Please do not walk on the dunes: Assessing cumulative impacts on coastal vegetated sand dune systems in Newfoundland, Canada

by © Meghan Power

A thesis submitted to the

School of Graduate Studies

in partial fulfillment of the requirements for the degree of

Master of Science

Department of Geography

Memorial University of Newfoundland and Labrador

July 2024

St. John's, Newfoundland and Labrador

Abstract

Vegetated sand dune systems are a relatively rare form of coastline on the Island of Newfoundland (NL), but they provide diverse benefits to regional ecology and human landscape use. Despite their importance to coastal biodiversity and inland protection, few vegetated sand dune systems are located within protected areas in NL. Under little to no protection, many of NL's dune systems are vulnerable to anthropogenic disturbances (e.g., dune trampling, all-terrain vehicle use). Boreal vegetated dunes, such as those in Atlantic Canada, are also subject to extensive natural disturbances that result from storm and precipitation events. Current climate change projections point to an increase in these types of events in NL, which, combined with the ongoing anthropogenic disturbance regime, may overwhelm the natural rejuvenation process of dune coastlines. Using a protected areas approach, we characterize the vegetation cover, plant community, and disturbance features on NL's dune systems. Vegetation cover was sparser in unprotected areas, which were also associated with a greater cover of non-endemic plant species. Regardless of protection status, substrate disturbance was also linked with a loss of total vegetation cover across the system. This research provides important empirical findings on the relationship between protected areas status, vegetation cover, plant community, and substrate disturbance on NL's coastal vegetated dunes, highlighting the need for additional land management initiatives to protect these vulnerable landscapes under the effects of human visitation and climate change.

Keywords: boreal dunes, protected areas, climate change, disturbance, dune vegetation, coastal landscape, biodiversity, dune morphology

Acknowledgements

It takes a community to write a thesis. I would first like to express my overwhelming gratitude to my advisor, Dr. Carissa Brown, whose unwavering support propelled me through both my honours and master's programs. Carissa, you have an extraordinary ability to make everyone you work with feel welcome and at ease. On so many occasions, you helped me to realize that what seemed like monumentally large tasks were in fact, no big deal at all. Thank you for welcoming me back into the Northern EDGE Lab (past the application deadline!) to pursue another project that I am truly passionate about. You taught me everything there is to know about being a researcher and a fiercely compassionate leader. I could not have done this without your support, our whiteboard meetings, lab arts and crafts, and catchy rhyming email refrains. My hat's off to you, for helping me pull through.

Secondly, I want to thank my mom and dad for their unconditional love and support throughout my program, and my life. From day one, you both made me feel like I could do anything I wanted to do and be anyone I wanted to be. You encouraged me to follow my life's dreams no matter what they were, and for that I will be eternally grateful. Mom, thank you for your endless love and care, and for sticking with me through the toughest times. Dad, thank you for all the times that we spent outside together canoeing, building snowmen, creating things, and feeding the ducks: these are the moments that later inspired my love for geography. To my nana, whom I consider to be like a second mother, thank you for all the hard work, hope, and love that you put into our family. No matter where I end up, I'll always know that I have three people whose love and pride I can fall back on. Your strength sends me onward. I love you all very much.

Next, I want to offer my sincerest gratitude to my committee members, Dean Bavington and Kerry-Lynn Atkinson, for their support throughout my program. Dean, your teaching opened my mind to many new ideas and perspectives during my undergraduate coursework. The humanity that you show to your colleagues and students inspires me to embrace gentleness in my own interactions. Kerry-Lynn, your expertise, acuity, and attention to detail were highly valued as I undertook my thesis writing. Having a committee member with extensive knowledge of and experience with dune management was incredibly helpful. Thank you for providing key guidance in sections of critical variability.

To all those at the forefront and periphery of my work before and during this project, thank you. Thank you to my field assistants, Madeline Hart, and Marina Cuselli, for their hard work hiking through the sand and dune grass (in rain or shine) with me during data collection. I would also like to extend my thanks to Hailey Paynter, for her time and assistance before and during my visit to Prince Edward Island National Park. To the professors in the Department of Geography, so many of you supported me throughout my undergraduate and graduate programs. You inspired me to pursue a career in geographic research, and your mutual respect elevates the department to excellency. Thank you, especially, to Norm Catto, Arn Keeling, Josh Lepawsky, Charles Mather, Julia Christensen, and Nicholas Lynch.

There are times when we learn more from teaching than we do from studying. I want to offer my sincerest gratitude to the 2021-2023 16-20 team at the CBS Silhouettes. Coaching you all was a privilege that I won't soon forget. To Jillian, Peyton, Emily, Emma, Hadley, Maddison, Abigail, and Abby: thank you for all our uplifting conversations, and for teaching me that we can move mountains with the power of hope, perseverance, and friendship. The future is safe in the hands of such bright and wonderful individuals. Additionally, thank you to my fellow coaches and volunteers, especially Lori Chaytor, for their support as I navigated the intricacies of taking on many roles at once. You have my utmost respect and appreciation.

Finally, I would like to extend my thanks to all the dearest friends that I made before and during this program, who have wittingly (or unwittingly) become my greatest champions and supporters over the past two years. To my best friend Rivers, you keep me going in my times of most prominent need. Thank you for your acceptance and encouragement throughout every season of my life; the future is always bright and hopeful with you, my brother, by my side. I’m so grateful to consider you a part of my forever chosen family. To Suzanne van Niekerk, thank you for all your beautiful artwork, and our lovely conversations. I’ll be eternally grateful for your relentless support of my dreams. Lastly, I want to offer special thanks to friends and colleagues in my graduate cohort, the Northern EDGE Lab, and Barnie’s Buds (Larch Park ultimate frisbee squad), especially Sam Morton, Morgan Manuel, Joshua Brown, Lena Dietz Chiasson, Ian Petty, Marina Cuselli, Amy Frost-Wicks, Pierrette Janes-Bourque, Colin DeCoste, Rachel Forbes, Braydon Scammell, Taylor Goodfellow, Maureen Levangie, and Hallie Arno. Thank you for all the laughs, time spent playing outdoors, and kind words in moments of uncertainty. You pulled me away from the computer and out into the sun. Thank you for your kindness, acceptance, and for welcoming me into your lives as a friend. I’m filled with gratitude to have so many loving and caring people surrounding me in my life. Thank you for everything.

Statement of Positionality and Land Acknowledgement

Author Meghan Power (she/they) is a settler researcher who was born in St. John's, Newfoundland and Labrador. Research and data collection for our project were conducted on the island of Ktaqmkuk (Newfoundland) and on Epekwitk (Prince Edward Island). We respectfully acknowledge the island of Ktaqmkuk to be the ancestral homelands and the unceded, traditional territory of the Beothuk, whose culture has now been erased forever. We also acknowledge Epekwitk and the island of Ktaqmkuk as the unceded, traditional territory of the Mi'kmaq. We further acknowledge Labrador as the traditional and ancestral homelands of the Innu of Nitassinan, the Inuit of Nunatsiavut, and the Inuit of NunatuKavut.

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Co-Authorship Statement

Dr. Carissa Brown is a co-author on all chapters of this thesis. As the primary author, I was the primary researcher for the literature review, designing the research proposal, logistical project planning, fieldwork, data analysis, and manuscript preparation. All parts of the project were completed in collaboration with Carissa Brown, who contributed to project conceptualization, study design, and manuscript preparation.

Chapter 1: Introduction and thesis overview

1.1 Introduction

1.1.1 Coastal sand dune ecosystems

1.1.1.1 Geographic incidence

Vegetated dune complexes typically occur along microtidal, low-energy coastlines, in which wave activity is dominated by littoral drift (Catto, 2012; Delgado-Fernandez, 2011). Among these beaches, all of those comprised of fine to medium grain sand and exposed to strong and/or consistent onshore winds will be backed by vegetated sand dunes, assuming adequate sediment supply and beach replenishment (Holm, 1968; Short, 2019). While dry, windy conditions favor the development of sand dunes, they can also develop in humid regions where periodic exposure to wind and sun dries the substrate and permits the transport of sediments. The genesis of coastal sand dunes differs from that of mainland and/or desert dunes, which form under different climatological and geomorphic processes, and are associated with their own distinct landforms (e.g., dome dunes, sand sheets) and vegetation assemblages (Holm, 1968).

While mainland and desert dunes cover vast land areas, coastal vegetated sand dunes are comparatively rare on global scale (Holm, 1968). Despite this rarity, coastal vegetated dune complexes are widespread and present on coastlines across the world. Previous dune system studies have been conducted throughout coastal areas of mainland Europe (Doing, 1985; Jungerius & van der Meulen, 1989); in Northern, Southwest, and Southeast Africa (Bate & Ferguson, 1996; Doing, 1985); in South and West Australia (Short, 2019); in Japan (Yokota et al., 2017); in Southern Iceland (Mountney & Russell, 2006); in Brazil (Short, 2019); along the West and East coasts of the United States (Doing, 1985; Short, 2019); as well as in Chile, Hawaii, throughout the Caribbean Islands, and in the Atlantic Provinces of Eastern Canada (Doing, 1985). The morphological processes driving dune formation remain relatively similar across the world, though climatic and moisture conditions may influence landform development as well as the presence or absence of specific vegetation species or assemblages (Martínez et al., 2001; Snow, 1984).

Vegetated dune complex development is rare in humid boreal and subarctic climates, because the sediment transport budget is limited by damp substrate conditions and the seasonal presence of offshore ice (Mountney & Russell, 2006). Despite this, vegetated sand dunes are present along the coasts of all the Atlantic Provinces in Eastern Canada. Previous studies have identified dune complexes along the shorelines of New Brunswick (Hogan & Brown, 2021; McCann & Bryant, 1973; Rosen, 1979), Nova Scotia (Eamer et al., 2022; Hill et al., 2010; Nichol & Boyd, 1993), Prince Edward Island (PEI) (Catto et al., 2002; Davies, 2011; George et al., 2021; Hesp et al., 2013; Ollerhead et al., 2013; Power et al., 2022), and Newfoundland and Labrador (Catto, 2002, 2012). Les Îles de la Madeleine, a Québec archipelago located North of PEI, also hosts coastal vegetated dunes (Giles & King, 2001). As the scope of this study is restricted to Atlantic Canada, subsequent discussion of dune characteristics and impacts will emphasize processes distinct to that region.

1.1.1.2 Physical characteristics

Coastal transverse vegetated sand dune complexes occur on beaches backed by transverse foredunes and parabolic dunes of various sizes (Catto, 2002; Catto et al., 2002). These dunes range considerably in height (30 cm-400 m) and width (1 m-1 km) and are formed by unidirectional-dominant shoreline wind regimes (Short, 2019) (Figure 1.1.1). Typically, sandy beaches backed by transverse dunes follow the same pattern of landform shape and genesis. These beaches can be divided into three areas: nearshore, extending from the water to the mean tide level; foreshore, extending from the mean tide level to the ordinary limit of wave activity; and backshore, extending from the wave activity limit onward (Davies, 2011) (Figure 1.1.2). Vegetated dune complexes develop in the backshore regions of sandy

Figure 1.1.1: Images of vegetated sand dunes in Prince Edward Island National Park.

beach coastlines, and contain a large foremost transverse dune – also called the foredune – which may or may not be backed by smaller secondary landward dunes (Hesp, 2002; Snow, 1984). The foredune is characterized by a gentler, ocean-facing stoss slope and a steeper, landward-facing lee slope (M. A. Clarke, 2014). A smaller incipient (or embryo) dune typically develops at the foot of the stoss slope (Hesp, 2002). Foredunes range from <1 m-35 m in height and up to hundreds of meters wide, while incipient dunes can be up to 1 m high and 5-6 m wide (Catto et al., 2002; Hesp, 2002; Ollerhead et al., 2013; Walker et al., 2017). Primary foredunes develop from these smaller incipient foredunes over time (Hesp, 2002). This process is driven by the accretional development of the incipient dune, which pushes the established dune landward to become a relict secondary dune as it is moved from the foremost beach position (Hesp, 2002; Ranwell, 1958). In coastal dune systems affected by frequent storm activity, the incipient foredune undergoes a continuous seasonal cycle of summer accretion and fall or winter storm-related erosion (Delgado-Fernandez, 2011; Martínez et al., 2001; Ollerhead et al., 2013; Ranwell, 1958). Ollerhead et al. (2013)

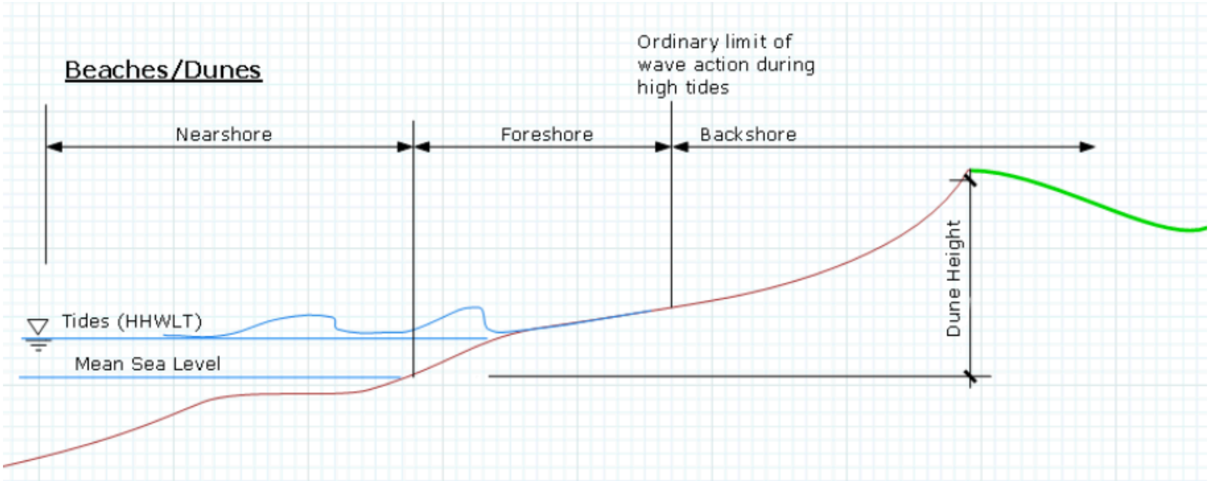

Figure 1.1.2: A diagram of beach zones typical to vegetated coastal dune systems (Davies, 2011).

identified four dune profiles typical to Atlantic Canadian coastlines, which they categorized as cliffed stoss, cliffed stoss with ramp, stoss, and stoss with embryo (Figure 1.1.3).

Sand supply remains the most significant control on dune development, extent, and morphology (Catto et al., 2002). Maintenance of vegetated dune complexes depends upon ample influx of sand into the system via longshore wave transport. Thus sediment flux, anthropogenic activity, regional climate, and coastal geomorphology are all key factors in the control of coastal dune complex development and stability (Catto, 2002; Catto et al., 2002). Other factors, such as wave run up, storm surge, tidal activity, salt spray, rainfall, snow/ice cover, and other spatial and/or temporal complexities may also impact sediment budget (Walker et al., 2017).

