years in eastern Scotland. Further, observations on the limestone barrens suggest the recovery of frost sorting after ~45years (Copp, pers. observ.) where substrate has not been entirely removed. These naturally disturbed, open non-vegetated areas are high quality critical habitat for the endemic *Braya longii* (Environment Canada, 2012) and other native limestone barrens flora.

Similarities between experimental treatments and the natural reference site in terms of freeze-thaw cycles were observed, while noted differences were expected given the area's successional clock has been reset (Bradshaw, 1987). Given the lack of substrate for natural recovery in most quarry sites, a restoration substrate mix to recover the native freeze-thaw disturbance regime is 1:3:3:5 of organic material, large limestone gravel, sand, and silt/clay, respectively. Given that the quarry floor when mixed displayed characteristics similar to the reference site, it can be suggested that quarry floors with adequate fine material may be compacted, hindering frost sorting as suggested by Rafuse (2005). Further some organic material is needed to amend the quarry floor to achieve a closer resemblance to the proposed natural reference site target mixture for substrate restoration.

However, this study emphasizes that without the assisted restoration of small-scale disturbance regimes, such systems and their rare flora will either take much longer to recover, not recover at all due to the complete lack of substrate or recover along an undesired trajectory not characteristic of the limestone barrens that will not support the native rare and endemic flora. Also, failure to remove the large amount of organic overburden will likely harbour a seedbank comprised of weedy species not native to the limestone barrens and producing a novel community. However, as outlined by Hiers et al. (2012), measuring project success towards the desired system is dynamic. Systems, including the reference site and its corresponding baseline information will change over time thus targets need to be adaptable (Hiers et al., 2012). Acknowledging this aspect will allow for the implementation of these protocols crucial in restoring function and structure in critical and globally rare limestone habitats.

3.6 Recommendations

Under typically climate condition for the region, the assisted restoration of limestone quarry sites following gravel extraction to re-establish the small-scale disturbance regime and native vegetation community is recommended. Allowing for spontaneous recovery used in hard rock quarries (Tomlinson et al., 2008) is not appropriate for limestone barrens habitats. Furthermore, on-site organic material stored in overburden piles should not be incorporated into the restoration of limestone habitats, contrary to the recommendations of other studies (Firlotte and Staniforth, 1996). Rather, its inclusion would hinder the redevelopment of the small-scale freeze-thaw cycling and frost sorting disturbance regime, likely preventing recolonization of listed endemic species, and promoting colonization of undesirable non-native invasive species, as has been observed at this site.

Future short and long term monitoring is needed to determine whether the constructed plots develop as predicted and display restoration of the native disturbance regime. Lack of development with time will trigger the implementation of adaptive management strategies. Strategies may suggest that more precise substrate fractions are needed or that the raised plot design should have been sunk into the ground similar to Ballantyne (1996) to reduce wind desiccation and increase potential of needle ice formation. Additionally, further monitoring of the nucleation sites are needed to determine if their inclusion into adaptive management and restoration design improves development of habitat function and structure within the historical range. Historically, the site was comprised of both limestone and *E. nigrum* barrens (see Chapter 2) and inclusion of both should prove beneficial in integrating the restored site into the existing landscape matrix.

Given the slow rate of recolonization in arctic and alpine environments, assisted revegetation is crucial (Forbes and Jefferies, 1999). Seeding demonstrated a low level of success, however seeds are long lived and may germinate in subsequent years. Further, the transplanting of established native plants rescued from the site into nucleation plots was to date found to be quite successful (Copp, pers. observ.) suggesting a combined use of seeding and planting. However, Urbanska (1997) observed that most death occurs within the first three to four years and further monitoring of these transplants is recommended to determine success. As an entrepreneurial venture, greenhouse operations growing common native plants for such restoration projects are ideal, though costly. Additionally, the use of turf transplants from active quarry locations should be attempted following the guidelines of Aradottir (2012). The dynamic relationship between open limestone habitat and vegetated habitat should be emphasized, developing restoration plans that incorporate both elements will be important for achieving the target trajectory and integration into the landscape matrix.

3.7 Acknowledgements

This study was funded by the Natural Sciences and Engineering Research Council of Canada (CGS to CC), Departments of Environment and Conservation (Wildlife) and Natural Resources (Mines and Energy); Limestone Barrens Habitat Stewardship Program, and Memorial University. We are grateful to those who helped setup the experimental treatments including J. Humber, M. Whalen and M. Wilkes; collect the data, including J. Hoddinott, D. House and A. Mason, volunteers Michael Burzynski and Anne Marceau, Sandy Cove community members, the local Green Teams, and Provincial Government employees including C. Hanel, T. Leonard and E. Smith.

3.8 References

Anderson, S. (1988). The upfreezing process: Experiments with a single clast. *Geological Society of America Bulletin*, **100**, 609–621.

Anderson, D.R. (2008). *Model Based Inference in the Life Sciences - A Primer on Evidence*. Springer.

Anderson, M.G., Clark, M. & Sheldon, A.O. (2014). Estimating climate resilience for conservation across geophysical settings. *Conservation Biology*, 1–15.

Aradottir, A.L. (2012) Turf transplants for restoration of alpine vegetation: does size matter? *Journal of Applied Ecology*, **49**, 439–446.

Ballantyne, C.K. (1996). Formation of miniature sorted patterns by shallow ground freezing: A field experiment. *Permafrost and Periglacial Processes*, **7**, 409–424.

Banfield, C.E. (1983). Chapter 3: Climate. *Biogeography and Ecology of the Island of Newfoundland* pp. 37–106. Dr. W. Junk Publishers, The Hague, The Netherlands.

Billings, W.D. (1973). Arctic and alpine vegetations: Similarities, differences, and susceptibility to disturbance. *BioScience,* **23**, 697–704.

Billings, W.D. & Mooney, H.A. (1968). The ecology of arctic and alpine plants. *Biological Reviews*, **43**, 481–529.

BirdLife/FFI/IUCN/WWF. (2014). *Joint Briefing Paper on Extraction and Biodiversity in Limestone Areas'*. Cambridge, UK.

Bischoff, A., Vonlanthen, B., Steinger, T. & Müller-Schärer, H. (2006). Seed provenance matters — Effects on germination of four plant species used for ecological restoration. *Basic and Applied Ecology*, **7**, 347–359.

Bliss, L.C. (1971). Arctic and Alpine Plant Life Cycles. *Annual Review of Ecology and Systematics*, **2**, 405–438.

Bradshaw, A.D. (1987). The reclamation of derelict land and ecology of ecosystems. *Restoration Ecology: A Synthetic Approach to Ecological Restoration* pp. 53–74. Cambridge University Press, Cambridge-New York, NY-Melbourne.

Callaham, M.A., Rhoades, C.C. & Heneghan, L. (2008). A striking profile: Soil ecological knowledge in restoration management and science. *Restoration Ecology*, **16**, 604–607.

Chantal, M. de, Rita, H., Bergsten, U., Löfvenius, M.O. & Grip, H. (2006). Effect of soil properties and soil disturbance on frost heaving of mineral soil: a laboratory experiment. *Canadian Journal of Forest Research*, **36**, 2885–2893.

Daanen, R.P., Misra, D., Epstein, H., Walker, D. & Romanovsky, V. (2008). Simulating nonsorted circle development in arctic tundra ecosystems. *Journal of Geophysical Research: Biogeosciences*, **113**, 1–10.

Denslow, J.S. (1985). Disturbance-Mediated Coexistence of Species. *The Ecology of Natural Disturbance and Patch Dynamics* pp. 307–323. Academic Press, Inc, Orlando, Florida.

Environment Canada. (2012). *Recovery Strategy for the Long's Braya (*Braya Longii*) and the Fernald's Braya (*Braya Fernaldii*) in Canada*. Environment Canada, Ottawa.

Environment Canada. (2013). *Daniels Harbour Newfoundland Daily Data Report for November 2013*. Environment Canada.

Finnis, J. (2013). *Projected Impacts of Climate Change for the Province of Newfoundland & Labrador*. Provincial Government of Newfoundland & Labrador, the Office of Climate Change, Energy Efficiency & Emissions Trading.

Firlotte, N. & Staniforth, R.J. (1996). Strategies for revegetation of disturbed gravel areas in climate stressed subarctic environments with special reference to Churchill, Manitoba, Canada: a literature review. *International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts*, **33**, 49–52.

Forbes, B.C. & Jefferies, R.L. (1999). Revegetation of disturbed arctic sites: constraints and applications. *Biological Conservation*, **88**, 15–24.

French, H.M. (2007). *The Periglacial Environment*, 3rd Ed. John Wiley & Sons, Ltd, Southern Gate, Chichester, West Sussex.

Greene, S. (2002). *Substrate Characteristics of Braya Habitat on the Limestone Barrens, Great Northern Peninsula, Newfoundland*. B.Sc. Honours thesis, Memorial University, Department of Geography, St. John's, NL.

Hallet, B. (2013). Stone circles: form and soil kinematics. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **371**, 1–17.

Haugland, J.E. & Beatty, S.W. (2005). Vegetation establishment, succession and microsite frost disturbance on glacier forelands within patterned ground chronosequences. *Journal of Biogeography*, **32**, 145–153.

Hermanutz, L. (2001). *Conservation of Rare Plant Species on the Limestone Barrens of Newfoundland*. CWS-WWF report, Endangered Species Recovery Fund, Toronto, Ontario.

Hermanutz, L.A., Mann, H., Anions, M.F.E., Ballam, D., Bell, T., Brazil, J., Djan-Chékar, N., Gibbons, G., Maunder, J., Meades, S.J., Nicholls, W., Smith, N. & Yetman, G. (2002). *National Recovery Plan for Long's Braya (*Braya Longii *Fernald) and Fernald's Braya (*Braya Fernaldii *Abbe)*. National Recovery Plan, Canadian Wildlife Service, Ottawa, Ontario.

Hermanutz, L., Squires, S. & Pelley, D. (2009). *2008 Limestone Barrens Research Report*. Wildlife Division, Department of Environment and Conservation, Government of Newfoundland and Labrador, Comer Brook, Canada.

Hiers, J.K., Mitchell, R.J., Barnett, A., Walters, J.R., Mack, M., Williams, B. & Sutter, R. (2012). The dynamic reference concept: Measuring restoration success in a rapidly changing no-analogue future. *Ecological Restoration*, **30**, 27–36.

Hjort, J. & Luoto, M. (2009). Interaction of geomorphic and ecologic features across altitudinal zones in a subarctic landscape. *Geomorphology*, **112**, 324–333.

Janes, H. (1999) *Braya Longii (*Long's Braya*), Braya Fernaldii (*Fernald's Braya*), and Disturbance on Newfoundland's Great Northern Peninsula*. B.Sc. Honours thesis, Memorial University, Department of Geography, St. John's, NL.

Jefferies, R.L., Walker, N.A., Edwards, K.A. & Dainty, J. (2010). Is the decline of soil microbial biomass in late winter coupled to changes in the physical state of cold soils? *Soil Biology and Biochemistry*, **42**, 129–135.

Jonasson, S. (1986). Influence of frost heaving on soil chemistry and on the distribution of plant growth forms. *Geografiska Annaler. Series A, Physical Geography*, **68**, 185–195.

Levin, S.A. & Paine, R.T. (1974). Disturbance, patch formation, and community structure. *Proceedings of the National Academy of Sciences*, **71**, 2744–2747.

Mason, A. (2014). *Temporal Patterns of Plant Recolonization on Limestone Quarries*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Meades, S.J. (1997). *COSEWIC Status Report on the Long's Braya,* Braya Longii *in Canada*. Ottawa, Ontario.

Müller, E., Cooper, E.J. & Alsos, I.G. (2011). Germinability of arctic plants is high in perceived optimal conditions but low in the field. *Botany*, **89**, 337–348.

NCSS. (2012). Chapter 565: Randomized block analysis of variance. *PASS Sample Size Software* pp. 1–11.