Following wave transport into the beach system, aeolian activity becomes the primary driver of sediment transport into the dune system (Catto et al., 2002; Ranwell, 1958). Aeolian sediment transport in dune morphology is extremely intricate and relies upon a variety of temporal (e.g., changes in wind speed, short term gusts, surface wetting and drying) and spatial (e.g., grain size, surface moisture distribution, fetch length, surface morphology) conditions (Davidson-Arnott et al., 2008; Davidson-Arnott & Bauer, 2009; Delgado-Fernandez, 2011). In established and prosperous vegetated dune systems, the combined effects of prevailing wind and surface topography steer air and sediment particles toward the

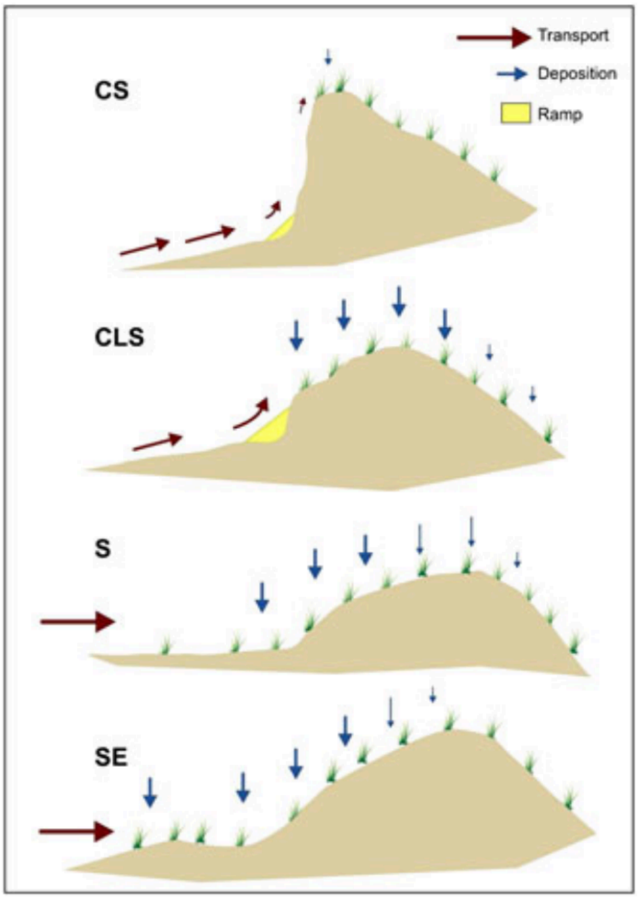

Figure 1.1.3: A diagram of boreal coastal dune profiles, including cliffed stoss (CS), cliffed stoss with ramp (CLS), stoss (S), and stoss with embryo (SE) (Ollerhead et al., 2013).

foredunes, where sand grains saltate up the stoss slope and avalanche down the lee slope. Grains may be deposited or lodged by dune vegetation at any point throughout this process, which, when repeated over time, results in a net accretional effect on the landscape (Clarke, 2014; Walker et al., 2006).

Vegetation species presence, dominance, and assemblage often differs spatially and seasonally across the dune landscape. Sediment transport, strong winds, salt spray, and nutrient-poor soils make coastal dunes uninhabitable for most plant species, and dune vegetation is typically comprised of species that have previously adapted to withstand such conditions (Snow, 1984). Broadly, dune vegetation includes diverse species of shrubs, herbs, grasses, sedges, creepers, and trees (Lucrezi et al., 2014). In Atlantic Canada, dune vegetation follows a pattern of spatial distribution. Coarse grasses and sedges such as *Ammophila breviligulata* (American marram grass) and *Leymus mollis* (American dunegrass) dominate the foredune, while smaller plants like *Cakile edentula* (American searocket) and *Batis maritima* (saltwort) are common on or surrounding backshore incipient dunes. Smaller flowering plants, like *Lathyrus japonicus* (beach pea) and species of *Solidago sempervirens* (seaside goldenrod) propagate on the lee slope seasonally during the summer and fall, and shrubs, such as *Myrica pensylvanica* (northern bayberry) or *Rosa virginiana* (Virginia rose) are present in sheltered areas (Byrne & McCann, 1993; Ollerhead et al., 2013; Tissier et al., 2013; Walker et al., 2017). Seasonal variation in the height and density of dune vegetation is also common, with plants demonstrating increased robustness during the summer and early fall (Delgado-Fernandez, 2011).

1.1.2 Potential disturbances

Coastal dune morphology and vegetation, as well as their corresponding generative and restorative processes, are often adversely impacted by natural and anthropogenic disturbances. In Atlantic Canada, vegetated dunes are threatened by shoreline retreat, as a combined result of rising sea level, coastal erosion, and successive storm impacts (Eamer et al., 2022). The effect of natural processes on vegetated dune systems is further exacerbated by human activity (e.g., trampling, vehicle use, infrastructural developments) on these vulnerable coastlines, resulting in damage (e.g., blowouts) or in some cases total destruction of the dune landscape (Nordstrom, 1994; Snow, 1984). This is especially relevant under the regime of climate change, which amplifies natural destructive processes and the subsequent erosion of dune systems (Catto et al., 2002). Walker et al. (2017) determined that while single, catastrophic storm events might appear to be the most significant contributor to dune erosion, the effect of cumulative moderate events (e.g., more frequent rainfall, increased human trampling) are often more significant in landscape dynamics, due to their sustained negative impact over long periods of time. This conclusion points to the combined importance of both natural and anthropogenic effects on coastal dune complexes, especially under the influence of climate change. The projected future increase in storm events (Finnis, 2013) may lead to moderate, long-term pressures and increased erosion on coastal dunes in Atlantic Canada, which could result in incremental eradication of dune landscapes over time.

1.1.2.1 Natural disturbances

Coastal erosion refers to the net landward retreat of a shoreline over a temporal scale, which exceeds cyclical patterns of coastal variability (Stephenson, 2013). Coastlines dominated by vegetated sand dunes are especially vulnerable to coastal erosion, due to the increased capacity for small grain sediments to be transported away from the system during disturbance events (Catto, 2012; Davies, 2011). Natural processes such as aeolian and wave activity, storm events, as well as the corresponding incidence and effect of climate-change related phenomena all contribute to the erosion of dune coastlines (Davies, 2011; Stephenson, 2013) (Figure 1.1.4).

The aeolian and wave processes that occur as part of regional weather variability frequently result in natural blowout development on the stoss slope of vegetated foredunes (Hesp, 2002; Jungerius & van der Meulen, 1989). Natural blowouts refer to circular, ovular, or elongated lobe-shaped areas of vegetation desiccation or burial, where the underlying sand sediments are exposed as a result of erosional processes (Figure 1.1.5) (Catto, 2002; Dech et al., 2005; Yokota et al., 2017). Blowouts that result from short-term variability in wind and wave dynamics are a natural part of vegetated dune systems. These blowouts develop and heal via vegetation recolonization over multi-year timescales as a part of the natural geomorphic processes driving dune genesis, maintenance, and restoration (Dech et al., 2005).

In Atlantic Canada, the tropical cyclones and post-tropical storms that are characteristic of the early-to-mid fall (i.e., September to November), as well as the mid-latitude cyclones that occur during the winter months (i.e., November to March) (Environment and Climate Change Canada, 2009) have moderate to severe erosional impacts

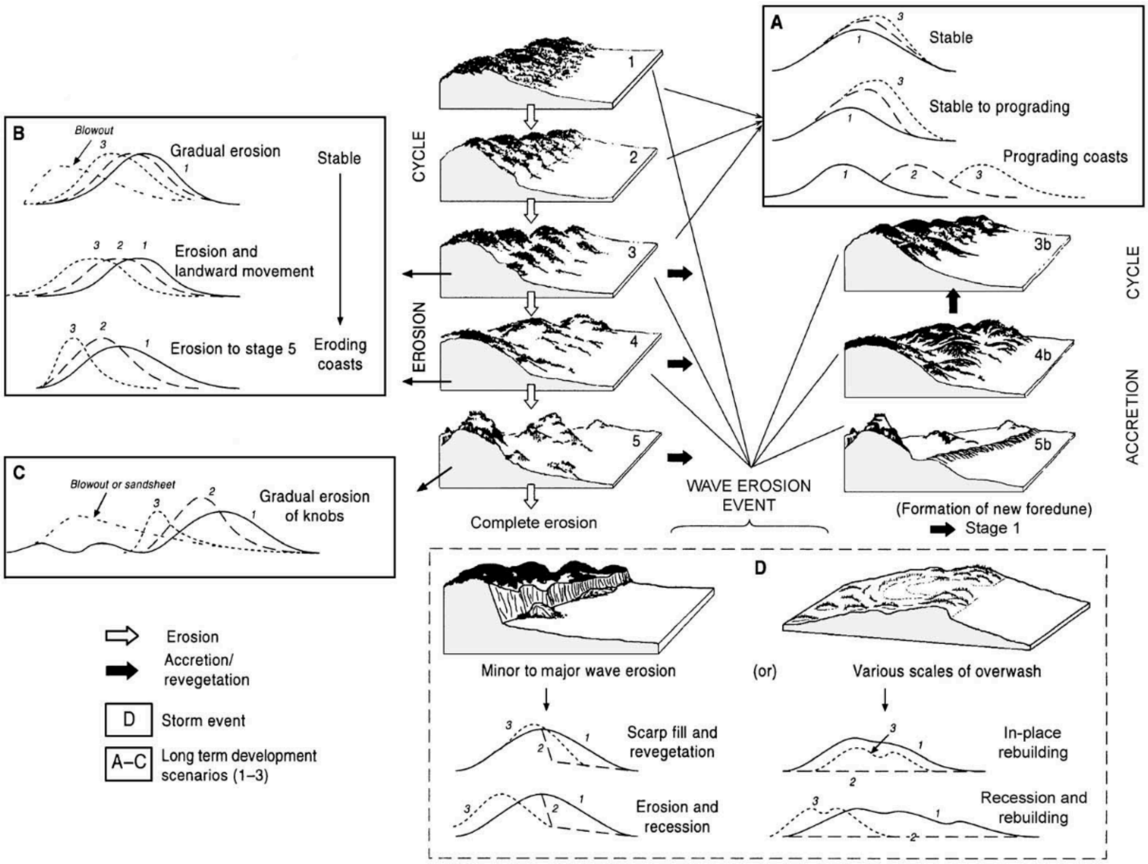

Figure 1.1.4: A diagram indicating the successional stages of erosional impact on coastal dune systems (Hesp, 2002).

on coastal dunes (Jolicoeur et al., 2010; Walker et al., 2017). Numerous storm-related phenomena (e.g., high wind speed, increased wave runup height, storm surge, intense rainfall, flooding, runoff, flying debris) result in detrimental erosional effects (e.g., vegetation loss, sedimentary erosion, dune scarping, dune overwash) or in some cases, complete destruction of dune systems along a given coastline (Ollerhead et al., 2013; Walker et al., 2017).

Mathew et al. (2010) conducted a case study at the Greenwich dune complex on the north coast of PEI. Through the analysis of multiple aerial photographs taken from 1936 onward, they were able to track the morphology of the Greenwich coastline after a series of catastrophic storm events in the fall of 1923. These events resulted in the complete erosion and destruction of the dune system at Greenwich, likely attributed to extreme storm surge and intense wave action over an extended period. After the events of 1923, the Greenwich foredunes underwent a 40-year interval of complete reestablishment, followed by an additional 30-year interval in which the inland transgressive dunes became fully stabilized and vegetated (Mathew et al., 2010). While this study points to the potentially catastrophic erosional capacity of intense storm events, it also reveals how vegetated dune coastlines can rejuvenate after such events occur. This finding is consistent with other studies conducted on vegetated dune complexes in Atlantic Canada, which suggest that coastal resiliency is high, but varies in timescale depending on the rate at which sediments are returned to the system via wave and aeolian processes (see for e.g., Davidson-Arnott et al., 2024; George et al., 2021; Rosen, 1979).

1.1.2.2 Human disturbances

The recorded study of the relationship between human settlements and vegetated dune coastlines has been ongoing since at least 1300 (Clarke & Rendell, 2015; Cowles, 1899; Jensen, 1994), evidencing a long history and recognition of the impact of human coastal activity and development on dune landscapes. The effect of anthropogenic influence on coastal dunes is distinct from the erosional effects of natural processes that also govern their development, maintenance, and restoration over time. Nordstrom (1994) asserts that human-altered landscapes behave differently than their natural counterparts, as while undisturbed dune complexes migrate and undergo long periods of restoration after destructive events, human-altered systems may become morphologically stagnant and require restorative management to persist over time. Human activities, in combination with infrastructural developments, have the capacity to exert negative erosional effects on vegetated dune coastlines (Nordstrom, 1994).

Much existing research points to human coastal activities (e.g., pedestrian trampling, offroad vehicle use, extraction, campfires, military training) as significant contributors to the development of blowouts along dune systems (Catto, 2002; Catto et al., 2002; Catto & Catto, 2009; Hesp, 2002; Nordstrom, 1994). Dune blowouts that result from anthropogenic activities differ in both size and shape from those that develop from wind and/or wave related pressures (Figure 1.1.5). Linear elongated or trough-shaped blowouts (up to tens of meters in length) develop in areas of frequent human trampling, typically for beach access, while large deflation basins develop as a result of campfires or extractive activities (Catto, 2002; Catto et al., 2002). All-terrain vehicle (ATV) use is particularly damaging to dune vegetation. Research conducted by Hogan et al. (2019) and Hogan & Brown (2021) concluded that ATV use in vegetated dune landscapes was associated with increased vegetation mortality, decreased vegetation cover, and decreased native species presence in the dune ecosystem. Over time, human pressures may give rise to the development of blowouts and dune crest deflation, or in extreme cases, may cause the landscape to fragment into smaller, earlier-successional stage dunes (Bate & Ferguson, 1996; Catto et al., 2002; Hesp, 2001).

The construction of infrastructure and other human developments near and/or on vegetated dune coastlines also has detrimental effects on their morphology and vegetation community integrity (e.g., species richness, vegetation density). This is particularly relevant in regions of human population growth, where coastal development is increasing to facilitate access to beaches located along vegetated dune coastlines, which are valued for their aesthetics and recreational potential (Stancheva et al., 2011). Despite their importance and rarity, dune systems are simultaneously undervalued in development decision-making, and continue to be exploited by developers for their tourism and recreation potential (Lucrezi et al., 2014). Coastal infrastructures and developments, such as roads (Catto et al., 2002), parking lots (Zhang et al., 2019), protective structures (Nordstrom, 1994), holiday resorts (Lucrezi et al., 2014), and beach houses (Stancheva et al., 2011) have all been associated with detrimental impacts to dune vegetation and morphology. The effects of human development on dune landscapes are varied, but include a reduction of dune width, non-native species

Figure 1.1.5: Aerial images of a natural dune blowout on the Rustico Island Causeway (left) and an anthropogenic dune blowout at Covehead (right) in Prince Edward Island National Park (Prince Edward Island National Park, 2023b, 2023a).

introduction, decreased vegetation height, or complete loss of the dune complex (Lucrezi et al., 2014). More generally, anthropogenic coastal developments place vegetated dune systems in a "coastal squeeze" (Lucrezi et al., 2014; Schlacher et al., 2008) between landward anthropogenic pressures and natural erosional processes, reducing ecosystem size and functionality.