Noel, L. (2000). *The Effect of Disturbance on the Seedling Recruitment and Persistence of* Braya Longii *and* Braya Fernadii. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Pelley, D.E.E. (2011). *Reintroduction Methods on the Limestone Barrens of Newfoundland for Three Endemic Plant Species: The Endangered Braya Longii, Threatened Braya Fernaldii (Brassicaceae), and the Endangered Salix Jejuna (Salicaceae)*. Masters of Environmental Science, Memorial University, St. John's, NL.

Perfect, E., Miller, R.D. & Burton, B. (1988). Frost upheaval of overwintering plants: A quantitative field study of the displacement process. *Arctic and Alpine Research*, **20**, 70–75.

Peterson, R.A., Walker, D.A., Romanovsky, V.E., Knudson, J.A., Raynolds, M.K. & Krantz, W.B. (2003). A differential frost heave model: cryoturbation-vegetation interactions. *Proceedings of the Eighth International Conference on Permafrost* pp. 885–890.

Ping, C.L. (2013). Gelisols: Part I. Cryogenesis and state factors of formation. *Soil Horizons*, **54**, 1–4.

Platt, W. (1975). Colonization and formation of equilibrium plant species associations on badger disturbances in a tall-grass prairie. *Ecological Monographs*, **45**, 285–305.

Prach, K., Řehounková, K., Řehounek, J. & Konvalinková, P. (2011). Ecological restoration of central European mining sites: A summary of a multi-site analysis. *Landscape Research*, **36**, 263–268.

Rafuse, G. (2005). *The Impact of off-Road Vehicles on the Limestone Barrens Habitat and Resident Plants Endemic to the Great Northern Peninsula, NL, Canada*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Ray, R.J., Krantz, W.B., Caine, T.N. & Gunn, R.D. (1983). A model for sorted patterned-ground regularity. *Journal of Glaciology*, **29**, 317–337.

Roberts, B.A. (1983). Chapter 4: Soils. *Biogeography and Ecology of the Island of Newfoundland* pp. 107–162. Dr. W. Junk Publishers, The Hague, The Netherlands.

Romanovsky, V.E., Marchenko, S.S., Daanen, R.P., Sergeev, D.O. & Walker, D.A. (2008). Soil climate and frost heave along the Permafrost/Ecological North American Arctic Transect. *Conference Proceedings* pp. 1–6. Fairbanks.

SER & IUCN. (2004). *Ecological Restoration, a Means of Conserving Biodiversity and Sustaining Livelihoods*. Society for Ecological Restoration International; IUCN, Tucson, Arizona, USA; Gland, Switzerland.

Sigafoos, R.S. (1952). Frost action as a primary physical factor in tundra plant communities. *Ecology*, **33**, 480–487.

Squires, S.E. (2010). *Insect Pests and Pathogens Compromise the Persistence of Two Endemic and Rare* Braya *(Brassicaceae)*. Doctor of Philosophy, Memorial University, St. John's, NL.

Sutton, J.T., Hermanutz, L. & Jacobs, J.D. (2006). Are frost boils important for the recruitment of arctic-alpine plants? *Arctic, Antarctic, and Alpine Research*, **38**, 273–275.

Thorpe, A.S. & Stanley, A.G. (2011). Determining appropriate goals for restoration of imperiled communities and species. *Journal of Applied Ecology*, **48**, 275–279.

Tilley, S. (2003). *The Factors Governing the Distribution of the Rare Plants* Braya Longii *and* Braya Fernaldii *(Brassicaceae) in Natural Habitats*. B.Sc. Honours thesis, Memorial University, Department of Biology, St. John's, NL.

Tomlinson, S., Matthes, U., Richardson, P.J. & Larson, D.W. (2008). The ecological equivalence of quarry floors to alvars. *Applied Vegetation Science*, **11**, 73–82.

Torrance, J.K. & Schellekens, F.J. (2006). Chemical factors in soil freezing and frost heave. *Polar Record*, **42**, 33–42.

Tropek, R., Kadlec, T., Hejda, M., Kocarek, P., Skuhrovec, J., Malenovsky, I., Vodka, S., Spitzer, L., Banar, P. & Konvicka, M. (2012). Technical reclamations are wasting the conservation potential of post-mining sites. A case study of black coal spoil dumps. *Ecological Engineering*, **43**, 13–18.

Urbanska, K.M. (1997). Safe Sites - Interface of Plant Population Ecology. *Restoration Ecology and Sustainable Development* pp. 81–110. Cambridge University Press.

Venable, W.N. & Ripley, B.D. (2002). *Modern Applied Statistics with S*, 4th ed. Springer, New York, NY.

Viklander, P. (1998). Laboratory study of stone heave in till exposed to freezing and thawing. *Cold Regions Science and Technology*, **27**, 141–152.

Walker, D.A., Epstein, H.E., Gould, W.A., Kelley, A.M., Kade, A.N., Knudson, J.A., Krantz, W.B., Michaelson, G., Peterson, R.A., Ping, C.-L., Raynolds, M.K., Romanovsky, V.E. & Shur, Y. (2004). Frost-boil ecosystems: complex interactions between landforms, soils, vegetation and climate. *Permafrost and Periglacial Processes*, **15**, 171–188.

Washburn, A.L. (1956) Classification of patterned ground and review of suggested origins. *Geological Society of America Bulletin*, **67**, 823–866.

White, P.S. & Pickett, S.T.A. (1985). Natural Disturbance and Patch Dynamics. *The Ecology of Natural Disturbance and Patch Dynamics* pp. 3–13. Academic Press, Inc, Orlando, Florida.

Zuur, A.F., Ieno, E.N. & Smith, G.M. (2007). *Analysing Ecological Data*. Springer, New York, NY.

Table 1. Average number of freeze-thaw cycles for observed for each month (±standard error). Abbreviations: L = limestone; F = fine silt/clay material; LB = limestone barrens; O = overburden (organic); QF = quarry floor.

Table 2. Average duration (h) of freeze-thaw cycles observed for each month. (±standard error). Abbreviations: L = limestone; F = fine silt/clay material; LB = limestone barrens; O = overburden (organic); QF = quarry floor.

Table 3. Analysis of deviance table (ANODEV Type I test) assessing whether the proportion of *B. longii* and *R. rosea* seeds that emerged differed as a function of treatment (fixed) and block (random). Treatment and block show no significant effect on seedling emergence. Calculations were run in R version 3.0.2, using the MASS package. Abbreviations: DF=degrees of freedom; LR = likelihood ratio.

Figure 8. Substrate particle composition and organic content (%) for each of the constructed experimental substrate treatment plots with standard error bars. Abbreviations: L = limestone; F = fine silt/clay material; LB = limestone barrens; O = overburden (organic); QF = quarry floor.

Figure 9. Freeze-thaw properties for each experimental substrate treatment in relation to the limestone barrens control (±standard error). Crowberry barren was only mearued for average maximum frost heave. A) Average number of freeze-thaw cycles observed for each month; B) Average durations (h) of each freeze-thaw cycle for each month; C) Average maximum frost heave observed for each treatment from October 2012 – June 2013. Abbreviations: CB = crowberry barrens; L = limestone; F = fine silt/clay material; LB = limestone barrens; O = overburden (organic); QF = quarry floor.

Table 1.

Treatment	Number of Freeze-Thaw Cycles (±SE) Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	Ave.
O	4.0 (±1.0)	3.5 (±0.5)	0.0 (±0.0)	0.0 (±0.0)	9.5 (±2.5)	6.0 (±2.0)	3.8 (±1.1)
O+L	3.0 (±1.0)	2.5 (±0.5)	0.0 (±0.0)	0.5 (±0.5)	8.0 (±7.0)	10.0 (±6.0)	4.0 (±1.6)
O+L+F	3.5 (±0.5)	3.0 (±1.0)	0.0 (±0.0)	0.0 (±0.0)	7.0 (±3.0)	8.5 (±5.5)	3.7 (±1.3)
L	2.5 (±2.5)	2.0 (±2.0)	0.0 (±0.0)	0.0 (±0.0)	13.5 (±3.5)	14.5 (±4.5)	5.4 (±2.0)
L+F	5.5 (±1.5)	4.5 (±0.5)	1.0 (±0.0)	0.5 (±0.5)	13.5 (±0.5)	13.0 (±0.0)	6.3 (±1.6)
QF	4.5 (±0.5)	3.5 (±1.5)	0.5 (±0.5)	0.5 (±0.5)	10.0 (±6.0)	15.5 (±2.5)	5.8 (±1.8)
LB	6.5 (±0.5)	5.5 (±0.5)	1.0 (±0.0)	1.0 (±0.0)	15.5 (±0.5)	16.5 (±1.5)	7.7 (±1.9)

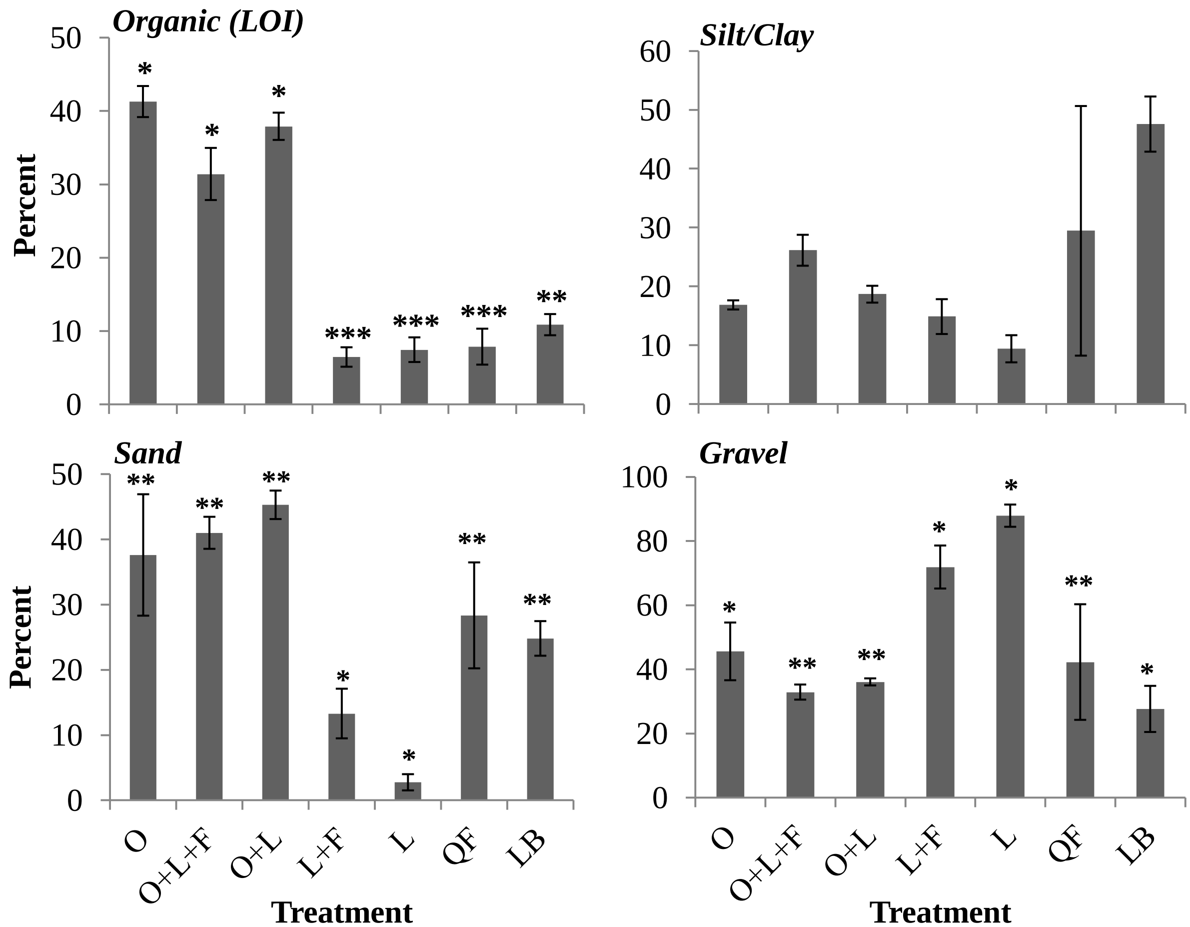
Table 2.

Treatment	Duration of Freeze-Thaw Cycles (hrs) (±SE) Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
O	39.6 (±20.1)	614.6 (±310.6)	-	-	19.3 (±5.5)	23.1 (±7.0)
O+L	62.5 (±23.7)	1056. 7 (±649.9)	-	698.0 (NA)	23.9 (±8.0)	18.6 (±5.1)
O+L+F	56.0 (±24.7)	700.3 (±389.0)	-	-	23.2 (±6.0)	15.1 (±5.2)
L	43.8 (±24.9)	515.5 (±400.5)	-	-	22.7 (±5.7)	16.0 (±2.8)
L+F	40.0 (±14.2)	211.3 (±79.8)	784.5 (±381.5)	707.0 (NA)	20.4 (±3.6)	13.9 (±2.0)
QF	51.22 (±17.7)	133.1 (±61.3)	403.0 (NA)	689.0 (NA)	18.2 (±3.4)	14.2 (±2.9)
LB	36.7 (±13.9)	161.8 (±56.7)	401.0 (±1.00)	694.0 (±7.0)	18.7 (±1.7)	14.1 (±2.3)

Table 3.

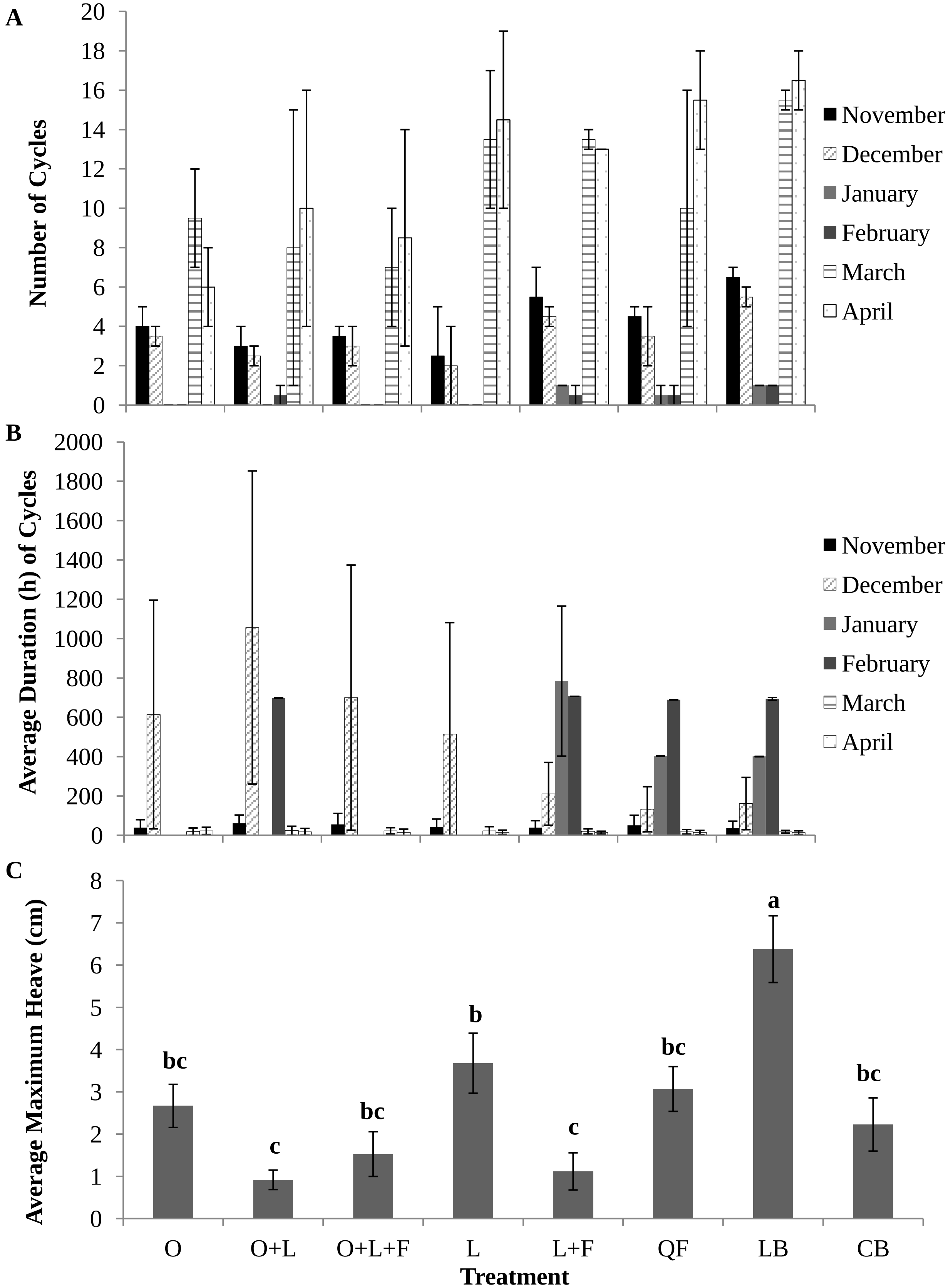
Species	Variable	LR Chisq	DF	Pr (>Chisq)
B. longii	**Treatment**	8.6071	5	0.1258
	Block	3.6182	2	0.1638
R. rosea	**Treatment**	1.6070	5	0.9004
	Block	2.3279	2	0.3123

Figure 8.



Organic (LOI)
Silt/Clay
Sand
Gravel
Percent
Treatment
O
O+L+F
O+L
L+F
L
QF
LB

Figure 9.



A
Number of Cycles
20
18
16
14
12
10
8
6
4
2
0
November
December
January
February
March
April
B
Average Duration (h) of Cycles
2000
1800
1600
1400
1200
1000
800
600
400
200
0
November
December
January
February
March
April
C
Average Maximum Heave (cm)
8
7
6
5
4
3
2
1
0
bc
c
bc
b
c
bc
a
bc
O
O+L
O+L+F
L
L+F
QF
LB
CB
Treatment

CHAPTER 4

4 SUMMARY AND CONCLUSIONS

In rare, at-risk ecosystems the urgency to restore degraded habitats is emphasized by the lack of intact natural areas remaining on the landscape that are important for unique floral assemblages and endemic species. Like many other limestone ecosystems, the limestone barrens of Newfoundland (Canada) have been degraded by human activities and their legacy effects. Determining reference sites and targets for the restoration of these sites is key given their unique characteristics such as arctic/alpine-like climate, flora, and freeze-thaw substrate properties. The use of reference sites, when present, is important for the recovery of structural components including landscape topography and vegetation, and the functional small-scale freeze-thaw disturbance regime within degraded rare at-risk ecosystems including limestone ecosystems. This thesis investigated the development of recommendations to inform protocols using remnant reference sites to restore critical limestone barrens habitat within old quarry sites as outlined in the Federal Recovery Strategy for *Braya fernaldii* and *B. longii*, but also to provide a broadly applicable approach to other at-risk limestone pavement ecosystems.

Reference sites for restoration are not only important for setting targets, but also for monitoring outcomes and success. Remnant high quality limestone habitat identified in aerial photos and described through field surveys is characterized by frost heave, frost sorting, high manganese, lithium, silt/clay and bare ground cover, and low phosphorus, and organic content. Furthermore, they are colonized predominately by *Juniperus horizontalis*, *Erigeron hyssopifolius*, *Dryas integrifolia*, *Thalictrum* *alpinum*, *Anemone parviflora* and *Packera paupercula*. In comparison, the degraded quarry floor and commonly used overburden material for restoration are dissimilar in terms of vegetation, substrate and nutrient composition. These differences underscores two key points: 1) the absence of vegetative and natural disturbance recovery of the study site towards limestone barrens on degraded sites emphasizing the need for human intervention, rather than a non-intervention expecting regeneration; and 2) unlike other quarry restoration efforts that utilize overburden material to restore soil and substrate it is not recommended here as it will hinder progression along the target structural and functional trajectory. Comparing the degraded site's abiotic and biotic characteristics to the reference site provides a goal for restoration and monitoring. Further, acknowledging that reference systems are not static and rather dynamic will inform the design and implementation of adaptive management strategies to assist the system along the target trajectory and appropriately define and redefine restoration success.

This thesis included historical aerial photograph analyses in the general site assessment procedure to determine how the landscape and limestone barrens ecosystem has been altered, fragmented, and lost due to human activities from pre-human modification (1948) to current conditions. Limestone barrens are noted to occur sparsely on the landscape, generally atop ancient beach ridges. This sparse distribution was supported by the low percent potential habitat (10%) observed at the study site in 1948. Historical human-modification of the study site and associated limestone barrens includes quarrying and road construction; the latter having the greatest impact. These activities resulted in an approximate 43% reduction of the potential habitat identified (i.e., of the 10%) in 1948 at the study site, with human activities degrading 39% of the study site as a whole. Surveying these remnant patches highlighted that not all observed potential limestone barrens identified in aerial photographs are high quality (open, non-vegetated, with intact freeze-thaw disturbance and frost sorting) promoting the inhabitation of rare flora such as *B. longii*. The limited high quality habitat reiterates the sparse distribution of suitable limestone barrens previously noted on the landscape for rare flora, which in combination with the level of observed degradation caused by road construction and quarry activity drives the need for restoration.

The acquired information was also used to inform landscape reconstruction to recover key characteristics such as slope for the restoration of small-scale freeze-thaw disturbance. This approach is unique in that it has not been previously utilized to restore historical site topography, differing from the use of the surrounding landscape to inform site reconstruction. The identification of remnant intact patches allowed for the construction of a surface model depicting the historic site topography which will assist restoration efforts and inform best practices for quarries upon closure. In combination, baseline information from the reference habitat and modeled surface topography will guide subsequent steps to restore key functional and structural aspects of limestone barrens habitat.

Using this baseline information as a foundation, the third chapter addressed restoring the small-scale freeze-thaw disturbance regime of the habitat. An understanding of the landscape topography and limestone barrens substrate characteristics was used to construct and assess substrate manipulations for the restoration of the disturbance regime in terms of maximum frost heave, and number and duration of freeze-thaw cycles. Treatments lacking added overburden material were the most similar to the reference site in terms of the average number of frost cycles and duration. These treatments also visually appeared to demonstrate frost sorting suggesting partial recovery of cold-soil processes. Treatments were not expected to perfectly mimic the natural limestone barrens reference site, however the observed similarities suggest the presence and re-establishment of the natural disturbance regime, supporting its continued inclusion in restoration efforts.

Given that time is a well-documented requirement for natural processes to resume at restoration sites, the quick recovery was unexpected. Long term monitoring is needed to determine how these treatments will continue to develop towards and in parallel with the limestone barrens target. Despite the need for continued monitoring of the current study plots, this study provides a starting point to begin the implementation of restoration efforts in old quarry sites. Incorporating the restoration of appropriate substrates into protocols is important for the continued conservation of this unique habitat and its endangered endemic flora such as *B. longii* who rely on its role in maintaining high quality habitat.

The native flora seeding experiments, including the endangered endemic *B. longii*, resulted in low percent emergence. Low emergence was expected given germination syndromes; and this does not suggest that the seeding of common native vegetation on the site is an ineffective means to assist recolonization. Rather, seeds are expected to germinate in subsequent years thus monitoring is needed. Also, an important reason for seeding is the inability of some species such as *Braya longii* to survive any other means of re-introduction (Hermanutz, pers. comm.). The presence of emergence indicates the ability of seeds, including those of the endemic *B. longii*, to germinate in the constructed treatments. Seeds are expected to continue to germinate in subsequent years and how these germinates respond over time will be key to determining persistence. However, other methods of revegetation should be explored including turf transplants from natural areas with the absence of invasive species, and nucleated transplants using cuttings to reduce burden on native seed sources. Determining the best methods for site revegetation given the lack of recolonization by native limestone barrens inhabitants since human disturbance will be critical to habitat development along the target trajectory.