While both natural and anthropogenic disturbances may result in similar impacts to vegetated dune ecosystems, the driving factors associated with each are fundamentally different. Both natural (Davies, 2011; Delgado-Fernandez, 2011; Forbes et al., 2004; George et al., 2021) and human-related impacts (Balduzzi et al., 2014; Finkl, 2013; Jungerius & van der Meulen, 1989; Walker et al., 2009) may be actively managed to preserve dune systems, but require the development of distinct management strategies to address each issue. However, similarity in some erosional features (e.g., blowouts) on dune landscapes between human and natural impacts remains a barrier to impact classification. While some features may be obvious (e.g., an ATV trail), others may be more indistinct. One way to establish the difference between anthropogenic and natural influences on a given landscape is to record impacts both in and out of protected areas, as dune complexes located within protected areas should be subject to less frequent anthropogenic use. Protected areas are assumed to be those affected predominantly by natural impacts, while their unprotected counterparts are subject to both natural processes and human influence. A number of previous studies have employed this method to achieve a similar understanding of anthropogenic and natural effects (Aretano et al., 2017; Coma et al., 2004; Cooke et al., 2023; Sánchez-Ferris, 2019; Virkkala et al., 2014).

1.1.3 Significance of the dune ecosystem

1.1.3.1 The Piping Plover

Across Atlantic Canada, coastal vegetated dune complexes provide a vital habitat to a variety of beach-nesting bird species, including the threatened Bank Swallow (*Riparia riparia*) (Power et al., 2022), the Killdeer (*Charadrius vociferus*), the Semipalmated Plover (*Charadrius semipalmatus*), the Sanderling (*Calidris alba*) (Environment and Climate Change Canada, 2012), and the endangered Piping Plover (*Charadrius melodus*) (Tarr et al., 2010). The management and preservation of Piping Plover habitat is an ecological concern in the Atlantic region. The Piping Plover is currently listed as endangered by both the Committee on the Status of Endangered Wildlife in Canada and by the Species at Risk Act (SARA), due to a low and declining population (Environment and Climate Change Canada, 2022; Powell & Cuthbert, 1992). The Piping Plover breeds and nests in dry sand or in sparsely vegetated areas on sandy beaches backed by vegetated dunes, across the coastlines of Newfoundland and Labrador, Nova Scotia, PEI, New Brunswick, and Les Îles de la Madeleine (Boyne et al., 2014; Environment and Climate Change Canada, 2022; Flemming et al., 1988; Seavey et al., 2011; The Government of Newfoundland and Labrador, 2021; White, 2023) (Figure 1.1.6).

The Piping Plover is threatened by many of the same natural and anthropogenic processes that impact vegetated sand dune ecosystems. Any event or repeated occurrence that disturbs the dry sand on the foreshore or the vegetated dune areas of the backshore has the capacity to negatively impact their breeding success, health, habitat, and survival (Environment and Climate Change Canada, 2012; Flemming et al., 1988; Gibson et al., 2018). This includes natural hazards such as sea level rise, coastal erosion, as well as tropical cyclone and post-tropical storm events, all of which may damage nests and/or result in individual mortality (Seavey et al., 2011). Human activities are generally more impactful to species well-being, as they disrupt normal breeding, foraging, resting, and/or young-rearing behaviors (Environment and Climate Change Canada, 2022). Anthropogenic disturbances are

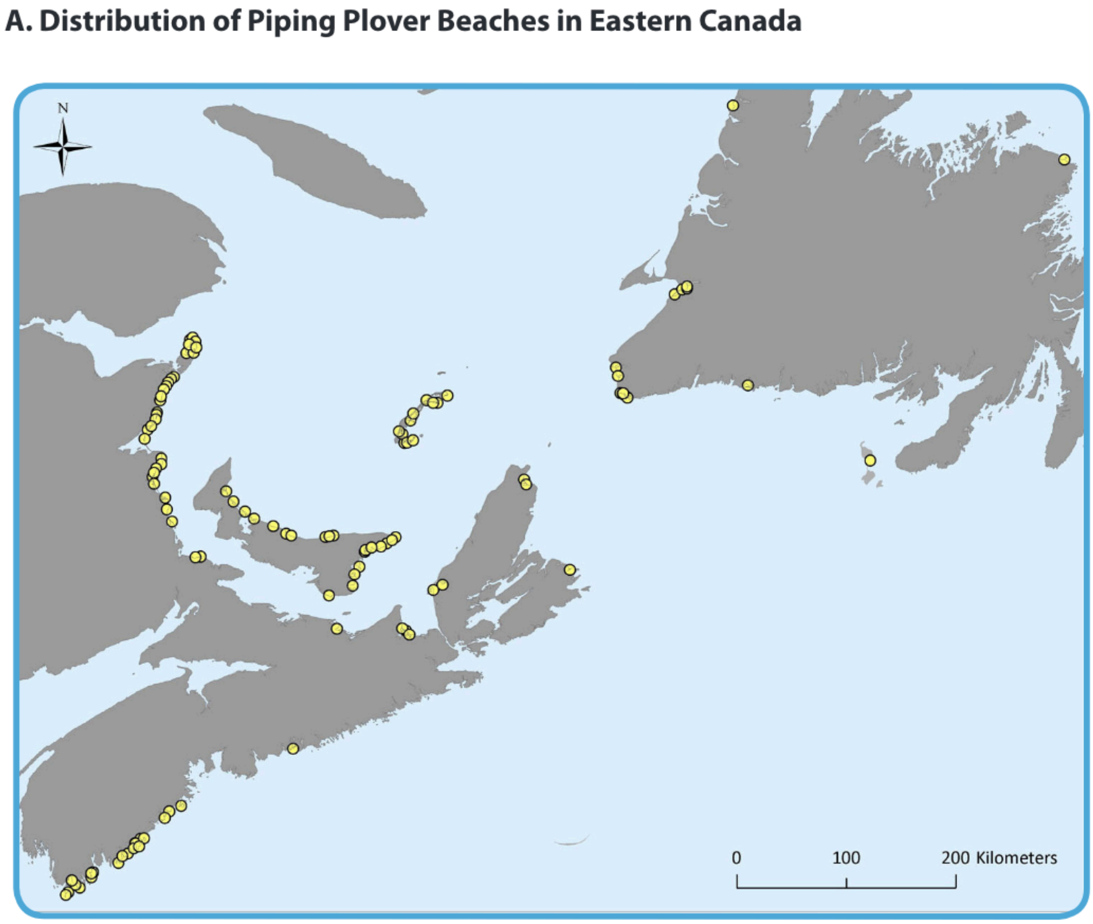

Figure 1.1.6: A map of known Piping Plover breeding locations in Atlantic Canada (Environment and Climate Change Canada, 2012).

both pervasive and varied, and include activities such as pedestrian traffic, campfires, unleashed pets, recreational sports, industrial effluent pollution, infrastructural development, and the use of motor vehicles on beach systems (Environment and Climate Change Canada, 2009, 2012, 2022; Seavey et al., 2011). Not only do these types of activities interrupt the behavioral processes of beach-nesting birds, they also disturb and destroy the dune landscape, resulting in vegetation mortality and morphological fragmentation of the ecosystem (Hesp, 2001).

1.1.3.2 Dune vegetation and coastal stability

In addition to the benefits provided to regional fauna, dune vegetation also supports the overall stability and robustness of the coastal landscape. The presence or absence of vegetation plays a key role in transverse dune morphology, as dune vegetation fosters depositional processes and discourages coastal erosion (Snow, 1984). Dune construction is facilitated by the stabilizing influence of the vegetation (Catto et al., 2002; Mountney & Russell, 2006), which creates wind resistance, traps moisture, and reduces sediment transport through the system (Byrne & McCann, 1993; Hesp et al., 2013). These findings are further evidenced by those of Hesp (2002), who concluded that the morphology and classification of individual dunes could be attributed to the presence or absence of specific types of vegetation. For example, tall or dense grasses tend to facilitate the development of higher and peaked dune forms, while smaller plants and shrubs tend to produce shorter dunes with rounded crests (Hesp, 2002). In addition to its contribution to dune formation, vegetation also impedes dune erosion through sediment capturing during intense wind, wave, or storm events, preventing sand migration away from the dune complex (Armon & McCann, 1979; Jungerius & van der Meulen, 1989). Correspondingly, a loss of vegetation cover has also been shown to result in an increase in foredune erosion (Hesp, 2002). In an assessment of coastal dune complexes across the world, Doing (1985) determined that the most diverse and extensive dune systems occurred in areas where the effects of wind disturbance and plant growth fixation were equally strong. Thus, vegetation acts as a stabilizing agent upon which aeolian transport deposits sediments, facilitating dune growth, complexity, and ecosystem diversity.

1.1.4 Coastal dunes in Newfoundland

On the Island of Newfoundland (hereafter referred to as Newfoundland), vegetated sand dune complexes are a comparatively rare coastal feature. Most of Newfoundland's dune-backed coastlines exist in the southwest region of the island, such as those near Burgeo, Channel-Port aux Basques, Cape Ray, and Stephenville Crossing. Vegetated dunes are also present along the coastline of Cape Freels and Lumsden in the northeast, in Gros Morne

National Park in the west, as well as across several scattered and isolated beaches on both the Avalon and Burin Peninsulas. Catto (2002, 2012) identified that Newfoundland's sand-dominated coastlines are present onshore of areas with shallow, gently sloping bathymetry, and are the product of the reworking of ancient glacial or glaciofluvial sediment deposits during earlier phases of the Quaternary. This indicates that the processes contributing to the dune system formation (i.e., wind, sediment availability, sediment transport) have since changed, rendering them more susceptible to destruction if and when damage occurs (Hesp, 2002).

The relative rarity and geomorphic history of Newfoundland's vegetated sand dune systems makes them a particularly vulnerable coastal feature. This issue is compounded by the collective influence of limited previous research, poor landscape management, climate change impacts, as well as the effects of natural and anthropogenic pressures. In Newfoundland, vegetated dune coastlines are subject to many anthropogenic strains, including sediment extraction, human recreation (e.g., campfires, walking, beach sports), pollution, as well as culturally significant activities like hunting, fishing, sheep herding, and ATV use (Catto, 2002; Waight & Bath, 2014). In addition to human disturbances, vegetated dune complexes are also threatened by coastal erosion, arising from the combined effects of storm activity (i.e., tropical cyclones, post-tropical storms, mid-latitude cyclones), diminished winter snow and ice cover, and intense precipitation events (Catto, 2012; Forbes et al., 2004). Climate change projections conducted by Finnis (2013) for Newfoundland predict increases in average temperatures, precipitation as rainfall, and significant precipitation events through the year 2070. These findings all suggest a projected increase in the frequency and severity of storm events (Finnis, 2013), and point to an increased future threat of coastal erosion under climate change (Catto, 2012; Finnis, 2013; Forbes et al., 2004).

Despite the research indicating a need for additional planning and management of coastal landscapes under the predicted effects of climate change (Barr et al., 2021; Jardine et al., 2021), the rarity of coastal dune landscapes in Newfoundland (Catto, 2002), and the observed need for the conservation of Piping Plover breeding sites (Environment and Climate Change Canada, 2012, 2022), few provincial protected areas cover transverse dune complexes. The Government of Newfoundland and Labrador (2023) defines a protected area as "an area of land and/or sea especially dedicated to the protection and maintenance of biological diversity, and of natural and associated cultural resources, and managed through legal or other effective means," and includes provincial parks, wildlife reserves, as well as wilderness and ecological reserves. Protected areas that cover some vegetated dune landscapes in Newfoundland include Gros Morne National Park, Sandbanks Provincial Park, Big Barasway Wildlife Reserve, JT Cheeseman Provincial Park, Codroy Valley Provincial Park, and Deadman's Bay Provincial Park (The Government of Newfoundland and Labrador, 2017), but many vegetated dune systems remain unprotected. While some research points to limited financial resources or incongruent cultural beliefs about ATV and other human recreation as a possible cause (Catto, 2002; Waight, 2014; Waight & Bath, 2014), the reasoning behind the scarcity of these protected areas remains unclear. Given the existing vulnerability of Newfoundland's vegetated dune coastlines, their role in supporting endangered beach-nesting bird species, the threat of anthropogenic pressure, and the predicted increase in the frequency and severity of natural impacts under climate change, additional research and management initiatives are needed to support these landscapes in the years to come.

1.1.5 Learning from managed and monitored regions

Despite the limited research, monitoring, and management of vegetated dune complexes in Newfoundland, it remains possible to assess other actively managed and monitored regions of Atlantic Canada, to inform future provincial management initiatives. Transverse vegetated dunes cover 14.7% of PEI's coastline (Davies, 2011), making them a prevalent and well known part of the landscape. PEI's vegetated dunes, particularly those on the north coast, have been subject to repeated research, ecological management, and monitoring through time (Armon & McCann, 1979; Bauer et al., 2009, 2012; Catto et al., 2002; Chapman et al., 2012, 2013; Davidson-Arnott et al., 2008; Davidson-Arnott & Bauer, 2009; Delgado-Fernandez, 2011; Delgado-Fernandez et al., 2012; George et al., 2021; Hesp et al., 2009, 2013; Jardine et al., 2021; Ollerhead et al., 2013; Walker et al., 2006, 2009, 2017; Yang & Davidson-Arnott, 2005). In addition to this research, the impacts of recent and severe storm events (i.e., Post Tropical Storm Dorian in 2009 and Hurricane Fiona in 2022) on PEI's dune coastlines were carefully monitored, managed, and studied to assess damage and inform future action (Davidson-Arnott et al., 2024; George et al., 2021; Jardine et al., 2021; Parks Canada, 2022, 2023; Yarr, 2022). The management of both anthropogenic and natural pressures on vegetated dunes has been extensive and long-established, including the incorporation of dune landscapes into PEI National Park (Delgado-Fernandez, 2011; Walker et al., 2017), restricting human foot traffic to a limited number of authorized beach access points (Catto et al., 2002), replanting *Ammophila breviligulata* in blowouts (Bate & Ferguson, 1996), and implementing sand fences to both restrict dune access and prevent erosion (Snow, 1984). Given their close geographical proximity and relative similarity in climate, the robust style, duration, and frequency of vegetated dune management in PEI can be used as a case study to inform management in other coastal dune regions of Atlantic Canada, including those in Newfoundland and Labrador.

1.2 Thesis overview and objectives

The purpose of this research was to categorize the ecology and assess the level of natural and anthropogenic disturbance on Newfoundland's transverse vegetated dune coastlines. This study was conducted with the primary aim of informing future coastal landscape management in Newfoundland, including recommendations for the implementation and governance of dune protected areas. By taking a protected areas approach, we were able to assess the potential effects of protected areas regulations and their relationship to anthropogenic coastal disturbance. In this chapter, I introduced dune ecology and morphology in Atlantic Canada and reviewed the driving context for this research. I discussed the types of dune system disturbances and reviewed their patterns of impact on the landscape. I also outlined the significance of the dune ecosystem, including its importance in the provision of faunal habitat as well as coastal protection. Finally, I discussed the prevalence of coastal dune systems in Newfoundland and how dune management practices in a similar ecological and climatological context (i.e., PEI) could inform future landscape governance. Chapter 2 provides a description of our study locations and design, and our findings, including a discussion of the differences in ecological and disturbance-related characteristics found inside and outside of Newfoundland's dune protected areas. Specifically, this project addressed the following research objectives:

1. **To determine how substrate, groundcover, and vegetation species change between protected and unprotected areas**

    H1: Protected areas restrict human landscape use and provide protective measures against anthropogenic disturbances, which are associated with a loss of vegetation cover and vegetative community disturbance. This means that

    P1: unprotected areas will demonstrate a greater incidence of anthropogenic landscape disturbance, vegetation sparseness, and will be more likely to host non-endemic species than protected areas.