This thesis proposes recommendations to inform sustainable protocols to restore limestone barrens habitat function and structure in un-rehabilitated quarry sites. It acknowledges the habitat's complexity, incorporating historical and current knowledge into the development of restoration protocols, emphasizing the continued use of reference sites using present and historical landscape characteristics as restoration guides. Furthermore, given that systems are not static, variables predicted to change such as climate are acknowledged and discussed. For example, the impact of climate change on small-scale freeze-thaw disturbance will be an important consideration in the adaptive management of restoration protocols in the future. Such considerations will shape strategies to assist habitat development, maintain small-scale disturbance regimes, ensure long-term persistence of threatened and endangered inhabitants, and allow for the incorporation of novel characteristics to attain achievable outcomes. The recommendations outlined in this thesis provide a baseline methodology to restore limestone barrens habitat in degraded quarry sites, addressing the Federal Recovery Strategy's target to expand and restore critical habitat, natural freeze-thaw disturbance and *B. longii* within its historical range.

4.1 RECOMMENDATIONS TOWARDS SUSTAINABLE RESTORATION PROTOCOLS

This thesis provides recommendations to restore limestone barrens habitat and its small-scale freeze-thaw disturbance regime, and increase critical habitat for the rare flora. It is suggested that historical aerial photographs be used as a preliminary assessment to visualize and reconstruct the landscape prior to human disturbance. This step outlines elements such as slope which are important for the restoration of the disturbance regime, and determines reference sites to set targets, and monitor restoration efforts.

A general assessment of the degraded study site relative to identified reference sites confirms that overburden piles with high organic fractions should not be used in limestone barrens habitat restoration. However, given the dynamic relationship between crowberry barrens and limestone barrens, some material should be saved and treated to remove undesirable seeds and species to restore crowberry barrens patches among limestone barrens restoration sites. Also, the removal of these piles will restore the gently sloping site topography. Quarry floors will need to be supplemented to improve substrate heterogeneity; increasing the fine and larger gravel fractions to more closely mimic limestone barrens and allow for the restoration of the small-scale freeze-thaw disturbance regime and the initiation of frost sorting.

Lastly, to revegetate the site with common native flora, both seeding and other methods such as turf transplants from new local quarry sites should be utilized. Direct planting is an option that has proven effective to date. Critical to overall success though will be continued monitoring and the implementation of adaptive management within any site that has been restored to ensure development towards the target trajectory and continued conservation of this unique ecosystem and its rare flora.

Appendix I: Key Terms and Abbreviations

Key Terms

Borrow pit: an area where material has been dug for use in another location. Here, material from the limestone barrens was used to construct the Viking trail highway.

Dynamic reference concept: both reference and restored sites change simultaneously along their target trajectories, emphasizing that the reference site is dynamic and not static (Hiers et al., 2012).

Ecological memory: Past environmental events such as glaciation, that shaped the current landscape, its heterogeneity and topography remains embedded in systems to form a component of ecosystem resilience (Balaguer et al., 2014).

Hybrid system: a system that retains historical characteristics, in addition to possessing novel characteristics (Hobbs et al., 2009).

Novel system: a system that does not retain any historical characteristics rather has differing functional and structural properties relative to the pre-existing historical state (Hobbs et al., 2009).

Reference site: the desired result of a restoration project in terms of functional and structural components. Provides the baseline data to monitor restoration progress towards the desired trajectory.

Abbreviations

Endangered Species Codes

G1 N1 S1	Critically imperiled Nationally imperiled Provincially imperiled	Very high risk of extinction due to rarity (Faber-Langendoen *et al.* 2012)

Plant Species Codes	Plant (Common Name)	Plant (Latin Name)
ACMI	Yarrow	*Achillea millefolium subsp. Lanulosa*
ANGL	Bog rosemary	*Andromeda glaucophylla*
ANPA	Anemone	*Anemone parviflora*
ARAL	Bearberry	*Arctous aplina*
ASsp	Milkvetch	*Astragalus sp.*
BARE	Bare cover	NA
BEGL	Dwarf birch	*Betula glandulosa*
BIVI	Alpine bistort	*Bistorta vivipara*
BRLO	Long's braya	*Braya longii*
CACA	Wild caraway	*Carum carvi*
CARO	Harebell	*Campanula rotundifolia*
CEsp	Chickweed	*Cerastium sp.*
COCA	Bunchberry	*Cornus canadensis*
DRIN	Hoary whitlowgrass	*Draba incana*
DRINT	Mountain avens	*Dryas integrifolia*

Plant Species Codes	Plant (Common Name)	Plant (Latin Name)
EMNI	Crowberry	*Empetrum nigrum*
EQAR	Field horsetail	*Equisetum arvense*
ERHY	Hyssopleaf fleanbane	*Erigeron hyssopifolius Michx.*
EUsp	Eyebright	*Euphrasia sp.*
FRVI	Strawberry	*Fragaria virginiana*
GEAM	Four-part gentian	*Gentianella amarella*
GENE	Island gentian	*Gentianopsis nesophila*
GRASS	Grass spp.	NA
HEAL	Alpine sweetvetch	*Hedyasrum alpinum*
HEMA	Cow parsley	*Heracleum maximum*
JUCO	Common juniper	*Juniperus communis*
JUHO	Creeping juniper	*Juniperus horizontalis*
LEMO	American dune grass	*Leymous mollis*
LICHEN	Lichen spp.	NA
MEMA	Oyster leaf	*Mertensia maitima*
MOSS	Moss spp.	NA
MYGA	Myria gale	*Myria gale*
OXPO	Inflated oxytrope	*Oxytropis podocarpa*
PAPA	Balsam ragwort	*Packera paupercula*
PIGL	White spuce	*Picea glauca*
PIVU	Butterwort	*Pinguicula vulgaris*
PLMA	Seaside plantain	*Plantago maritima*
POAN	Silverweed	*Potentilla anserina*
POFR	Shrubby cinquefoil	*Potentilla fruticosa*
POsp	Poa sp.	*Poa sp.*
POTR	Three-toothed cinquefoil	*Potentilla tridentata*
PRLA	Primula	*Primula laurentiana*
PRsp	Primula	*Primula sp.*
RAAL	Common buttercup	*Ranunculus acris*
RHMI	Yellow rattle	*Rhinanthus minor sudp. Groenlandicus*
RHRO	Rhodiola	*Rhodiola rosea*
RHsp	Rhytidiadelphus	*Rhytidiadelphua sp.*
RUAR	Plumboy	*Rubus arcticus subsp. Acaulis*
SACA	Limestone willow	*Salix calcicolavar. Calcicola*
SACAN	Sage willow	*Salix candida*
SACO	Salix cordata	*Salix cordifolia*
SAGL	Salix glauca	*Salix glauca*
SAOP	Purple saxifrage	*Saxifraga oppositifolia*

Plant Species Codes	Plant (Common Name)	Plant (Latin Name)
SARE	Net-veined willow	*Salix reticulata*
SAsp	Willow sp.	*Salix sp.*
SEDGE	Sedge spp.	*Carex sp.*
SHCA	Soapberry	*Shepherrdia canadensis*
SOMU	Northern goldenrod	*Solidago multiradiata*
STLO	Longstalk starwort	*Stellaria longipes*
TAsp	Dandelion sp.	*Taraxacum sp.*
THAL	Alpine meadowrue	*Thalictrum alpinum*
TRPR	Clover	*Trifolium pratense*
VAUL	Alpine bilberry	*Vaccinium uliginosum*
VAVI	Partridgeberry	*Vaccinium vitis-idaea subsp. Minus*
VICR	Cow vetch	*Vicia cracca*
VIFE	Viviparous fescue	*Viviparous fescue*

Environmental Code	Variable Name
P	Phosphorus
LOI	Loss-on-ignition
X. SiltClay	Percent Silt/Clay
Mn	Manganese
Li	Lithium
BARESOIL	Bare ground cover

Appendix II: Chapter 2 Methods

Digitization of Aerial Photographs

Aerial photographs and their respective transparencies were scanned at a high resolution (1200dpi) into Adobe Photoshop® and saved as TIFF files for orthorectifcation. Aerial photos and transparencies were orthorectified to a SPOT5 image (NRCAN 2007) and digital elevation model (DEM; NRCAN 2004) using PCI Geomatica 2012 Orthoengine® version 4.7.1. The DEM was used to incorporate relief displacement, increasing spatial accuracy of the rectified images. Transparencies for each year were heads-up digitized in ArcMAP®, creating line (i.e. elevation, trails, roads, highways) and polygon (i.e. dwellings, human-disturbance, natural habitat, ponds) feature classes.

Data Point Correction and Projection

Collected points were downloaded into GPS Pathfinder Office® for post-processing. The file was differentially corrected using the reference position of the base provider SOPAC, STJO CACS-ACP, daily. The differential correction resulted in points with estimated accuracies of: 49% within 0.30-0.50m; 48.5% within 0.50-1.00m; 2.3% within 1.00-2.00m; and 0.1% within 2.00-5.00m. Differentially corrected points were exported to an ESRI shape file for use in ESRI® ArcMAP™ version 10.1 and interpolated surface model construction. The point file geographic location was defined as the WGS 1984 World Geographic Coordinates, then reprojected in NAD 1983 Zone 21N projected coordinate system given that the study site falls within this UTM zone.

Table AII.1. Dichotomous key for the determination of human- and natural-disturbed substrate.

Table AII.1.

	Criteria	Response
1.	Area is non-vegetated (<50% Cover)	Go to **Step 1a**
	Area is vegetated (>50% Cover)	Go to **Step 2**
a.	Substrate is more than 20m from the ocean	Go to **Step 1b**
	Substrate is less than 20 m from the ocean	**Beach Cobble**
b.	There is substrate over bedrock	Go to **Step 1c**
	There is no substrate over bedrock	**Bedrock**
c.	Substrate demonstrates frost action	Go to **Step 1d**
	Substrate does not demonstrate frost action	Go to **Step 1h**
d.	Substrate is heterogeneous	Go to **Step 1e**
	Substrate is homogeneous	Go to **Step 1i**
e.	Substrate demonstrates frost sorting	Go to **Step 1f**
	Substrate does not demonstrate frost sorting	Go to **Step 1j**
f.	Evidence of Bulldozer use	Go to S**tep 1g**
	Evidence of off-road vehicle (ORV) use	**Low human disturbance**
	No evidence of ORV and/or Bulldozer use	**Natural high disturbance**
g.	Substrate has been removed	**High human disturbance**
	Substrate has not been removed	**Moderate human disturbance**
h.	Evidence of bulldozer use	Go to S**tep 1g**
	Evidence of off-road vehicle (ORV) use	**Low human disturbance**
	No evidence of ORV or Bulldozer use	**Natural low disturbance**
i.	Evidence of bulldozer use	Go to S**tep 1g**
	Evidence of off-road vehicle (ORV) use	**Low human disturbance**
	No evidence of ORV or Bulldozer use	**Natural moderate disturbance**
2.	Cover dominated by Crowberry	Go to S**tep 2a**
	Cover dominated by Grass	Go to **Step 2c**
	Cover dominated by Spruce	**Forest**
a.	Evidence of ORV or Bulldozer use	Go to S**tep 2b**
	No evidence of ORV or Bulldozer use	**Natural low disturbance**
b.	Evidence of Bulldozer use	Go to S**tep 2c**
	Evidence of ORV use	**Low human disturbance**
c.	Substrate has been removed	**High human disturbance**
	Substrate has not been removed	**Moderate human disturbance**
d.	Is on an overburden pile	**High human disturbance**
	Is not on an overburden pile	Go to **Step 2d**
e.	Evidence of ORV or Bulldozer use	Go to S**tep 2e**
	No evidence of ORV or Bulldozer use	**Natural low disturbance**
f.	Substrate has been removed	**High human disturbance**
	Substrate has not been removed	**Low human disturbance**

Appendix III: Chapter 2 Results

Surface interpolation model allows for original site topography reconstruction and landscape restoration using remnant reference habitat

Elevation data collected in the field demonstrated non-normality, autocorrelation and a global trend. Normality was determined using a histogram and QQ-plot. The histogram demonstrated a bimodal spread despite having similar mean and median value (8.58m; 8.51m), which support normality. In contrast, the kurtosis value was below three (1.69m) and the data had a small negative skew (-0.13) (ESRI, 2004). The QQ-Plot demonstrated an ‘S-curve’, showing deviations from standard normal values at 5m, 11m and 15m. The semivariogram cloud indicated autocorrelation in the Southwest-Northeast direction, supporting anisotropy (i.e. rate of change in elevation is greater in this direction). High values observed in this cloud are distributed evenly, and are attributed to point pairs running perpendicular to the coast from low elevation to high elevation. Trend analysis indicated an upside down ‘U’ in both the East-West and North-South direction, supporting the common removal of a second order polynomial trend from the data prior to statistical analysis (Chaplot 2006).

Table AIII.1. Species richness and Shannon-Weiner diversity for sampled human-modified sites (i.e. overburden piles) relative to natural limestone and crowberry barrens which make up the limestone barrens ecosystem. Disturbed sites were sampled using two transects with three 1m^2 quadrats (n=6). Natural areas were surveyed with 2-4 transects with three equally spaced 1m^2 quadrats (n=6-12) given they encompassed a greater area. Species richness and Shannon-Weiner diversity index calculated in R version 3.0.2.

Table AIII.2. Dominant taxa within each surveyed site (i.e. disturbed overburden, and natural limestone and crowberry barrens). Taxa comprising more than 1% cover on average are shown. Note that Grass spp. dominate the disturbed sites, while bare ground cover and woody vegetation dominant natural sites.

Table AIII.3. Summary statistics for the physical and geochemical substrate properties of human-modified sites and natural areas at the study site. Those variables bolded, are those identified by means of forward selection and VIF factors around three when predicting observed vegetation.

Table AIII.4. Average percent cover and standard errors (SE) for seven cover classes, including two vegetation and five substrate subdivisions. Other refers to both woody and herbaceous cover.

Table AIII.5. PERMANOVA test comparing percent cover of soil, fines, gravel and boulders in response to disturbance ranging from high human disturbance to high natural disturbance. Test was conducted in R version 3.0.2 using the Vegan package.

Table AIII.6. Validation and cross validation of training subset (n=302) with the test subset (n=34). Analysis was conducted using the ESRI® geostatistical wizard in ArcMap™ version 10.1. Kruskal-Wallis test was conducted using R software version 3.0.2.

Table AIII.7. Cross validation results of final model in comparison to the validation model. Leave one out cross validation in ESRI® geostatistical wizard in ArcMAP™ was used to obtain statistical results. The following model parameters were used: nugget=0.03; partial sill=0.62; shape=stable; anisotropy=True.

Figure AIII.1. Natural (a=crowberry barrens; b=limestone barrens; and c=bedrock/beach) and human modified (d=vegetated overburden; e=non-vegetated overburden; and f=quarry floor) areas located at the study site. All sites were surveyed to determine similarities of human-disturbed sites relative to natural remnant sites.

Figure AIII.2. Ground truthed remnant potential limestone pavement patches. Map created in ESRI® ArcMAP™ version 10.1.

Figure AIII.3. 3D Surface model coarsely depicting the study site landscape pre-road and -quarry disturbance, guiding site topography restoration. Model constructed using collected remnant natural areas elevation points outlined in aerial photographs, and ordinary kriging interpolation in ESRI® ArcMAP™ version 10.1. Model was constructed in R version 3.0.2 with the MBA package (Finley and Banerjee, 2010).

Table AIII.1.

Location	Site	Species Richness	SW Diversity
Sandy Cove – Human-modified	Young-1	24	1.53
	Young-2	31	2.30
	Young – Total	**31**	
	Mid-1	27	1.99
	Mid-2	22	1.31
	Mid – Total	**32**	
	Old-1	22	1.53
	Old-2	15	1.32
	Old-3	20	1.43
	Old - Total	**29**	
Sandy Cove – Natural	Crowberry-1	27	2.18
	Crowberry-2	39	2.46
	Crowberry - Total	**47**	
	Limestone Barrens-1	18	1.23
	Limestone Barrens-2	28	1.76
	Limestone Barrens-3	29	1.01
	Limestone Barrens - Total	**39**	

Table AIII.2.

Sandy Cove – Human-modified						Sandy Cove – Natural			
Young (N=2)		Mid (N=2)		Old (N=3)		Limestone Barrens (N=3)		Crowberry Barrens (N=2)	
Taxa	Ave % Cover ±SE	Taxa	Ave % Cover ±SE	Taxa	Ave % Cover ±SE	Taxa	Ave % Cover ±SE	Taxa	Ave % Cover ±SE
Grass spp.	49±3	*Leymus mollis*	33±5	Grass spp.	57±1	Bare ground	64±2	*Empetrum nigrum*	20±2
Bare ground	9±2	Grass spp.	28±3	Bare ground	10±2	*Dryas integrifolia*	20±1	*Dryas integrifolia*	18±2
Salix spp.	8±2	*Salix candida*	8±2	*Taraxacum spp.*	8±1	*Juniperus horizontalis*	4±1	*Salix reticulata*	17±3
Rhodiola rosea	7±2	*Vicia cracca*	4±2	*Plantago maritima*	6±1	*Erigeron hyssopifolius*	2±1	*Betula pumila*	13±3
Taraxacum spp.	5±1	*Moss spp*	4±2	*Salix spp.*	4±1	Grass spp.	2±1	Lichen spp.	5±2
Trifolium pratense	3±1	*Salix spp.*	3±2	*Equisetum arvense*	3±1	*Moss spp.*	2±1	*Vaccinium uliginosum*	3±1
Empetrum nigrum	3±1	Bare ground	3±1	*Potenilla anserina*	2±1			*Salix cordifolia*	3±1
Equisetum arvense	3±1	*Taraxacum spp.*	3±1	*Empetrum nigrum*	2±1			Bare ground	2±1
Salix candida	3±1	*Cerastium sp.*	3±1	*Moss spp.*	2±1			Grass spp.	2±1
Moss spp.	2±1	*Erigeron hyssopifolius*	1±1	*Ranunculus acris*	2±1			*Juniperus communis*	2±1
Plantago maritima	2±1	*Carum carvi*	1±1					*Moss spp.*	2±0
Bistorta vivipara	2±1	*Alchemilla filicaulis*	1±1					*Solidago multiradiata*	1±1
Conioselinum sp.	1±1	*Equisetum arvense*	1±1					*Plantago maritima*	1±1
								Oxytropis podocarpa	1±1
								Andromeda glaucophylla	1±1
								Tofieldia pusilla	1±1
								Erigeron hyssopifolius	1±1

Table AIII.3.

	Site											
	Mid (N=2)		Old (N=3)		Limestone Barrens (N=2)		Crowberry Barrens (N=1)		Young (N=2)		Quarry Floor (N=1)	
	Ave.	±SE	Ave.	±SE	Ave.	±SE	Ave.	±SE	Ave.	±SE	Ave.	±SE
Bare Ground Cover (%)	**3.7**	**1.8**	**9.6**	**2.6**	**56.6**	**2.6**	**1.83**	**1.6**	**8.8**	**2.6**	**65.3**	**1.3**
Particle Composition												
Gravel (%)	35.6	2.9	23.6	2.2	38.9	3.7	9.06	3.5	22.6	3.3	63.2	1.1
Sand (%)	33.6	2.5	45.0	2.3	19.8	2.4	71.33	3.3	43.3	3.7	22.7	0.9
Silt/Clay (%)	**18.1**	**1.6**	**12.4**	**1.3**	**38.4**	**3.2**	**17.33**	**3.4**	**13.0**	**2.0**	**14.1**	**1.0**
Geochemical Composition												
pH	7.6	0.4	7.4	0.4	7.8	0.2	7.24	0.3	7.6	0.3	8.1	0.1
Aluminum (%)	1.8	0.3	1.9	0.3	1.7	0.6	1.23	0.7	1.7	0.6	2.4	0.3
Calcium (%)	10.5	1.2	7.0	0.8	12.4	1.2	6.02	1.8	7.1	1.1	12.8	0.5
Iron (%)	1.3	0.2	1.5	0.3	1.7	0.6	1.26	0.7	1.3	0.5	1.8	0.3
Potassium (%)	1.6	0.3	1.6	0.2	1.8	0.7	1.15	0.7	1.4	0.5	1.8	0.2
Loss-On-Ignition (%)	28.9	3.0	46.6	2.0	11.6	1.7	60.95	4.6	48.8	3.2	7.8	0.5
Magnesium (%)	6.1	1.0	3.9	0.7	7.5	1.0	2.85	1.5	3.8	0.9	7.7	0.4
Sodium (%)	0.2	0.2	0.2	0.2	0.1	0.1	0.12	0.1	0.2	0.3	0.3	0.2
Barium (ppm)	141.2	4.1	127.0	2.2	155.9	6.3	89.11	5.8	113.4	4.7	176.4	3.5
Chromium (ppm)	21.1	1.22	22.4	1.0	14.9	1.6	8.80	2.0	20.2	1.9	25.0	0.9
Copper (ppm)	19.3	2.1	21.5	2.1	15.2	1.4	14.39	1.6	14.8	1.9	13.4	0.4
Lanthanum (ppm)	10.5	0.7	13.4	0.8	10.2	1.6	8.39	1.8	12.2	1.6	13.2	0.7
Lithium (ppm)	**13.5**	**0.8**	**13.4**	**1.2**	**8.9**	**0.9**	**6.02**	**1.9**	**11.9**	**1.6**	**18.7**	**0.5**
Manganese (ppm)	**557.0**	**6.3**	**658.8**	**5.5**	**1239.8**	**15.2**	**1487.99**	**25.3**	**593.5**	**10.8**	**717.3**	**4.0**
Phosphorus (ppm)	**634.6**	**9.5**	**1098.1**	**10.5**	**565.3**	**10.3**	**768.97**	**12.6**	**1016.2**	**13.1**	**551.3**	**3.9**
Lead (ppm)	72.8	4.3	151.6	7.1	31.3	1.9	32.80	2.7	47.6	5.1	18.4	0.7
Rubidium (ppm)	29.3	1.0	31.4	1.1	23.0	2.0	14.10	2.4	28.9	2.2	36.7	0.8
Scandium (ppm)	3.8	0.4	4.4	0.4	3.1	0.7	1.93	0.9	4.2	0.9	5.7	0.5
Strontium (ppm)	92.8	1.5	99.1	2.2	71.1	2.4	66.40	1.9	113.2	2.6	116.5	2.2
Tin (ppm)	856.6	6.3	966.6	6.8	712.1	11.9	496.26	13.8	866.8	13.1	1366.5	9.3
Vanadium (ppm)	25.5	0.9	28.4	1.1	30.7	2.5	19.80	2.7	26.2	2.2	35.7	1.3
Zinc (ppm)	73.0	4.1	144.3	9.8	36.7	2.0	32.29	3.8	56.4	4.8	33.4	1.2
Zirconium (ppm)	20.2	1.4	19.6	1.2	23.8	2.4	10.25	1.9	17.1	1.9	26.8	1.2

Table AIII.4.