2. **To determine the impact of disturbance on vegetated characteristics and cover**

H2: Coastal dune disturbance is associated with a loss of vegetation cover and landscape disintegration. This means that **P2:** regardless of protected areas status, areas with more disturbance will also display a lower vegetation cover and a greater loss of dune landscape integrity.

Finally, in Chapter 3, I outline our qualitative and observational findings that we noted at each of our study locations, providing a review of dune landscape management in Newfoundland and PEI. Lastly, I outline the limitations of our study and point to areas requiring additional future research. The ongoing effects of climate change will continue to impact Newfoundland's most vulnerable and beloved coastal areas. Collectively, human and natural disturbances have the potential to fragment the dune ecosystem, resulting in a loss of ecological diversity and landscape integrity. Integrating our findings into current and future landscape management practices is essential to the preservation of Newfoundland's dune systems, which hold cultural, ecological, and economic importance to people and wildlife alike.

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Chapter 2: Please do not walk on the dunes: Assessing cumulative impacts on coastal vegetated sand dune systems in Newfoundland, Canada

2.1 Introduction

Coastal ecosystems are among the most biodiverse and productive regions of the world, as they facilitate the interface between aquatic, avian, and plant communities (Calvão et al., 2013; Suyadi et al., 2021). In boreal regions, such as Atlantic Canada, vegetated dunes form one type of coastal landscape that contributes key services to the surrounding human and wildlife communities, including: providing habitat for multiple species of beach-nesting shorebirds (Boyne et al., 2014; Power et al., 2022), contributing to coastal plant biodiversity (Tissier et al., 2013), protecting communities from storm events (Spalding et al., 2014), and contributing to local tourism or recreation activities (Catto et al., 2002; Delgado-Fernandez et al., 2019; Lucrezi et al., 2014). Simultaneously, sand dune coastlines are also subject to various natural (Bate & Ferguson, 1996; Dech et al., 2005; Jungerius & van der Meulen, 1989) and anthropogenic (Aretano et al., 2017; Nordstrom, 1994; Stancheva et al., 2011) disturbances, which, when combined with poor land management practices, can result in the degradation of ecological and morphological integrity over time (Hesp, 2001).

In Atlantic Canada, coastal vegetated dune ecosystems are vital to regional ecological prosperity. They provide seasonal habitat to several species of beach-nesting shorebirds, including the Piping Plover (Environment Canada, 2009; Flemming et al., 1988). The Piping Plover is in population decline and is currently listed as endangered in Canada under Schedule 1 of the *Species at Risk Act* (Environment and Climate Change Canada, 2022). Piping Plover individuals migrate to the vegetated dune beaches of Nova Scotia, PEI, New Brunswick, and Newfoundland during the breeding season, which runs from April to mid-October (Boyne et al., 2014; Environment and Climate Change Canada, 2012). During these months, they nest in areas of dry sand, sand and cobble, or in the sparsely vegetated edges of the dune vegetation (Powell & Cuthbert, 1992). In addition to providing shorebird habitat, dunes also contribute to coastal plant biodiversity. Boreal dunes often host a variety of endemic plant species that cannot grow on coastlines dominated by other substrates (e.g., rock, soil). These include several salt and frost tolerant species that grow on mixed-humidity sandy substrates, such as *Ammophila breviligulata*, *Leymus mollis*, *Lathyrus japonicus*, and *Cakile edentula*, among others (Hesp, 2002; Hogan & Brown, 2021; Tissier et al., 2013; Zhang et al., 2019). The plant communities endemic to vegetated dunes contribute to heterogeneity in boreal coastal ecology, which predicts and supports broader regional biodiversity in both plant and animal species (Hekkala et al., 2023). The long-term conservation of boreal vegetated dune beaches is paramount to the preservation of floral and avian biodiversity and the restoration of Piping Plover populations in this region (Environment and Climate Change Canada, 2022).

Coastal ecosystems are also critical to local risk reduction (Spalding et al., 2014), and vegetated dunes play an important role in shoreline protection from erosion and storm events (Cunha et al., 2021). During storms or other high-energy wind and wave events, dunes act as a coastal shield that protects inland areas from erosion and damage (Davidson-Arnott & Bauer, 2009). Coastal communities protected by vegetated dunes have been previously shown to incur fewer financial losses to infrastructure during storm events, when compared to coastal areas that had undergone erosion and habitat loss (Cunha et al., 2021). Additionally, dune complexes are self-restoring, meaning that in the absence of other disturbances and with adequate sediment supply, even heavily damaged dune systems will return to baseline after a period of time (Mathew et al., 2010; Ollerhead et al., 2013). Though dune shorelines provide a variety of benefits, they are a relatively rare coastal ecosystem in Atlantic Canada (Catto, 2002; Chapman et al., 2012; McCann & Bryant, 1973; Nichol & Boyd, 1993). While this can foster tourism and human recreation (see for e.g., Government of Canada, 2023; Parks NL, 2023), increased human use of these sensitive landscapes produces adverse effects over time (Catto, 2002; Catto et al., 2002).

Anthropogenic use of vegetated dune coastlines is frequent and commonly produces disturbances that exceed what would normally be the result of natural processes (e.g., tropical cyclone events). Anthropogenic activities are typically chronic and more degenerative when compared with the isolated impacts of natural hazards (Stancheva et al., 2011). Human disturbance often compounds the effects of natural events, leading to a greater incidence and severity of blowout formation and a decrease in vegetation cover (Calvão et al., 2013; Delgado-Fernandez et al., 2019; Hesp, 2001). Previous studies have highlighted the most problematic types of human disruption in dune systems, including: ATV use (Hogan et al., 2019), trampling (Delgado-Fernandez et al., 2019), construction (Catto, 2002), and dogs (Environment and Climate Change Canada, 2012). While not a direct physical impact, the persistent mismanagement of dune systems over time has also been identified as an enabling factor in anthropogenic disturbance (Calvão et al., 2013). Given the observed and projected increases in precipitation and storm events as a result of climate change, the cumulative effects of human use and natural events may lead to an increase in disturbance to Atlantic Canadian dune ecosystems (Finnis, 2013; Jardine et al., 2021).

Coastal vegetated sand dunes in Newfoundland are affected by the same mechanisms and limitations as those in other Atlantic Canadian provinces. In Newfoundland, dunes are a relatively rare type of coastal landform, and few studies have been conducted to evaluate their ecological integrity or to identify conditions of landscape disturbance (Catto, 2002, 2012; Waight, 2014). Despite their rarity and importance to regional ecology, Newfoundland’s vegetated dune ecosystems are not well protected; most exist along unprotected coastal segments or within low regulation protected areas (e.g., provincial or municipal parks) (The Government of Newfoundland and Labrador, 2017, 2023a, 2023b).

The future effects of anthropogenic disturbance and natural hazard events, combined with insufficient landscape management, may lead to deleterious impacts on the ecology and landscape integrity of Newfoundland's coastal vegetated dunes. If the current circumstances remain the same, they may lead to extensive landscape disintegration, vegetation sparseness, as well as a loss of shorebird habitat and coastal plant biodiversity. The destruction of vegetated dune systems in Newfoundland could also affect nearby human communities through a decrease in regional tourism and a loss of coastal protection during severe storm events.

Here, our goal was to evaluate the status of Newfoundland's vegetated dune coastlines, identify vulnerable areas, and inform future management procedures. We aimed to assess the relationships between protected areas, levels of disturbance, and ecological integrity by quantifying i) how substrate, groundcover, and vegetation species change between protected and unprotected areas and ii) how disturbance features impact vegetation characteristics and cover. We predicted that i) unprotected areas would display a greater incidence of anthropogenic disturbance, vegetation sparseness, and non-endemic species than protected areas, and that ii) regardless of protected areas status, disturbed regions would have less overall vegetation cover and a greater loss of dune landscape integrity. Gathering current data on the ecological robustness and landscape stability of Newfoundland's vegetated dune systems is imperative to understanding the best practices for their management as we advance into the complex future dynamics of climate change.

2.2 Methods

2.2.1 Study location

Our research occurred on the traditional territories of the Mi'kmaq and Beothuk on Ktaqmkuk, the island of Newfoundland, along segments of vegetated dune-backed coastline. Newfoundland is characterized by mild summers with average daily temperatures near 16°C and cold winters with average daily temperatures near -5°C. Monthly precipitation ranges from 90-100 mm of rainfall in the summer months to 150-165 mm of mixed precipitation (i.e., rain, snow, sleet) during late fall and early winter months (Environment and Climate Change Canada, 2023). The island's coastal areas are affected by the impacts of tropical cyclones and post-tropical storms that move through Atlantic Canada from August to October, as well as by mid-latitude cyclones that occur from December to April during the winter months (Environment and Climate Change Canada, 2009). The coastline of Newfoundland is dominated by rocky cliffs, bluffs, and medium-to-coarse gravel beaches, while fine-sediment sand shorelines are comparatively rare. Vegetated dune complexes are present on some of these fine-sediment beaches, and are more common along the southwestern, western, and northeastern regions of the island (Catto, 2012; Steele, 1983). The vegetative community on Newfoundland's dune coastlines is typical to that of sand dunes located in other boreal regions, hosting several grasses and salt-tolerant plant species such as *Ammophila breviligulata*, *Leymus mollis*, *Lathyrus japonicus*, and *Cakile edentula* (Byrne & McCann, 1993; Lucrezi et al., 2014; Ollerhead et al., 2013; Snow, 1984; Tissier et al., 2013; Walker et al., 2017).

2.2.2 Study design

Our study covered beaches in three primary regions: from Cape Freels to Deadman's Bay in the northeast (Figure 2.2.1), from Stephenville Crossing to Shallow Bay in the west (Figure 2.2.2), and from Burgeo to Cape Ray in the southwest (Figure 2.2.3). Within these regions, we selected study sites previously identified by Catto (2002) as having coastal transverse dune complexes. In the context of this study, these refer to fine sediment coastal areas with a smaller incipient dune, followed by a tall (>1m to 10m), primary vegetated foredune located at the back of and extending across the width of the beach (Catto, 2002). We made the distinction between coastal dune complexes and other interior sand dune landforms

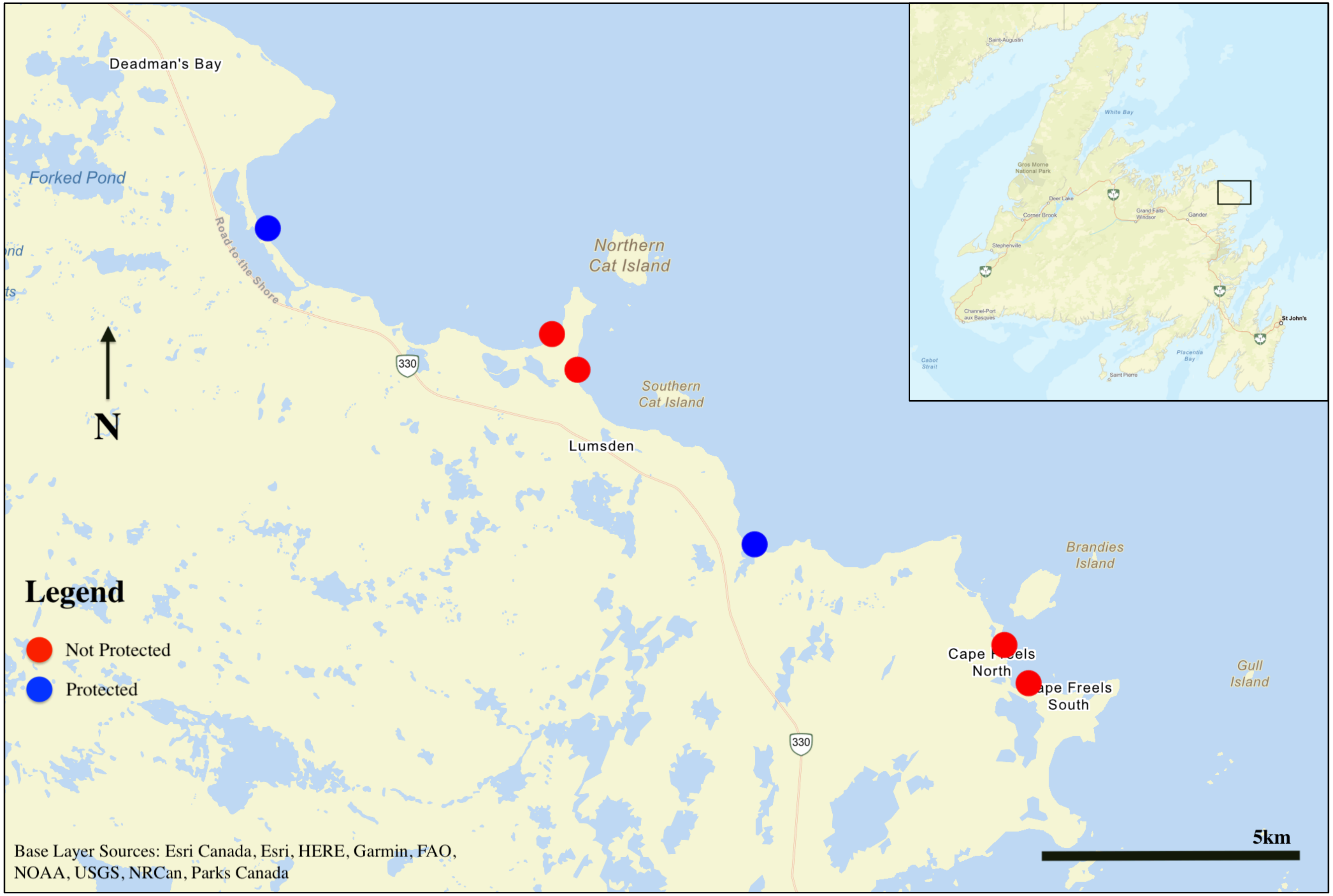


Figure 2.2.1: Map of northeast study locations with protected areas status indicated.

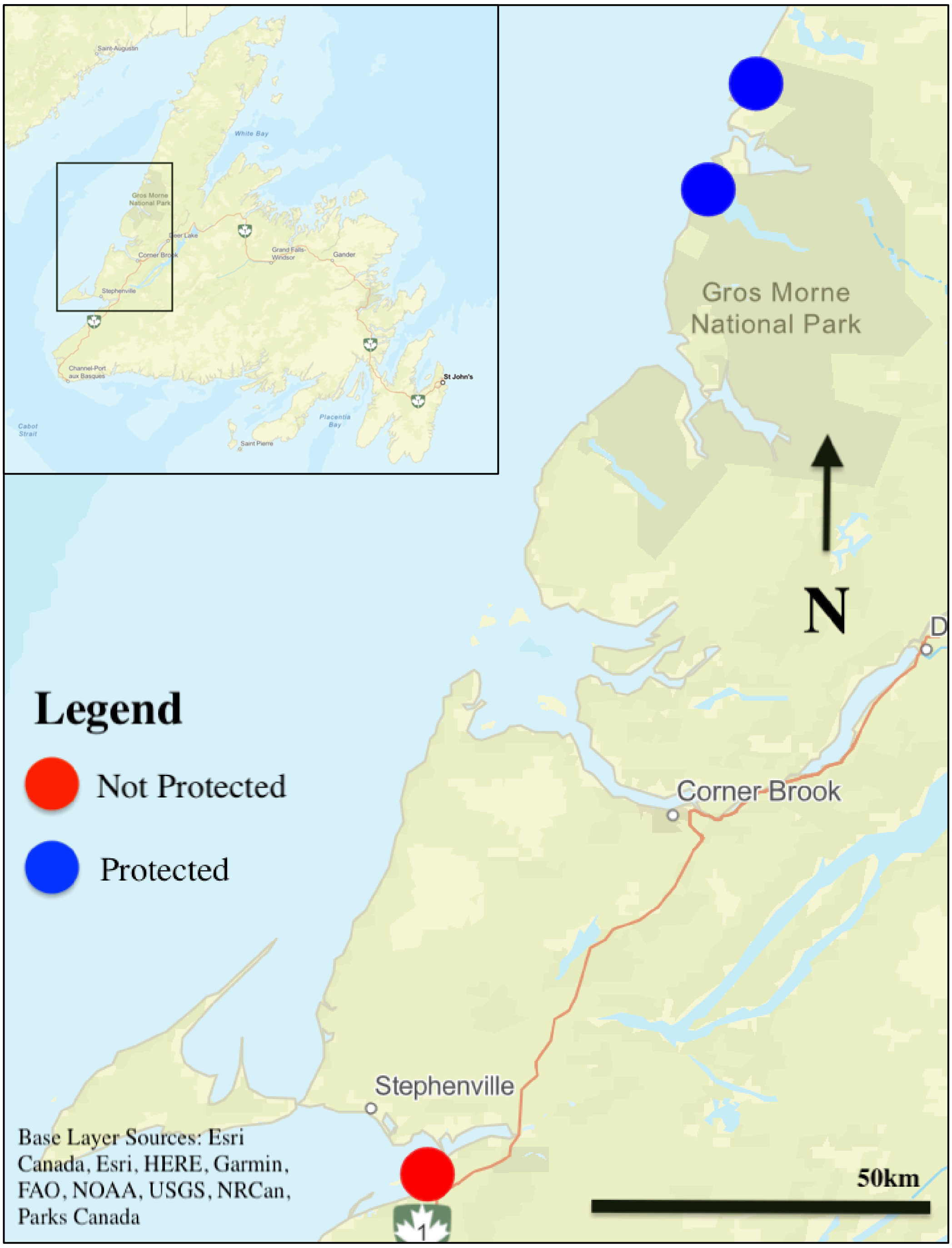


Figure 2.2.2: Map of west study locations with protected areas status indicated.

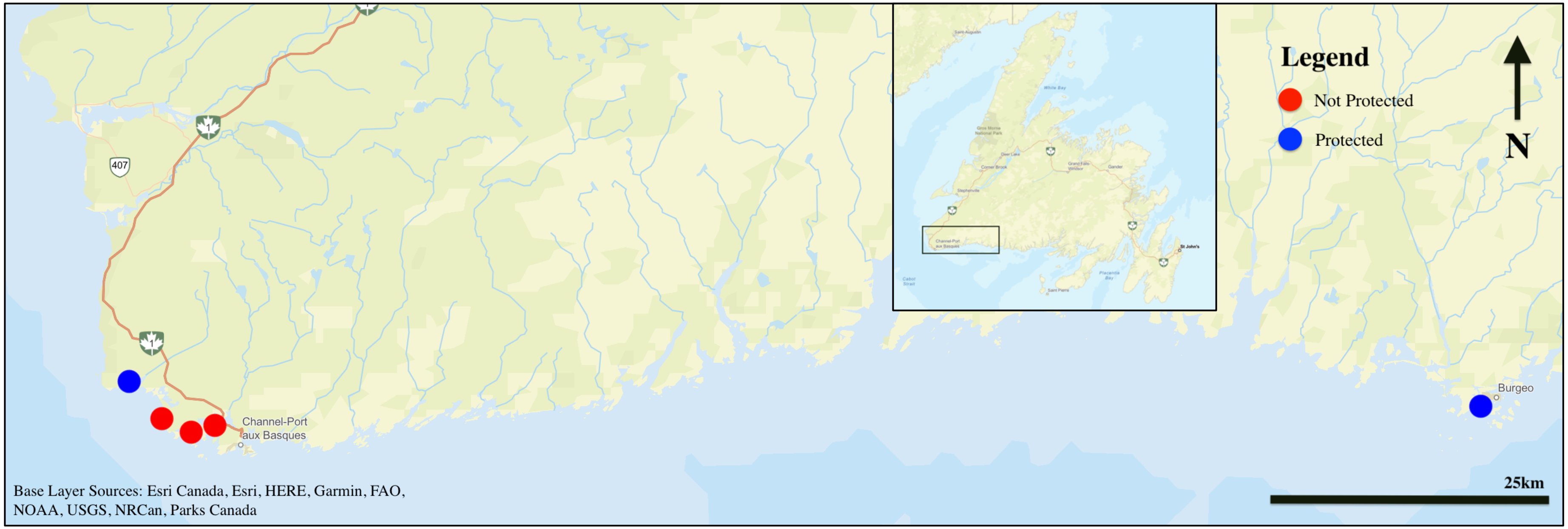


Figure 2.2.3: Map of southwest study locations with protected areas status indicated.

(e.g., dome dunes, sand sheets) to maintain uniformity across study sites and to target regions that were of greater conservation significance due to shorebird habitat suitability (Boyne et al., 2014; Environment and Climate Change Canada, 2012) and anthropogenic use factors (Catto, 2002, 2012).

To appropriately compare landscapes in protected and unprotected areas, we selected transverse dune-backed beaches located both inside and outside of protected areas within each of our three primary research regions for study (Table 2.2.1). Coastal segments were designated as having protected areas status if they were located within a municipal, provincial, or federal protected area (e.g., a provincial or national park) (Figure 2.2.4). Unprotected study sites were all those located outside of official and current protected areas. For example, sites located in areas nominated for future protection, but not presently having protected areas status, were considered unprotected areas. Due to the comparative rarity of transverse dune complexes in Newfoundland, and the sporadic coverage of coastal protected areas, selecting equal ratios of protected and unprotected research sites within each region and across the study was not possible. However, study sites located in protected and unprotected areas were represented in all three of our primary research regions (the northeast, west, and southwest coastlines).

Beaches were first assessed using Google Earth in reference with the Government of Newfoundland and Labrador's (2017) map of parks and protected areas on the island, to identify transverse dune complexes within each region that were representative of each protected area site type. If a site had more than one transverse dune beach in immediate succession, one beach was selected for study to maintain consistency. In such cases, chosen sites were typically the 'primary' beach in the given area (i.e., the easiest to access and most trafficked). Permissions to conduct research were obtained from municipal representatives,

Table 2.2.1: All research sites listed according to region and protected areas status.

Region	Site	Protected Areas Status
Northeast	Cape Freels South Beach	Not Protected
	Cape Freels North Beach	Not Protected
	Windmill Bight Municipal Park	Protected
	Lumsden North Beach	Not Protected
	Lumsden Back Beach	Not Protected
	Deadman's Bay Provincial Park	Protected
West	Stephenville Crossing	Not Protected
	Gros Morne – Western Brook Pond Outlet	Protected
	Gros Morne – Shallow Bay	Protected
Southwest	Sandbanks Provincial Park	Protected
	Grand Bay East Beach	Not Protected
	Grand Bay West Beach	Not Protected
	Rocky Barachois Outlet	Not Protected
	JT Cheeseman Provincial Park	Protected

Qalipu Mi'kmaq First Nation, and if applicable, the appropriate land conservation entities. Data collection was performed within a two-month window during July and August of 2023.

2.2.3 Sampling methods

2.2.3.1 Field methods

We employed data collection methods that are well established in previous assessments of both anthropogenic and vegetative features on coastal dune landscapes (see for e.g., Hogan & Brown, 2021; Lucrezi et al., 2014; Tissier et al., 2013). At each study site, we conducted transect-plot assessments of the landscape, to establish an understanding of the type and cover of vegetation species as well as the level of both anthropogenic and natural disturbance. Additionally, we took opportunistic field observations of macroscale disturbance features that might not have been otherwise covered by our transect measurements at each location. These observations included qualitative notes about anthropogenic use features (e.g., buildings, signage, parking lots) as well as recording measurements of large (> $1m^2$) dune blowout features (e.g., linear blowout walking trails, wind blowouts, campfire deflation hallows). Blowout disturbances were also classified according to suspected origin: human activity or natural processes.

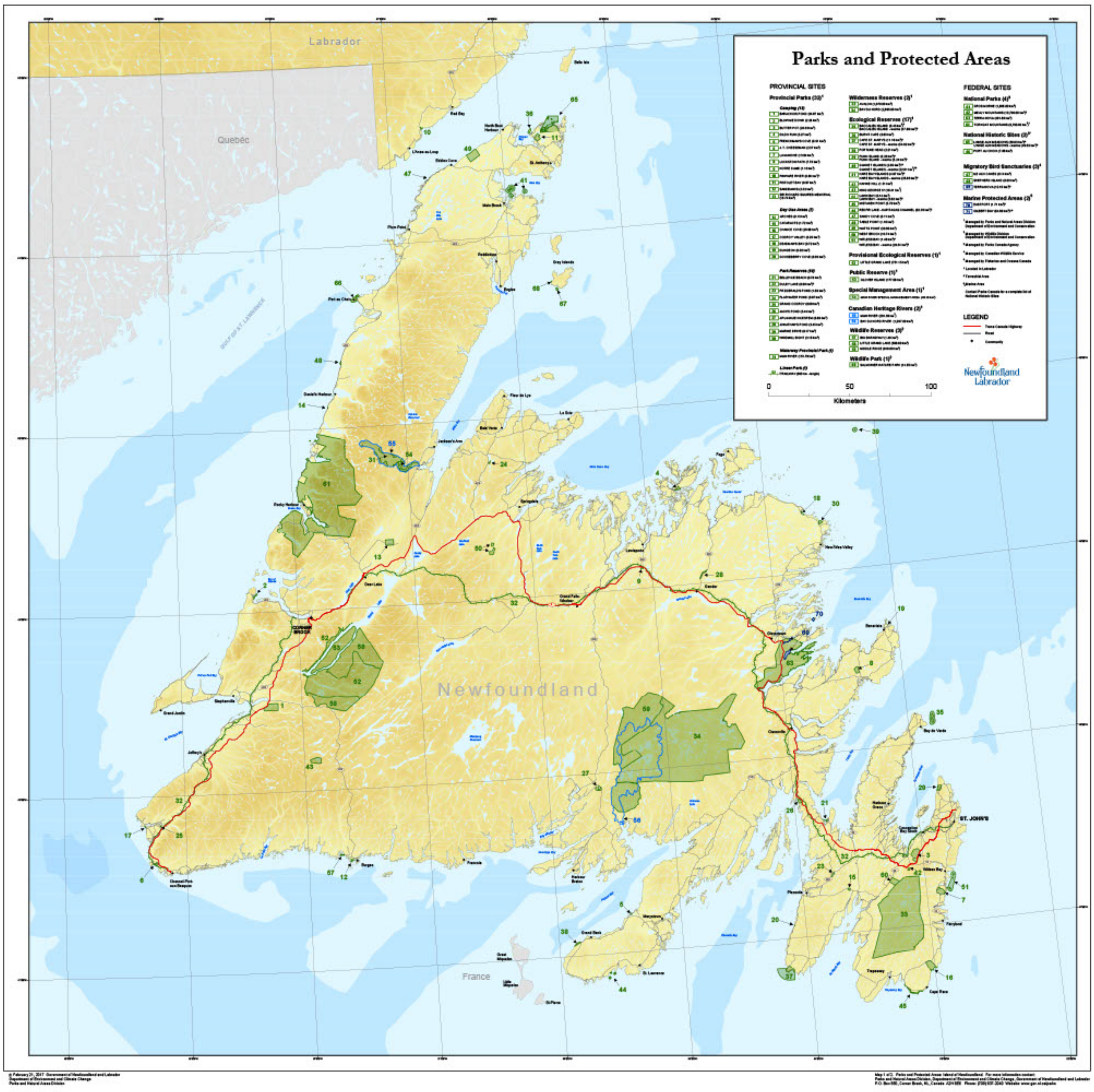


Figure 2.2.4: Map of parks and protected areas in Newfoundland, Canada (The Government of Newfoundland and Labrador, 2017).

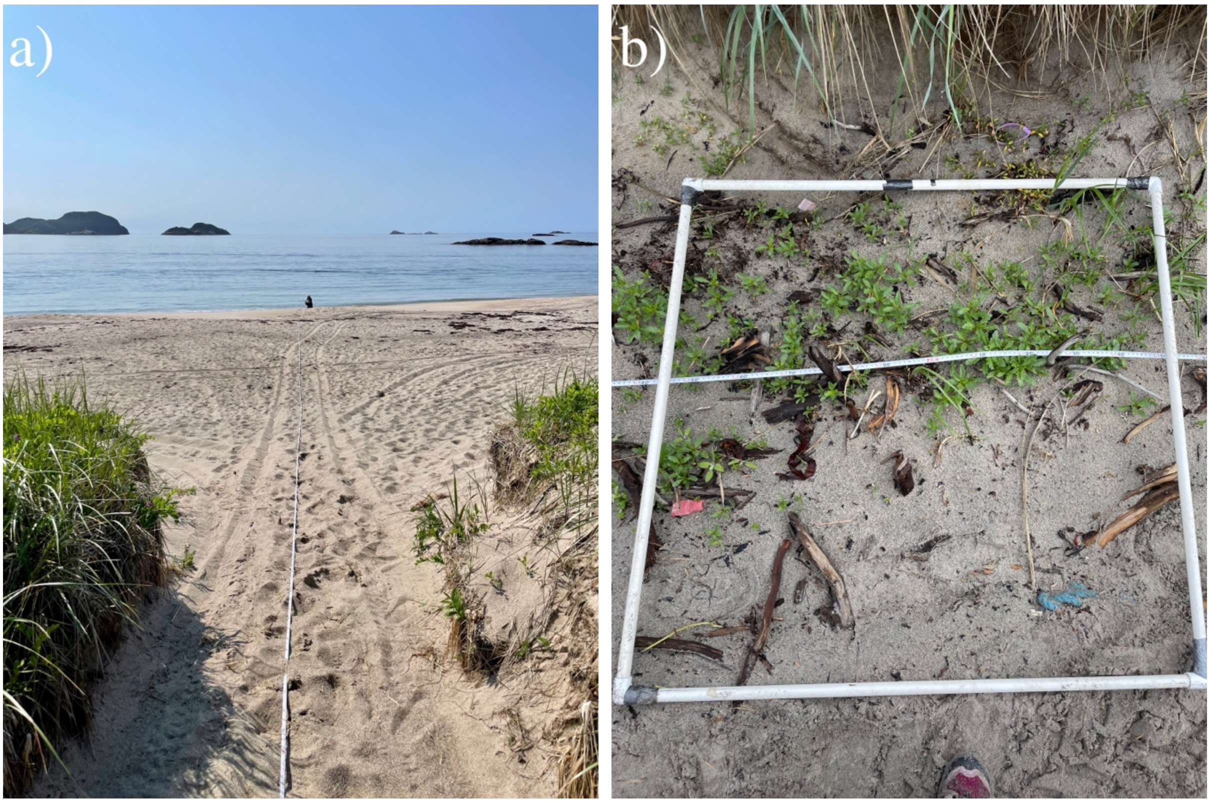


Figure 2.2.5: Layout of a) a transect along a beach entry point (in Sandbanks Provincial Park), and b) a 1m x 1m plot (in Deadman's Bay Provincial Park). Five transects were placed per beach, with the first oriented along the beach access point. Plots were placed every 5m along each transect line.