Cover Class	Human-Disturbed		Natural - Disturbed			
Vegetation	**Medium (N=1)**	**High (N=3)**	**Low (N=4)**	**Medium (N=2)**	**High (N=6)**	**Heath (N=1)**
Moss	4.1 ±2.8	12.3 ±2.3	1.0 ±0.4	2.4 ±0.4	1.4 ±0.5	6.2 ±2.0
Other	24.1 ±4.7	10.1 ±1.9	26.9 ±2.0	27.4 ±2.3	25.7 ±1.1	28.0 ±5.0
Substrate						
Soil	0.0	0.1±0.2	1.8 ±0.9	1.8 ±0.9	0.6 ±0.3	2.9 ±1.8
Fines	9.2 ±3.2	11.7±2.0	0.1 ±0.2	2.3 ±1.1	7.1 ±1.2	2.7 ±1.8
Gravel	27.5 ±4.9	**51.2±2.5**	**64.8 ±2.4**	**49.5 ±0.0**	**58.1 ±1.3**	**57.0 ±4.7**
Boulders	0.0	0.8±0.7	1.8 ±0.4	6.0 ±1.2	1.4 ±0.6	0.0
Bedrock	**34.0 ±5.2**	12.2 ±2.4	3.4 ±1.4	9.0 ±1.6	4.8 ±1.0	2.0 ±2.5

Table AIII.5.

	DF	Pseudo-F	r^2	Pr (>F)
Explanatory **Disturbance Rank** (High, moderate and low human disturbance = -3, -2 & -1, respectively; Crowberry barrens = 0; High, moderate & low natural disturbance = +3, +2, +1, respectively)	5	5.07	0.13	0.001

Table AIII.6.

Kernel (Weighting)	Mean	RMSE	Mean Standardized	RMSE Standardized	Average SE	R^2	χ^2 Stat*
			Geostatistical				
Constant	-0.0096	0.63	-0.0039	0.99	0.70	0.98	0.019
Quartile	0.0034	0.58	0.58	0.98	0.67	0.98	0.017
Guassian	-0.0017	0.60	0.00083	0.98	0.66	0.99	0.018
Exponential	0.0014	0.59	0.0027	0.99	0.62	0.99	0.014
			Deterministic				
IDW	0.17	0.81	-	-	-	-	-

*t_{crit}=2.03 with 33 df, a hypothesized mean difference of 0 and using a two tailed test

Table AIII.7.

Kernel (Weighting)	Mean	RMSE	Mean Standardized	RMSE Standardized	Average SE	R^2
			Validation Model			
Exponential	0.0014	0.59	0.0027	0.99	0.62	0.99
			Final Surface Model			
Exponential	-0.0038	0.57	-0.0019	0.97	0.59	0.98

Figure AIII.1.

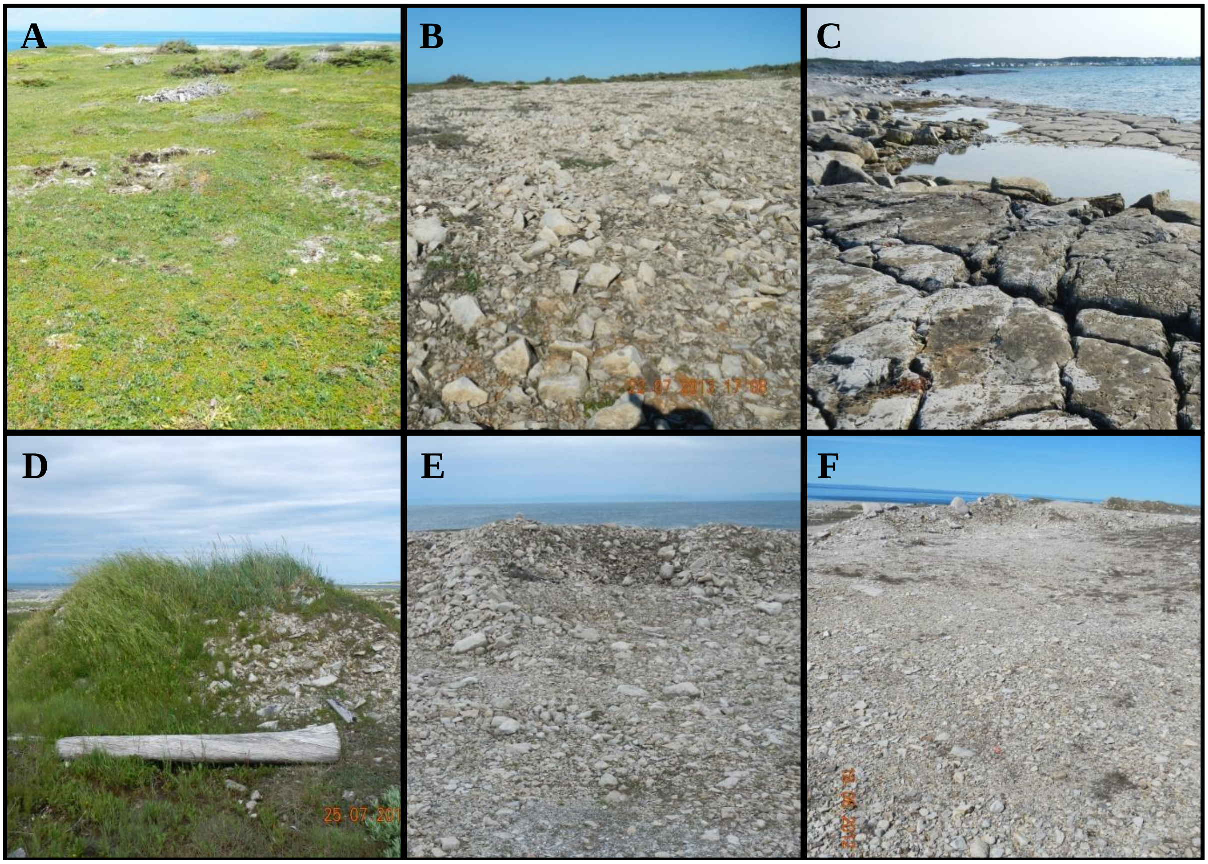


Figure AIII.2.

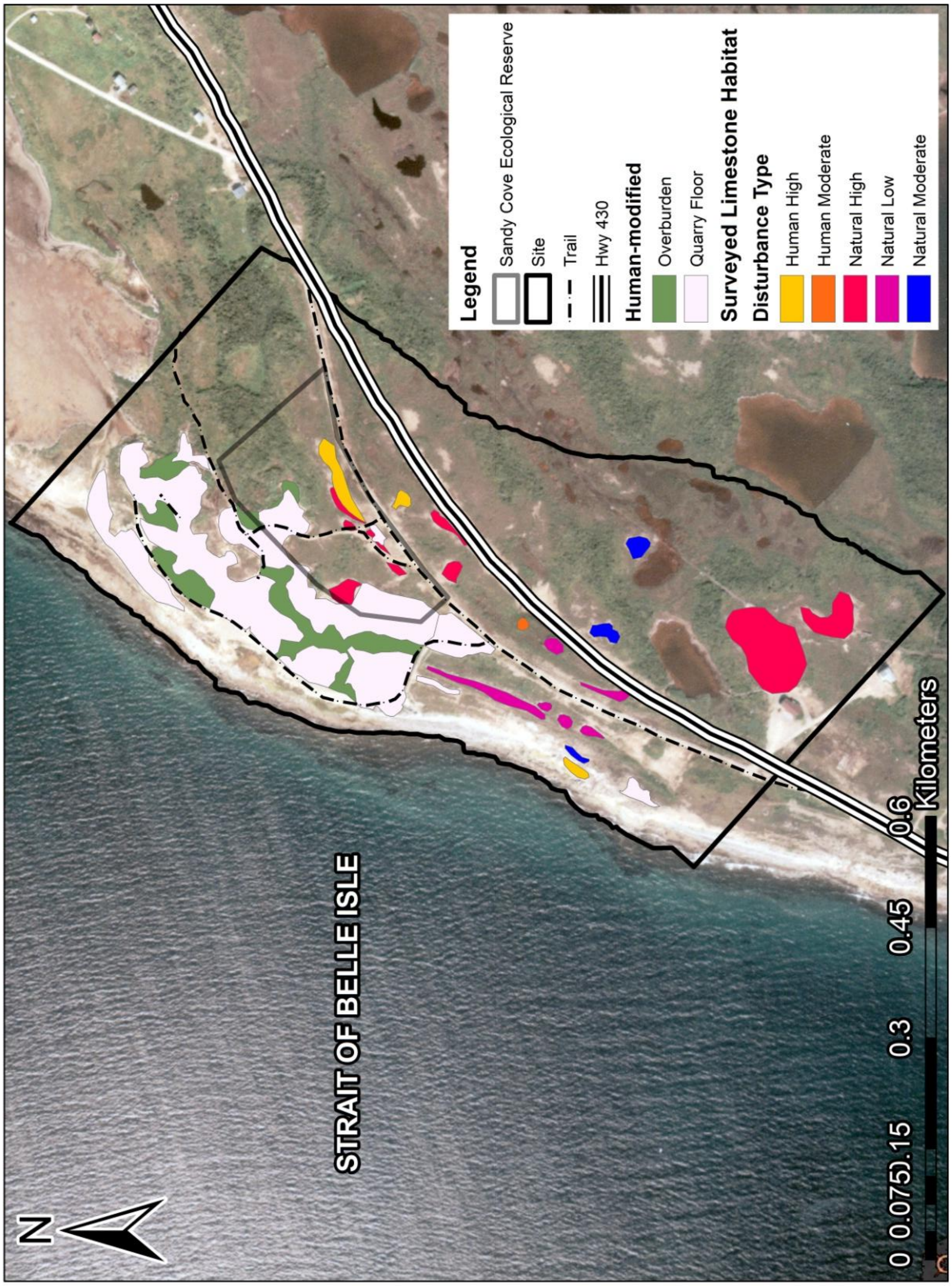
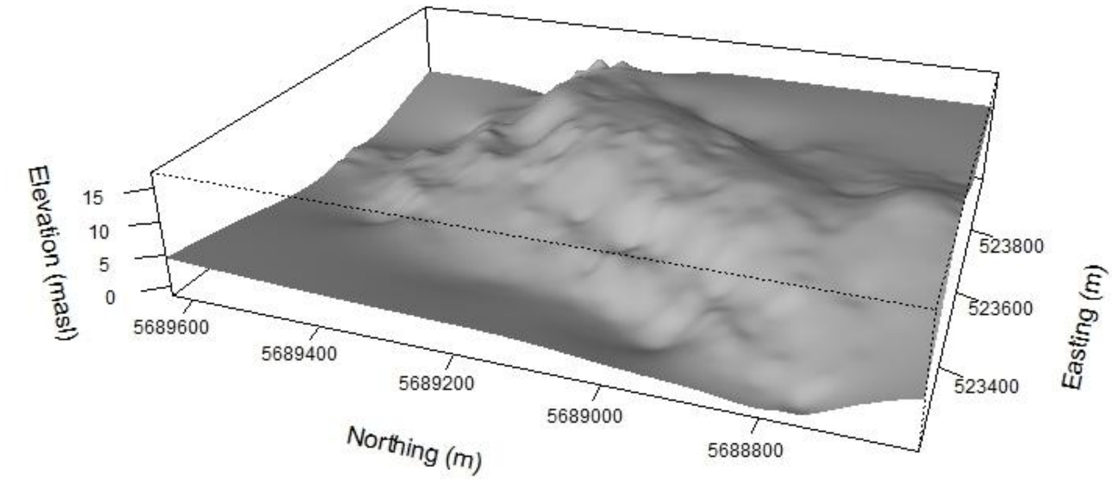


Figure AIII.3.



Appendix IV: Yankee Point Data

Defining reference limestone pavement patches and current site characteristics

The overburden piles at the Sandy Cove site were also compared to a newly quarried area in Yankee Point, Newfoundland (~1-2yrs old). This location similarly occurs within outlined critical habitat of *Braya longii* (Environment Canada 2012). Vegetation surveys (n=12), and substrate (n=12) and nutrient samples (n=12) were collected from two randomly selected overburden piles. These samples were not included in the results given their high dissimilarity.

Table AIV.1. Species richness and Shannon-Weiner diversity for sampled the recently human-modified site (i.e. overburden piles) in Yankee Point (New). The overburden piles (N=2) was sampled using two transects with three $1m^2$ quadrats (n=6). Species richness and Shannon-Weiner diversity index were calculated in R version 3.0.2.

Table AIV.2. Dominant taxa within the Yankee Point surveyed site. Taxa comprising more than 1% cover on average are shown.

Figure AIV.1. NMDS ordination displaying species compositions across the Sandy Cove and Yankee Point study sites. Stress is 0.17 after 13714 tries using previous.best. Abiotic factors are fit to the species ordination. The Vegan package's metaMDS and envfit functions in R software version 3.0.2 were used to run analysis and create plots. Abbreviations: NV=Non-vegetated.

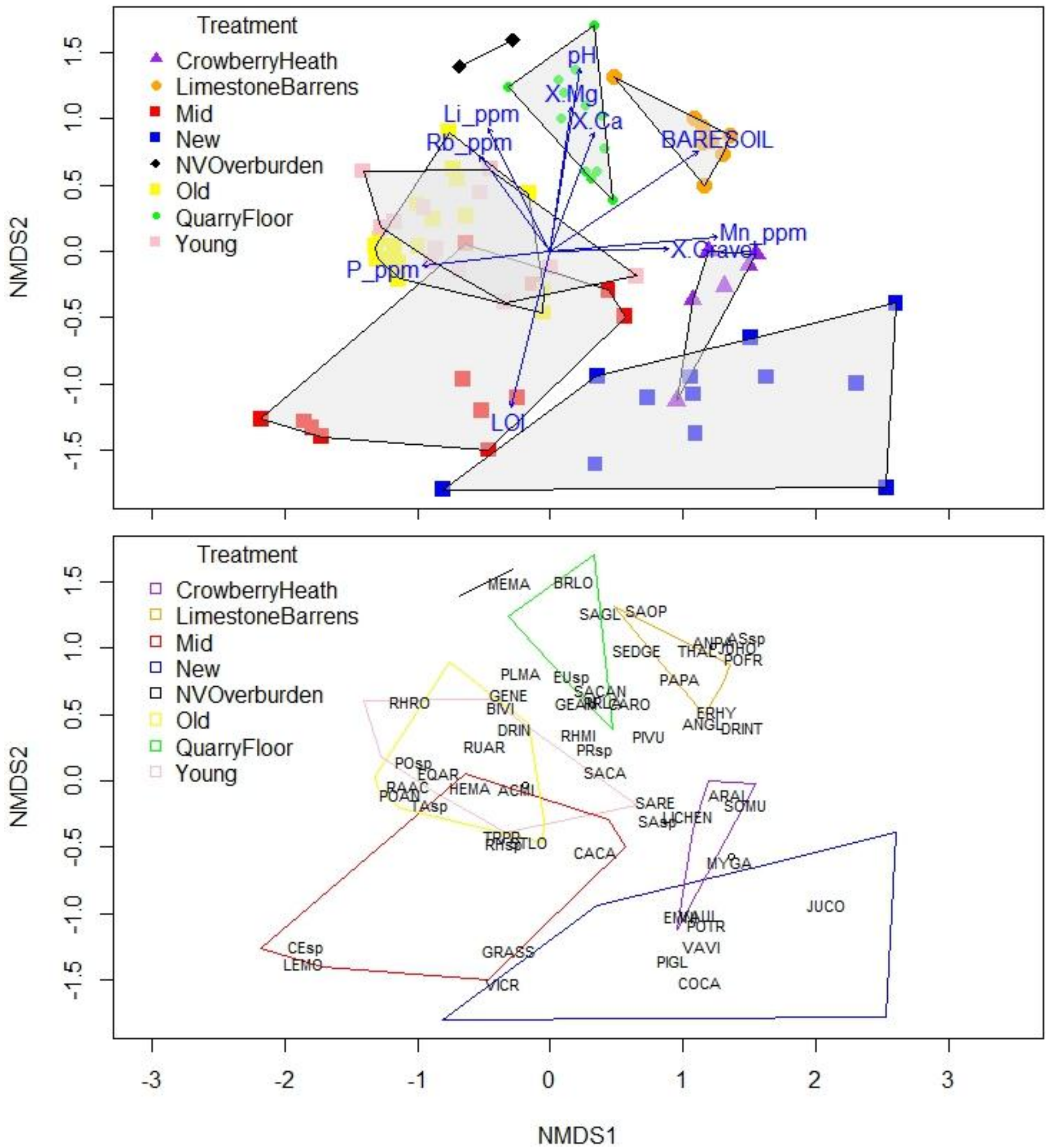
Table AIV.1.

Location	Site	Species Richness	SW Diversity
Yankee Point – Human-modified	New-1	20	1.10
	New-2	17	1.13
	New – Total	**24**	

Table AIV.2.

	New (N=2)
Taxa	**Ave % Cover±SE**
Bare ground	71.67±0.77
Empetrum nigrum	15.84±0.69
Vaccinium uliginosum	2.17±0.69
Vaccinium vitis-idaea	2.00±0.00
Juniperus communis	1.42±0.54
Cornus canadensis	1.25±0.94

Figure AIV.1.



Treatment
CrowberryHeath
LimestoneBarrens
Mid
New
NVOverburden
Old
QuarryFloor
Young
pH
X.Mg
X.Ca
Li_ppm
Rb_ppm
BARESOIL
Mn_ppm
X.Gravel
P_ppm
LOI
NMDS2
NMDS1

Appendix V: Chapter 3 Methods

Site Preparation

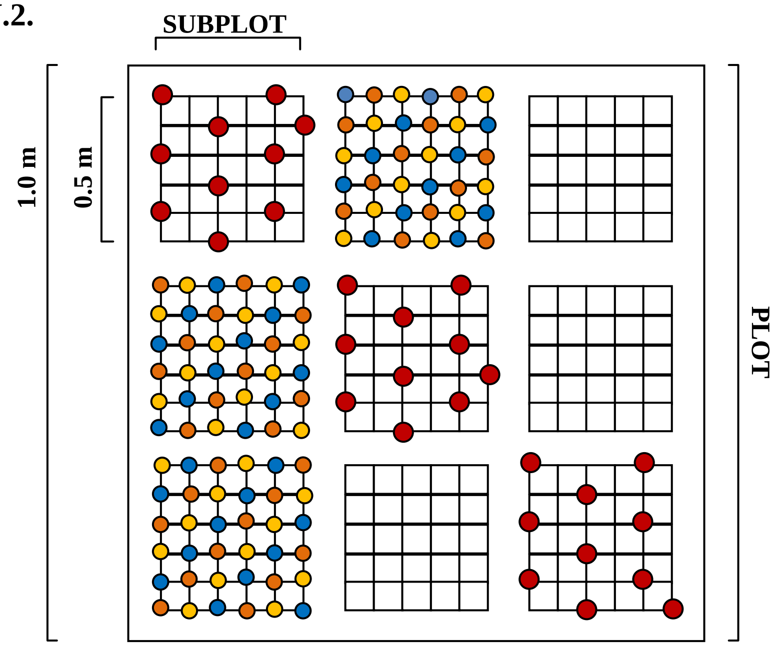
Prior to constructing experimental substrate treatment plots, native vegetation including *Dryas integrifolia*, *Saxifrage oppositifolia*, *Salix spp*., *Shepherdia canadensis*, *Draba incana*, *Juniperus horizontalis* and *Juniperus communis* were flagged on site, removed, and potted. Species such as the junipers and *Silene acaulis* were immediately replanted upon removal due to their large size. Following the construction of the experimental substrate treatment plots, all potted plants (n=111) were sunk into the site to overwinter. In June 2013, all potted plants were transplanted into the graded area within small nucleation sites; mini focal communities comprised of a few to several species contributing to assisted site revegetation via seed input and facilitation along the desire trajectory (Corbin and Holl, 2012). Each nucleation site was surrounded by a border of stone to mimic frost storing which displaces larger substrate particles to the edges which act as a barrier to the wind. On the graded and bare limestone areas, 25 and 8 islands, respectively with three to four species were constructed.

Figure AV.1. Heave device installed in experimental test plots. The design was modified from Walker et al. (2004).

Figure AV.2. Seeding design of each experimental test plot (2.0 x 2.0 m).Of the 9 subplots (0.5 x 0.5 m), 3 were seeded with 10 *Braya longii* (red), 3 with 12 *Rhodiola rosea* (orange), 12 *Draba incana* (blue) and 12 *Primula laurentiana* (yellow) seeds, and 3 with remained unseeded.

Figure AV.1.

Figure AV.2.



Appendix VI: Chapter 3 Results

Table AVI.1. Summary statistics of substrate treatment properties including percent organic material and substrate particle composition. Treatments are ranked in descending order of similarity to the limestone barrens reference site. Summary statistics calculate in R version 3.0.2 using the doBy package (Højsgaard et al. 2013). Abbreviations: SE=standard error; N=sample size.

Table AVI.2. Summary statistics for the geochemical properties of experimental treatment plots. Treatments are ranked from left to right based on similarity to limestone barrens reference site. Summary statistics calculate in R version 3.0.2 using the doBy package (Højsgaard et al. 2013). Abbreviations: N=sample size; SE=standard error; LB=limestone barrens; O=overburden (organic); L=large limestone gravel; F=fine silt/clay material; QF=quarry floor.

Table AVI.3. Analysis of variance table (ANOVA) for maximum frost heave (cm), controlling for plot treatment and type of measuring device. Statistical analysis was conducted in R version 3.0.2.

Table AVI.4. Summary statistics for the hourly duration of monthly freeze-thaw cycles occurring within the experimental treatments from November – April, relative to a natural location (i.e. limestone barrens). Summary statistics calculate in R version 3.0.2 using the doBy package (Højsgaard et al. 2013). Abbreviations: N=sample size; SE=standard error; O=overburden; L=large limestone gravel; F=fine silt/clay material; QF=quarry floor.

Table AVI.5. Generalized linear model with negative binomial distribution and log link to determine difference in the number of freeze-thaw cycles between treatments controlling for month. Analysis was conducting in R version 3.0.2 using the MASS package (Venables & Ripley 2002).

Table AVI.6. Generalized linear model, using a negative binomial distribution, assessing if the duration of freeze-thaw cycles differs between treatments controlling for block and month. Analysis conducted in R software version 3.0.2 with the MASS package.

Figure AVI.1. Average daily substrate temperature for the constructed experimental substrate treatment plots. Daily temperatures are averaged across blocks (n=2) for each treatment (n=7). Dotted line represents the corresponding average daily air temperature at the Plum Point weather station (Environment Canada 2014). Abbreviations: QF=quarry floor; L=limestone; O=overburden (organic) and; F=fine silt/clay material.

Table AVI.1.

Treatment	Description	N	LOI	Gravel	Sand	Silt/Clay
LB	Limestone Barrens	2	10.9 (±1.4)	27.6 (±7.2)	24.8 (±2.7)	47.6 (±4.7)
T6	Quarry Floor	3	7.86 (±2.45)	42.22 (±18.02)	28.33 (±8.12)	29.45 (±21.21)
T2	Overburden (organic) + Limestone + Fines	3	31.40 (±3.55)	32.86 (±2.35)	40.99 (±2.46)	26.15 (±2.62)
T4	Limestone + Fines	3	6.45 (±1.33)	71.84 (±6.70)	13.28 (±3.80)	14.88 (±2.96)
T5	Limestone	3	7.45 (±1.68)	87.85 (±3.46)	2.74 (±1.24)	9.41 (±2.31)
T3	Overburden (organic) + Limestone	3	37.90 (±1.86)	36.04 (±1.10)	45.28 (±2.19)	18.68 (±1.44)
T1	Overburden (organic)	3	41.28 (±2.12)	45.55 (±9.00)	37.59 (±9.31)	16.86 (±0.78)

Table AVI.2.