We set five transect lines at each study site. The first transect line was run at the beach's main point of human entry, which was typically a linear blowout running through the foredune (Figure 2.2.5a). Subsequent lines were run 25m apart according to the orientation of the first beach access line. For example, if the main point of entry was located near the center of the beach, we ran two lines at 25m and 50m away on both sides of the first transect. Transects were always organized in a way that prioritized the entry point for the placement of the first line, but which also provided the most coverage of the beach dune system. We took this approach to maintain uniformity while simultaneously tailoring our research to the unique morphology at each study location. We ran our transect lines from a point approximately 15m from the incipient foredune to the base of the main foredune's lee slope (Figure 2.2.6). Due to differences in dune size and profile, transect lines varied in length across and between research locations. Maintaining an approximate 15m buffer between the

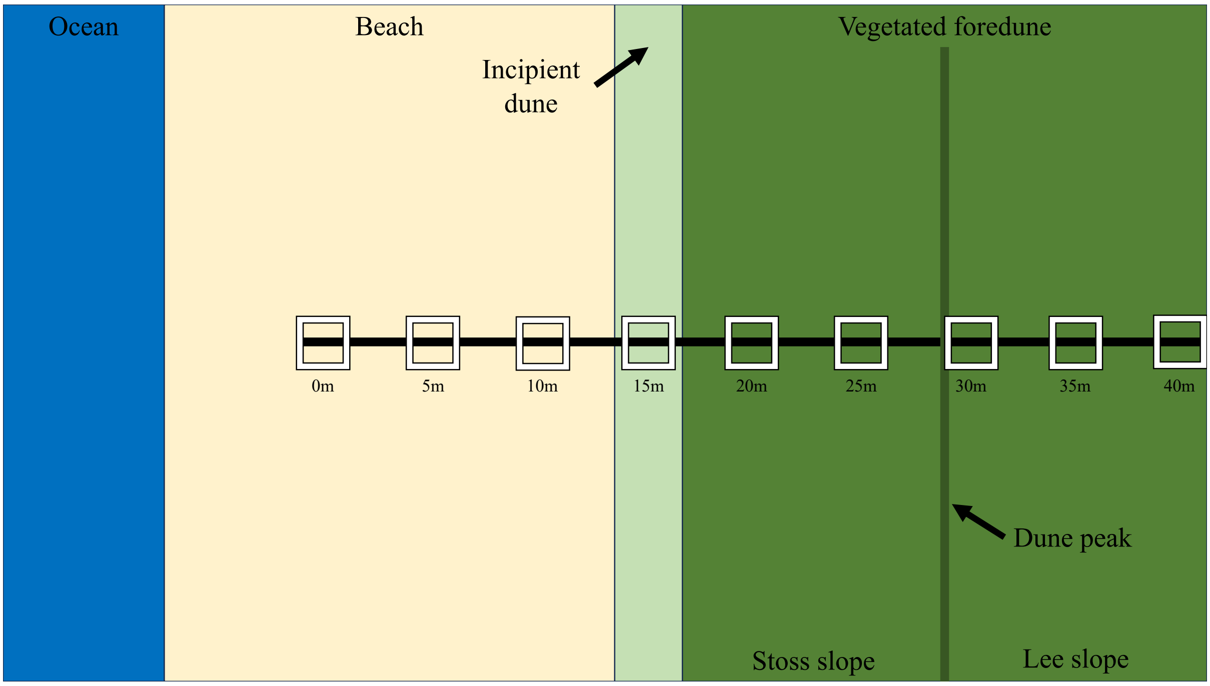


Figure 2.2.6: Diagram representation of one transect line and corresponding 1m x 1m plot placements.

start of the transect and the incipient dune enabled us to cover the same proportional beach and dune area at each site.

Starting at the 0m mark and continuing by 5m intervals on each transect, we set a 1m x 1m pre-measured PVC plot square centered around the 5m interval measurement and aligned perpendicular to the transect line (Figure 2.2.6, Figure 2.2.5b). Within each plot, we first identified its zone in relation to the dune system (beach, incipient dune, or vegetated foredune) and then measured the total groundcover as a percentage by sorting it into four categories: vegetation, disturbed substrate, undisturbed substrate, and human features (sum of categories = 100%). Next, we performed a count and identification of each individual vegetation species as well as its percentage cover with respect to the total plot area. In cases of species overlap (such as in densely vegetated plots), the percentage sum of species had the potential to exceed 100%. Identifiable anthropogenic (e.g., footprints, litter, ATV trails) or natural (e.g., wind blowouts, dune scarping) disturbance features within each plot were also recorded. Groundcover and species measurements as well as disturbance identification were completed by the same individual (Power) to ensure consistency in percentage estimations and feature classification.

2.2.3.2 Statistical analyses

To better understand the relationships between ecological integrity, landscape disturbance, and area type across our study sites, we compared our empirical measures of vegetation characteristics between sites. The plot groundcover and vegetation characteristics recorded during our transect-plot landscape assessments helped inform both the ecological and the landscape integrity of each study location. Factors influencing ecological integrity included measurements of plot level species richness (#), total vegetation cover (%), and species-specific cover (%), while measurements of disturbed and undisturbed substrate (%) were indicators of landscape integrity. All univariate statistical analyses were conducted with all plots included, and then with plots located in the beach zone removed. Removing the beach plots from our second round of analyses enabled us to eliminate any potential biases in our data that might have arisen due to the presence of beach plots, which often had a greater incidence of substrate disturbance. Though beach disturbance can be an important factor in landscape integrity, we determined the beach plots to be less critical to conclusions about the comprehensive bio-geomorphic robustness of the dune system.

All statistical analyses were performed using R version 4.3.1 (R Core Team, 2023) via RStudio version 2023.09.1+494 (Posit Team, 2023). We used pairwise comparisons to first compare groundcover and vegetation characteristics against protected areas status, to test our hypothesized differences in these factors between area types. We then used general linear mixed models (GLMMs) to model the interactive effects of our predictor variables on each of i) plot-level species richness, and ii) vegetation cover, both with and without beach plots included, for a total of four GLMMs. Each model included percent disturbed substrate, protected areas status, and the interaction of the two variables as predictor variables with transect as a random factor. Because of the structure of count data, species richness was analyzed using a Poisson model, while vegetation cover was analyzed using a Gaussian model (Appendix I).

2.2.3.3 Multivariate analysis

To characterize the dune vegetation community in Newfoundland, we performed non-metric multidimensional scaling (NMDS) using the "vegan" package (version 2.6-4; Oksanen et al., 2022). NMDS is a non-parametric ordination technique that places ecological data on a chosen number of axes based on the similarity of plot points. We used dune vegetation species and data plots as the basis for the ordination. Our NMDS plots used Bray-Curtis coefficients as measures of dissimilarity (Oksanen et al., 2022), and we determined our results to be best represented under two dimensions.

Our first NMDS analysis was performed on all plots and observed vegetation species, regardless of ubiquity. For example, species that were identified in only one plot or that had a very low percentage cover across all plots were both included. The presence of these outliers led us to perform a secondary NMDS analysis, removing species with < 50% total coverage across all plots. Our ordination diagrams were then fitted to represent plots in terms of protected areas status as well as research region (northeast, west, southwest), and groundcover vectors were added to represent potential relationships between substrate coverage, vegetation species, and plot location status.

2.3 Results

We found 24 species in 486 plots across 14 study sites in Newfoundland. Site level species richness ranged from two species to 10 species per site, while plot level species richness ranged from zero species to seven species per plot. We also identified 47 major disturbance features across our 14 study sites, ranging from one to seven major disturbances per site. Of these, 37 (79%) were caused by human activity (i.e., dune trampling, ATV use, beach recreation activities) and 10 (21%) were caused by natural processes (i.e., wind blowouts, dune scarping from wave activity). In anthropogenic disturbances, we identified 31 linear blowouts, three instances of infrastructure constructed through the foredune, and three campfire deflation hallows. In natural disturbances, we identified eight instances of dune scarping and two wind blowouts.

Most of Newfoundland's dune systems were subject to some level of anthropogenic disturbance, regardless of protected areas status. We noted instances of ATV and/or personal vehicle use within protected areas in Deadman's Bay Provincial Park, Sandbanks Provincial Park, and JT Cheeseman Provincial Park, despite signage prohibiting such activities. Across all regions, unprotected dune areas were subject to extensive human visitation and the resultant effects, including linear blowouts from vegetation trampling and ATV or personal vehicle use, campfire deflation hallows, and dune disintegration. Beaches in Gros Morne National Park did not display any evidence of ATV use but did feature several small linear blowouts resulting from dune trampling. Most of the research sites in southwest Newfoundland featured storm-related natural impacts, including dune scarping and wind blowouts (Appendix II).

2.3.2 Plot characteristics between protected area types

Characteristics pertaining to vegetation diversity and assemblage as well as substrate disturbance can serve as markers of the landscape integrity and overall habitat suitability of a vegetated dune system. Results from our measurements of plot level species richness, percentage groundcover, and percentage vegetation cover in both protected and unprotected areas were mixed. The average species richness per plot was similar between protected (1.02 ± 1.41) and unprotected (0.95 ± 1.37) areas, when including beach plots. In the tests where we removed beach plots from the analyses, we noted a greater difference in the mean number of species per plot at 2.02 ± 1.40 for protected areas and 1.66 ± 1.51 for unprotected areas

Table 2.3.1: Summary statistics of plot characteristics between protected area types. Means are shown with standard deviation in parentheses. (A) indicates the tests with beach plots included and (B) indicates the tests with beach plots removed.

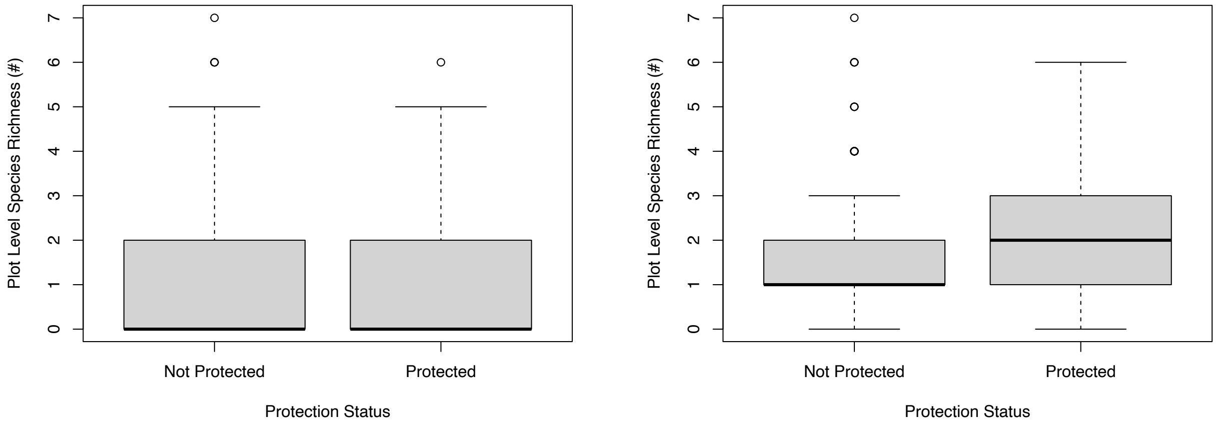
Variable	Protected Area	Summary (A) All Plots	Summary (B) Beach Plots Removed
Plot Level Species Richness (#)	Y	1.02 (1.41)	2.02 (1.40)
	N	0.95 (1.37)	1.66 (1.51)
Vegetation Cover (%)	Y	21.69 (34.97)	43.35 (38.87)
	N	15.34 (28.79)	28.01 (34.29)
Disturbed Substrate (%)	Y	55.65 (46.47)	39.07 (43.56)
	N	51.73 (46.69)	47.00 (47.35)
Undisturbed Substrate (%)	Y	22.52 (37.11)	17.44 (29.15)
	N	32.61 (40.59)	24.71 (34.27)
***Ammophila breviligulata* Cover (%)**	Y	15.61 (30.06)	31.22 (36.39)
	N	8.28 (19.25)	15.20 (24.08)
***Lathyrus japonicus* Cover (%)**	Y	3.12 (7.95)	6.25 (10.36)
	N	2.27 (8.87)	4.19 (11.72)

Table 2.3.2: Summaries of pairwise comparisons of plot characteristics between protected area types. (A) indicates the tests with beach plots included and (B) indicates the tests with beach plots removed. Parameter estimates from Analysis of Variance tests are shown with standard error in parentheses. Estimates significant at $\alpha \leq 0.05$ are bolded.

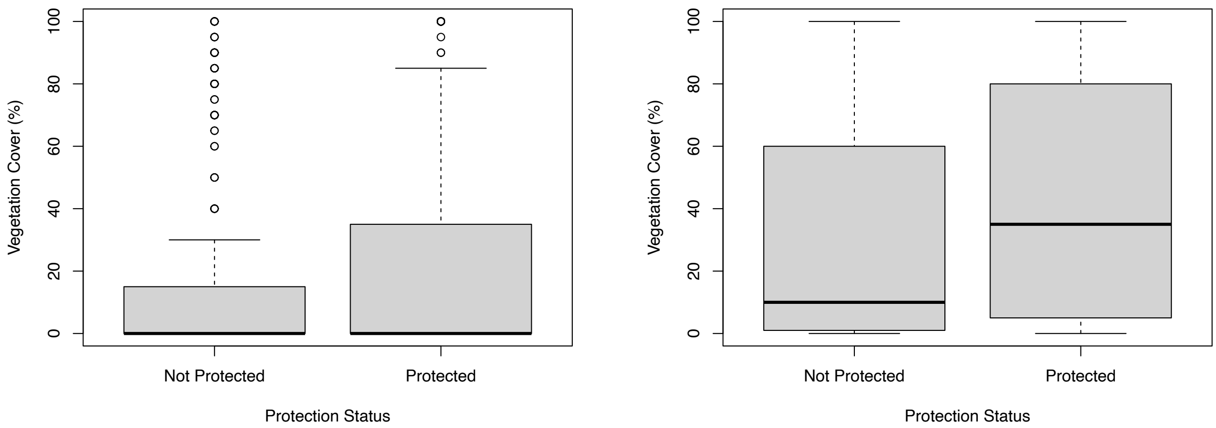
	(A) All Plots		(B) Beach Plots Removed	
Response Variable	**Parameter Estimates**	***p*-value**	**Parameter Estimates**	***p*-value**
Plot Level Species Richness (#)	0.07 (0.13)	0.569	0.36 (0.19)	0.061
Vegetation Cover (%)	**6.35 (2.94)**	**0.031**	**15.34 (4.72)**	**0.001**
Disturbed Substrate (%)	3.92 (4.39)	0.372	-7.93 (6.05)	0.191
Undisturbed Substrate (%)	**-10.10 (3.71)**	**0.006**	-7.27 (4.28)	0.090
***Ammophila breviligulata* Cover (%)**	**7.34 (2.24)**	**0.001**	**16.02 (3.80)**	**<0.001**
***Lathyrus japonicus* Cover (%)**	0.85 (0.80)	0.291	2.06 (1.48)	0.166