Geochemical Element	N	Treatment (±SE) LB (Ref.)	T6 QF	T4 L+F	T2 O+L+F	T5 L	T3 O+L	T1 O
Loss-on-Ignition (%)	3	8.8 (2.9)	7.9 (2.5)	6.5 (1.3)	31.4 (3.6)	7.5 (1.7)	37.9 (1.9)	41.3 (2.1)
Aluminum (%)	3	1.9 (0.3)	2.4 (0.4)	2.2 (0.1)	2.3 (0.1)	2.3 (0.2)	2.5 (0.2)	2.4 (0.0)
Arsenic (ppm)	3	6.4 (1.6)	8.4 (0.1)	4.4 (1.0)	6.0 (1.1)	6.7 (0.1)	6.3 (0.3)	6.1 (0.1)
Barium (ppm)	3	154.9 (45.0)	154.9 (30.7)	206.3 (20.9)	188.5 (6.0)	138.4 (9.6)	165.9 (4.2)	159.9 (0.7)
Beryllium (ppm)	3	0.3 (0.1)	0.6 (0.1)	0.5 (0.0)	0.5 (0.0)	0.6 (0.1)	0.6 (0.1)	0.6 (0.0)
Calcium (%)	3	12.4 (1.6)	12.6 (1.0)	13.6 (0.6)	9.0 (0.8)	13.2 (0.6)	7.0 (0.6)	7.0 (0.4)
Cerium (ppm)	3	33.9 (5.7)	37.1 (7.1)	34.5 (4.1)	36.8 (2.2)	37.7 (3.1)	41.8 (2.4)	40.6 (0.7)
Cobalt (ppm)	3	3.9 (0.7)	6.0 (1.5)	5.3 (0.8)	4.70 (0.40)	102.6 (95.4)	5.5 (0.3)	5.0 (0.2)
Chromium (ppm)	3	18.0 (2.5)	24.3 (4.2)	21.9 (1.2)	24.7 (1.6)	37.5 (16.8)	26.6 (0.8)	24.7 (0.6)
Copper (ppm)	3	13.5 (2.9)	15.5 (1.8)	29.5 (2.5)	39.7 (10.7)	37.8 (2.9)	25.3 (6.3)	30.3 (9.7)
Dysprosium (ppm)	3	1.0 (0.2)	0.9 (0.4)	0.7 (0.1)	0.7 (0.0)	0.9 (0.1)	0.8 (0.1)	0.8 (0.1)
Iron (%)	3	1.8 (0.4)	1.5 (0.2)	1.8 (0.1)	1.8 (0.1)	1.9 (0.2)	2.1 (0.1)	1.8 (0.0)
Potassium (%)	3	2.0 (0.4)	2.0 (0.2)	1.7 (0.1)	1.7 (0.1)	1.8 (0.1)	2.0 (0.1)	1.9 (0.0)
Lanthanum (ppm)	3	10.3 (3.0)	14.3 (3.8)	12.8 (1.7)	14.7 (1.1)	13.2 (1.8)	17.9 (1.4)	17.2 (0.6)
Lithium (ppm)	3	11.4 (2.2)	14.5 (2.0)	12.1 (1.3)	11.2 (0.6)	15.3 (0.6)	12.9 (0.5)	12.4 (0.2)
Magnesium (%)	3	7.6 (1.1)	7.8 (0.6)	8.0 (0.2)	5.1 (0.5)	8.1 (0.3)	4.1 (0.4)	3.9 (0.2)
Mangenese (ppm)	3	1194.8 (282.9)	811.6 (71.4)	829.7 (68.5)	867.2 (42.0)	804.4 (100.2)	966.8 (31.4)	896.2 (35.4)
Nickel (ppm)	3	14.6 (1.8)	3.0 (0.5)	3.8 (0.3)	3.0 (0.1)	3.0 (0.2)	2.9 (0.3)	2.5 (0.2)
Phosphorus (ppm)	3	528.1 (132.2)	14.9 (1.7)	13.7 (1.1)	12.9 (1.0)	18.9 (3.3)	14.3 (1.0)	12.5 (0.4)
Lead (ppm)	3	28.9 (6.3)	748.3 (231.3)	506.8 (142.9)	866.5 (113.0)	608.8 (71.7)	1079.4 (42.4)	1112.5 (29.6)

Table AVI.2 Cont'd

		Treatment (±SE)						
Geochemical Element	**N**	**LB (Ref.)**	**T6 QF**	**T4 L+F**	**T2 O+L+F**	**T5 L**	**T3 O+L**	**T1 O**
Rubidium (ppm)	3	26.4	25.0	63.6	124.7	39.2	126.6	106.2
		(2.7)	(2.5)	(13.0)	(32.5)	(10.2)	(38.0)	(16.5)
Scandium (ppm)	3	3.7	29.4	27.4	28.3	26.8	31.5	31.1
		(0.5)	(4.9)	(2.2)	(0.8)	(1.6)	(2.5)	(0.3)
Strontium (ppm)	3	66.0	6.2	4.6	4.6	6.3	5.5	5.3
		(5.1)	(1.5)	(0.8)	(0.4)	(1.0)	(0.4)	(0.1)
Titanium (ppm)	3	830.0	89.5	112.8	115.2	108.1	110.6	110.6
		(127.5)	(10.8)	(3.6)	(1.7)	(9.3)	(3.5)	(4.3)
Vanadium (ppm)	3	32.0	1225.3	1018.6	1079.7	1260.6	1260.2	1209.1
		(6.8)	(234.4)	(110.0)	(67.5)	(126.5)	(84.2)	(16.1)
Yttrium (ppm)	3	7.4	30.3	22.9	26.2	33.2	33.0	31.8
		(1.3)	(5.2)	(4.3)	(2.6)	(5.1)	(2.0)	(0.6)
Zinc (ppm)	3	32.6	7.8	6.6	6.6	7.4	7.5	7.35
		(8.8)	(2.0)	(0.8)	(0.4)	(0.6)	(0.4)	(0.2)
Zirconium (ppm)	3	24.4	33.8	31.7	125.6	31.2	148.9	86.9
		(6.5)	(3.3)	(2.0)	(50.4)	(1.9)	(46.3)	(9.8)

Table AVI.3.

Parameter	Df	Sum of Squares	Mean Square	F Value	Pr (>F)
Foot	5	18.49	3. 70	2.19	0.077
Plot	7	131.19	18.74	11.10	2.65×10^{-7}

Table AVI.4.

	Df	Deviance	Resid. Df	Resid. Dev	Pr(>Chi)
Month	5	333.40	78	102.86	$<2.2\times10^{-16}$
Treatment	6	23.38	72	79.48	0.00068

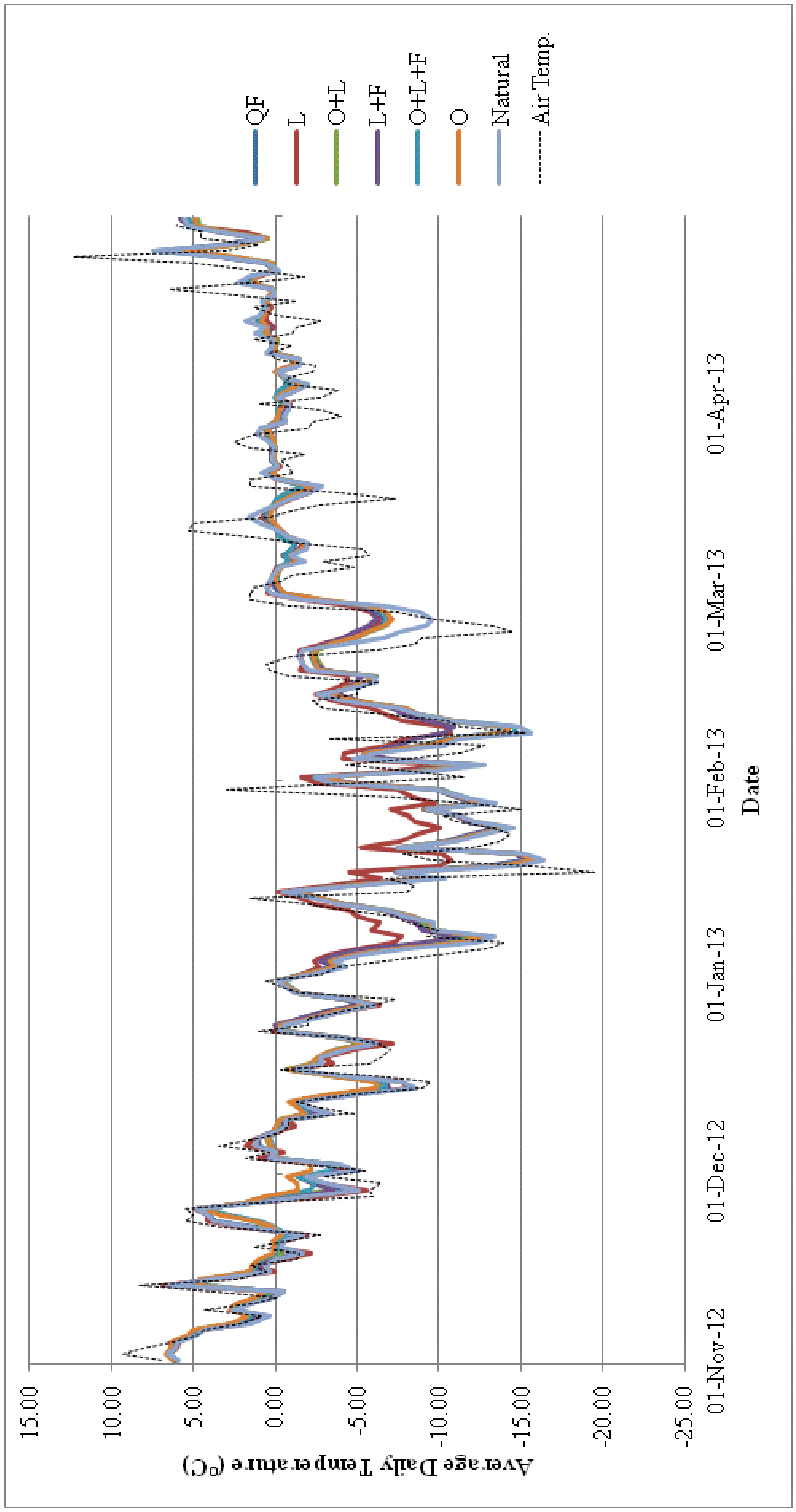
Table AVI.5.

	Df	Deviance	Resid. Df	Resid. Dev.	Pr(>Chi)
Block	1	17.90	455	1303.05	2.33×10^{-5}
Month	5	780.81	450	522.24	$<2.20\times10^{-16}$
Treatment	6	11.66	444	510.59	0.0701

Table AVI.6.

Treatment	Description	n	Heave (cm)	±SE
B1T1	Overburden (organic)	6	2.67	0.51
B1T2	Overburden (organic) + Limestone + Fines	6	1.53	0.53
B1T3	Organic + Limestone	6	0.92	0.23
B1T4	Limestone + Fines	6	1.12	0.44
B1T5	Limestone	6	3.68	0.71
B1T6	Quarry Floor	6	3.07	0.53
LB	Limestone Barrens	6	6.38	0.79
CB	Crowberry Barrens	6	2.23	0.63

Figure AVI.1.


QF
L
O+L
L+F
O+L+F
O
Natural
Air Temp.
15.00
10.00
5.00
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
Average Daily Temperature (°C)
01-Nov-12
01-Dec-12
01-Jan-13
01-Feb-13
01-Mar-13
01-Apr-13
Date