Beach Plots Included   Beach Plots Removed

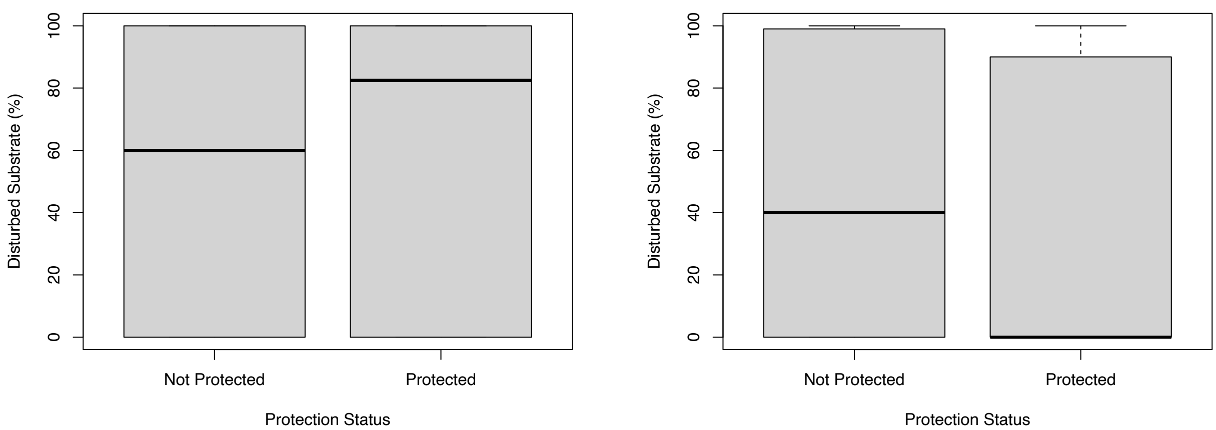
a)



b)



c)



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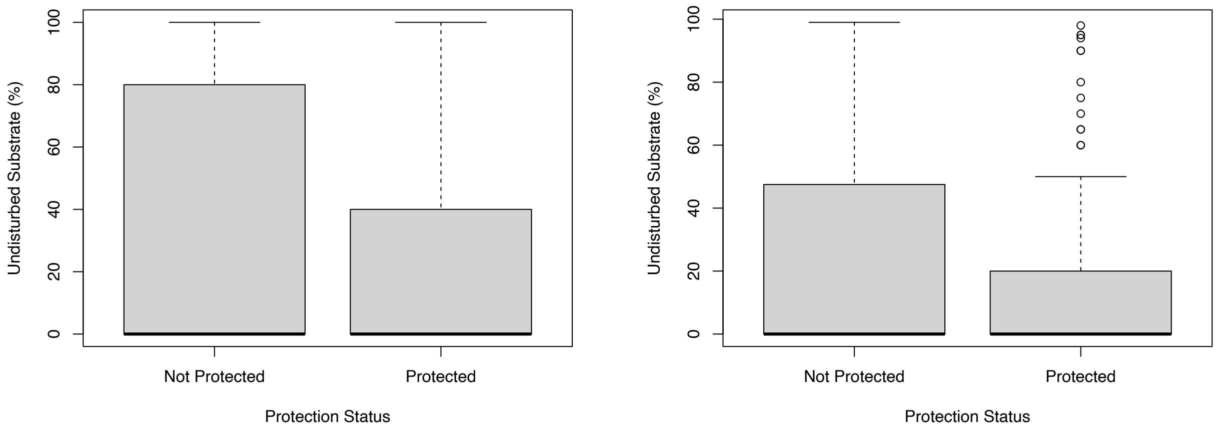

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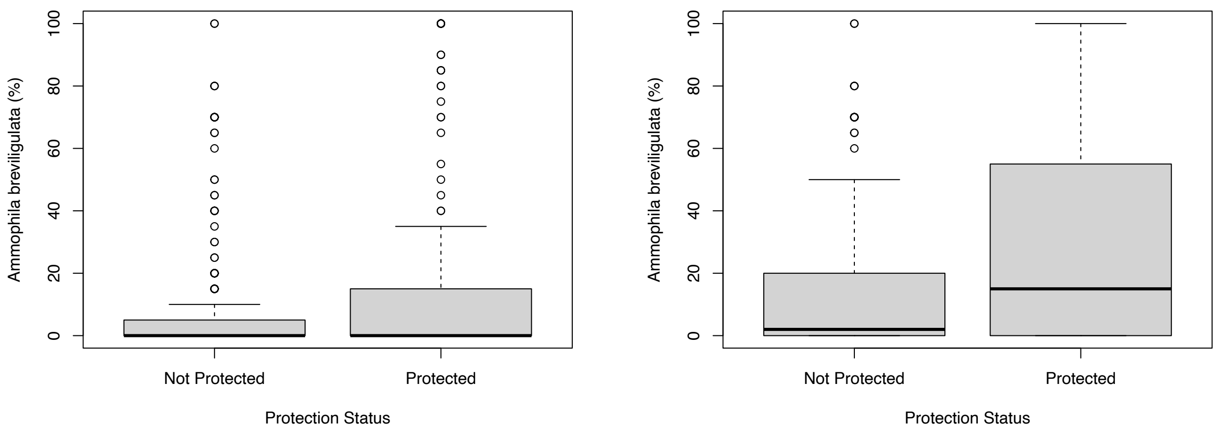

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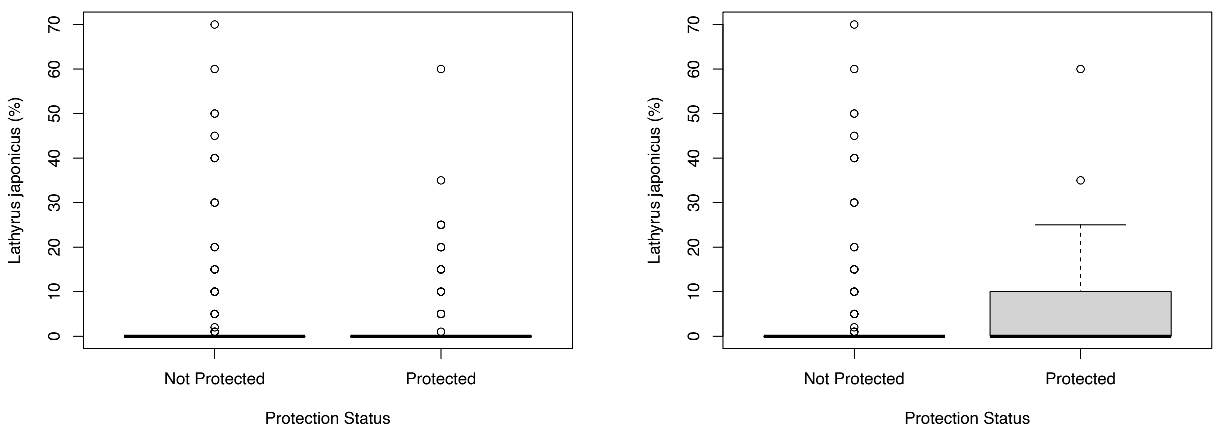


Figure 2.3.1: Boxplots depicting groundcover and vegetation characteristics observed in protected and unprotected areas. The whiskers extending beyond the boxes represent the 95% quartiles, and extreme observations are points beyond the whiskers. Pairwise comparison results are summarized in Table 2.3.2.

(Figure 2.3.1, Table 2.3.1). Although this change did not meet the threshold for significance ($\alpha \leq 0.05$), the p-value reduced dramatically between the tests with beach plots included (0.569) and beach plots removed (0.061) (Table 2.3.2).

Mean vegetation percent cover was significantly higher in protected areas (21.69 ± 34.97%) compared to unprotected areas (15.34 ± 28.79%) when beach plots were included, and this difference was maintained with the removal of beach plots (43.35 ± 38.87% for protected and 28.01 ± 34.29% for unprotected). Average percent cover of undisturbed substrate was significantly higher in unprotected areas (32.61 ± 40.59%) than in protected areas (22.52 ± 37.11%) with beach plots included. While the mean across unprotected areas remained higher in the test with beach plots removed, the significance between site types was lost (p = 0.090). We found that the mean percent cover of *Ammophila breviligulata* in protected areas (15.61 ± 30.06% and 31.22 ± 36.39%) was approximately twice that of unprotected areas (8.28 ± 19.25% and 15.20 ± 24.08%) – a result that was significant in tests both including and removing beach plots (Table 2.3.2). Conversely, while the mean percent cover of *Lathyrus japonicus* was slightly higher in protected areas with and without beach plots included, this difference did not meet the threshold for significance.

2.3.3 Vegetation and substrate disturbance

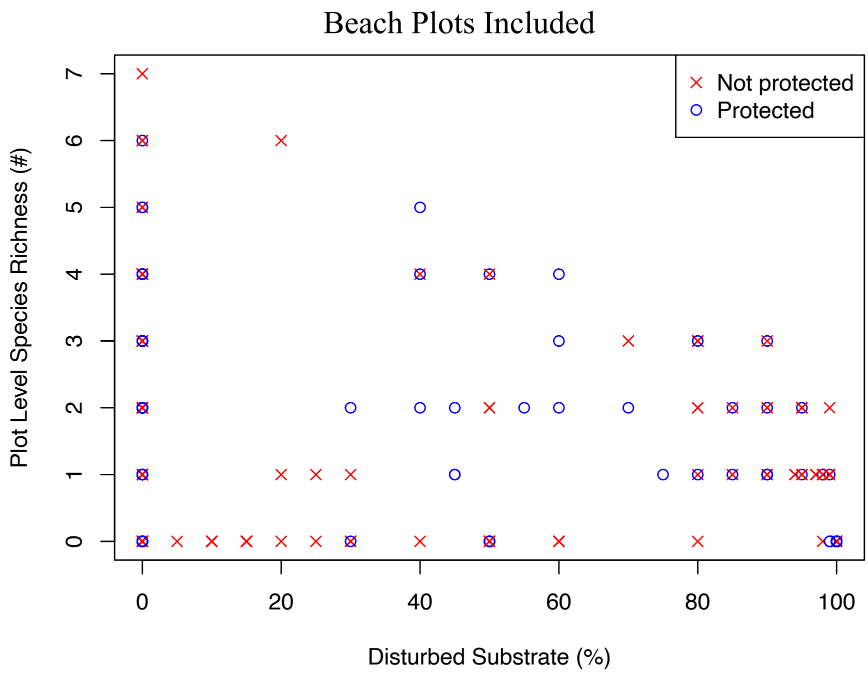
Our GLMMs assessing the relationship between vegetation characteristics, disturbed substrate, and protected areas status revealed several significant correlations between these factors across our study sites. Plot-level species richness was negatively associated with percent cover of substrate disturbance, both with (p = <0.001) and without (p = <0.001) beach plots included; i.e., a greater number of species were present per plot in regions with a lower percentage of substrate disturbance (Figure 2.3.2; Table 2.3.3). No significant correlation was found in the relationship between plot level species richness, percent cover of disturbed substrate, and protected areas status, meaning that although species richness was

Table 2.3.3: Summaries of general linear mixed models of number of species per plot, assuming a Poisson distribution of residuals. (A) indicates the tests with beach plots included and (B) indicates the tests with beach plots removed. Both models included percent disturbed substrate, protected area status, and their interaction as predictor variables, with sampling transect as a random factor. Parameter estimates are shown with standard error in parentheses. Estimates significant at $\alpha \leq 0.05$ are bolded.

	(A) All Plots		**(B) Beach Plots Removed**	
Response Variable	**Parameter Estimates**	***p*-value**	**Parameter Estimates**	***p*-value**
Disturbed Substrate (%)	**-0.014 (0.002)**	**<0.001**	**-0.013 (0.001)**	**<0.001**
Protection Status	0.215 (0.132)	0.105	0.103 (0.103)	0.315
Disturbed Substrate (%): Protection Status	-0.004 (0.003)	0.212	0.001 (0.002)	0.586

Table 2.3.4: Summaries of general linear mixed models of vegetation cover, assuming a Gaussian distribution of residuals. (A) indicates the tests with beach plots included and (B) indicates the tests with beach plots removed. Both models included percent disturbed substrate, protected area status, and their interaction as predictor variables, with sampling transect as a random factor. Parameter estimates are shown with standard error in parentheses. Estimates significant at $\alpha \leq 0.05$ are bolded.

	(A) All Plots		**(B) Beach Plots Removed**	
Response Variable	**Parameter Estimates**	***p*-value**	**Parameter Estimates**	***p*-value**
Disturbed Substrate (%)	**-0.314 (0.032)**	**<0.001**	**-0.502 (0.041)**	**<0.001**
Protection Status	**15.735 (3.752)**	**<0.001**	**17.967 (4.517)**	**<0.001**
Disturbed Substrate (%): Protection Status	**-0.147 (0.053)**	**0.006**	**-0.169 (0.074)**	**0.023**



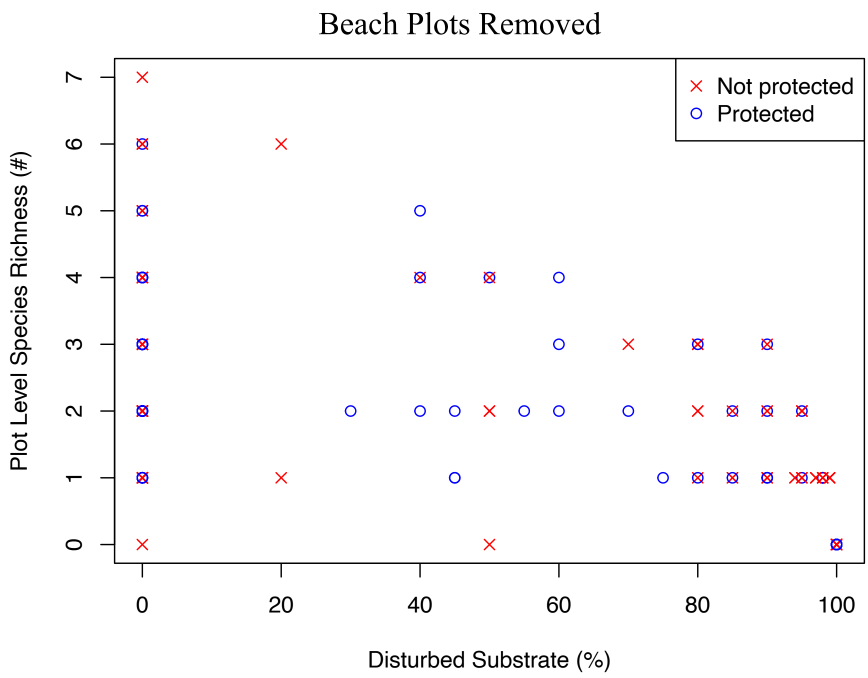
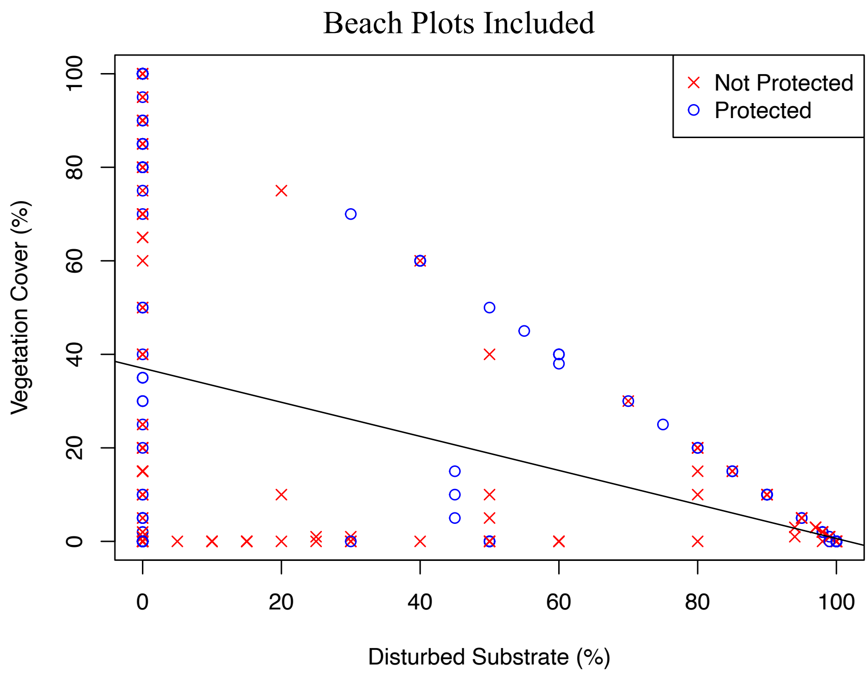


Figure 2.3.2: Scatterplots depicting species per plot against disturbed substrate and protected areas status. Results of GLMMs summarized in Table 2.3.3.



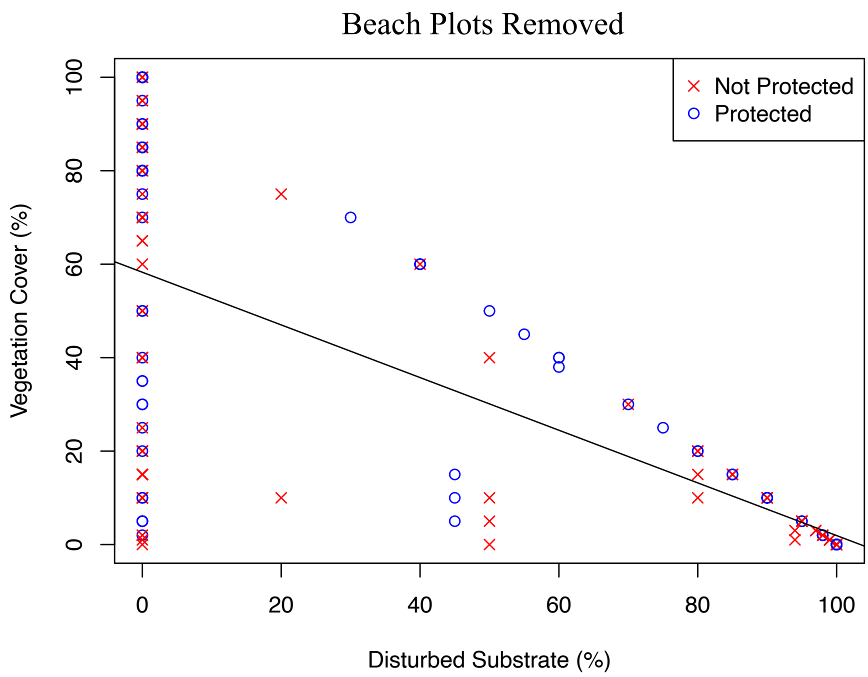


Figure 2.3.3: Scatterplots with linear model lines depicting vegetation cover against disturbed substrate and protected areas status. Results of GLMMs summarized in Table 2.3.4.

higher in areas with a lower percentage of substrate disturbance, this effect was similar across protected and unprotected sites.

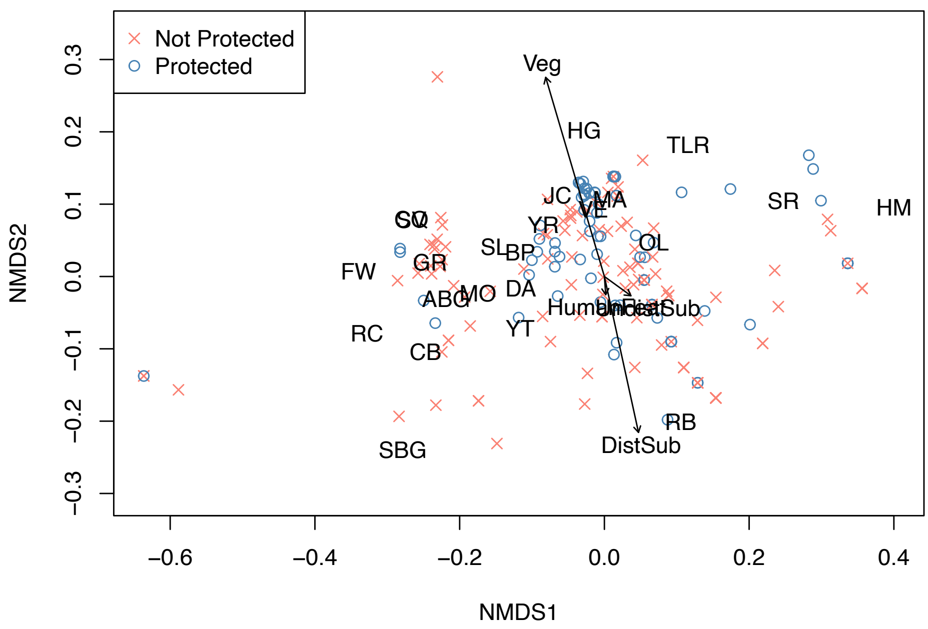
In tests with beach plots included and removed, the correlation between percent vegetation cover, percent substrate disturbance, and protected areas status was found to be significant in our GLMM results (Table 2.3.4). We noted an inverse correlational relationship between percent vegetation cover and percent substrate disturbance. Plots with less substrate disturbance had a significantly higher percent cover of vegetation, while plots with a more substrate disturbance had a lower percent cover of vegetation (Figure 2.3.3). The significance of this correlation was maintained when accounting for protected areas status (Table 2.3.4); i.e., a higher level of substrate disturbance inside of protected areas also correlated with a reduction in percentage vegetation cover.

2.3.4 Vegetation and groundcover characteristics between site types

Our NMDS ordination indicated that plots located in protected areas were generally had more similar plant communities to one another, indicated by their spatial clustering, than those within unprotected areas, which showed greater spread across the ordination space (Figure 2.3.4a/b). Plots in protected areas were also more closely associated with specific plant species, including *Ammophila breviligulata*, *Vicia sativa* (common vetch), and *Juncus effusus* (soft rush). These findings suggest that the vegetation community of dune systems located inside protected areas may be more similar and more homogenous in terms of species identity, regardless of research location. For example, vegetated dunes located in Sandbanks Provincial Park (Burgeo, southwest coast of the island) may have a similar species community and groundcover ratio to dunes in Shallow Bay (Gros Morne National Park, west coast of the island), despite differences in location. There were, however, large areas of overlap between protected and unprotected regions, and thus in addition to these noted differences, there was also much similarity in plant species across the study regions.

Our groundcover vectors suggested dissimilarities between plots with a higher percentage cover of vegetation and plots with a higher percentage cover of disturbed substrate. This association indicates that dune vegetation growth may be denser and/or more robust in areas with less substrate disturbance; thus, substrate disturbance may be an inhibiting factor in vegetation establishment. Additionally, despite large areas of overlap between protected and unprotected plot sites, protected sites tended to be more closely associated with vegetation as a dominant groundcover, while unprotected sites tended to be more closely associated with disturbed substrate. These findings may point to a greater incidence of substrate disturbance in unprotected areas as well as a higher percentage of vegetation cover in protected areas. Undisturbed substrate and human features as groundcover vectors were not closely associated with any vegetation species or site types.

When including divisions for whether plots were located on the northeast, west, or southwest coasts, the ordination plots pointed to several possible associations (Figure 2.3.4c/d). Plots located in unprotected areas on the northeast coast were clustered, indicating their similarity to one another, and were associated with several species, including *Leymus mollis, Poaceae* (grasses), *Trifolium pratense* (red clover), and *Senecio pseudoarnica* (seabeach groundsel). This pattern shows that the vegetation community in unprotected sites on the northeast coast may be distinct from the communities located in either site type on the southwest and west coasts. However, several west coast plots in protected areas also showed a similarity in vegetation community to those unprotected plots on the northeast coast. Other protected west coast plots were dissimilar to the unprotected northeast coast plots in their communities and favored several outlying vegetation species, including *Cakile edentula, Nabalus trifoliolatus* (three-leaved rattlesnake root), and *Artemisia stelleriana* (hoary mugwort). These findings point to a greater diversity in plant communities amongst the west coast protected sites. Conversely, plots located at sites of either type along the southwest a)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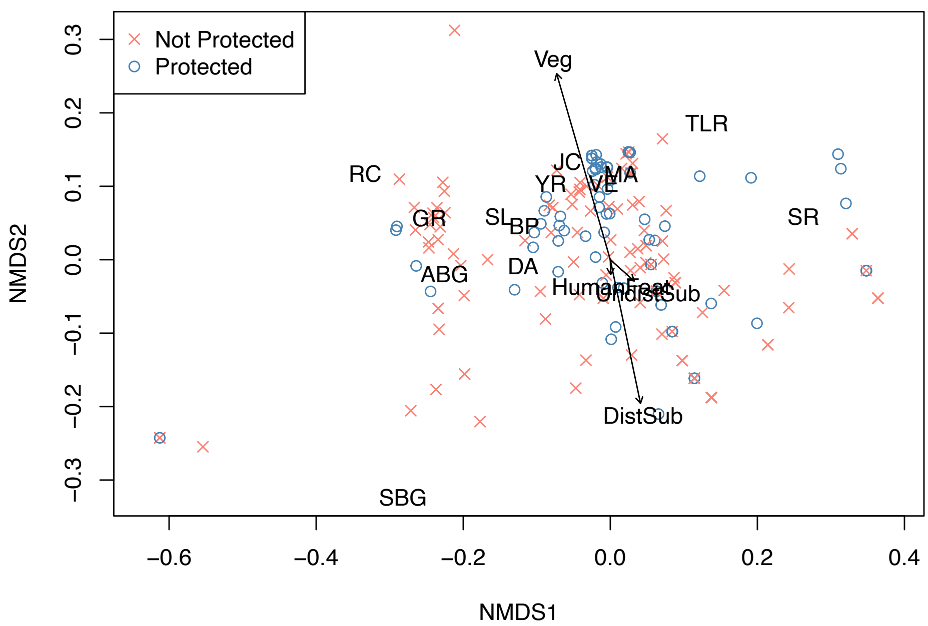
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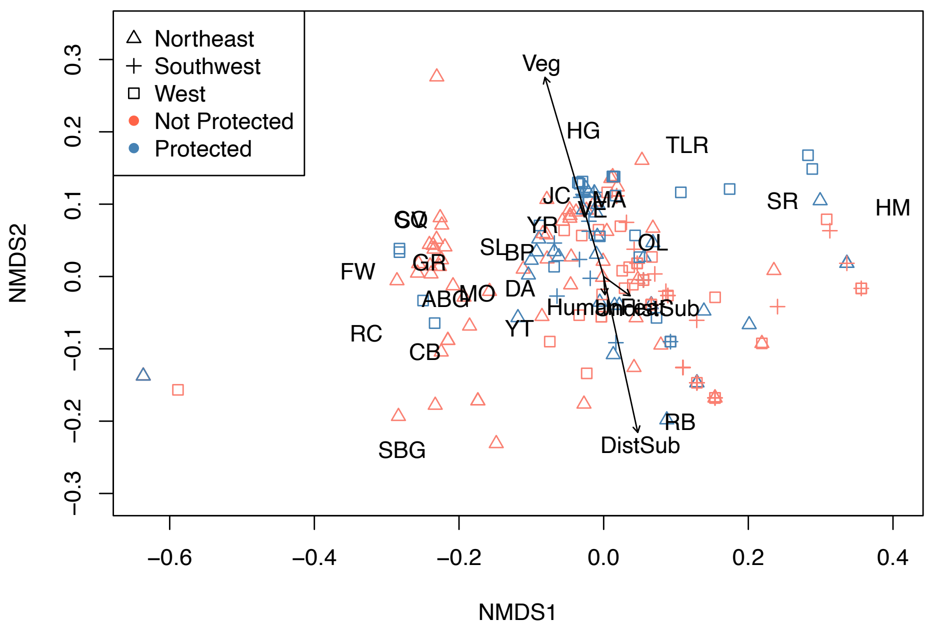

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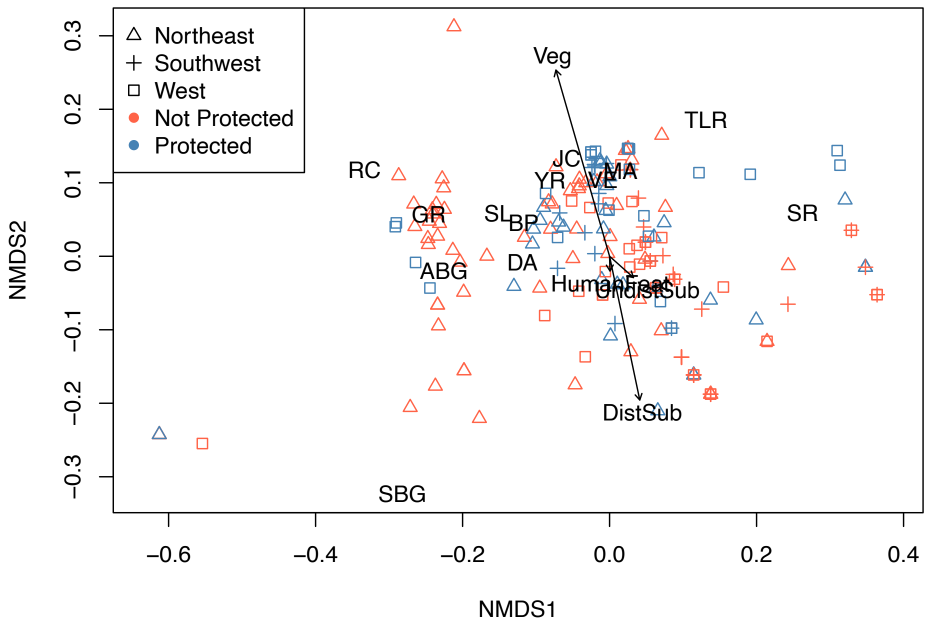

Figure 2.3.4: NMDS ordination of vegetation communities comparing all plots, species, and study regions (stress = 0.2448 in 2 dimensions). Point colors indicate protected areas status and shapes indicate study regions (plots c and d depict study regions). Plots show ordination with (a and c) and without (b and d) infrequently encountered species (<50% coverage combined across all plots). Groundcover vectors depict how groundcover types relate to species and plot communities, where the length and direction of the arrow indicate the strength of the relationship.

coast were more closely associated with one another and thus may share a greater level of similarity in their vegetation communities, though these sites also did not show an association with any specific vegetation species. Protected east coast sites and unprotected west coast sites were highly diverse and showed no association with any species or plot type. Additionally, the groundcover vectors were not closely associated with sites from any region, pointing to a range of dominant ground cover types across the northeast, west, and southwest coasts. Though there were some notable associations between plot types across our primary research locations, there were also many areas of overlap and plots for which no similarity was apparent. This lack of association suggests some level of homogeneity and similarity of the plant communities and dominant ground cover types on coastal vegetated dunes in Newfoundland, regardless of location or protected areas status.

2.4 Discussion

Through our research, we aimed to characterize the vegetation community and disturbance features present on vegetated coastal dunes in Newfoundland, and to identify potential differences in these features between protected and unprotected areas. We found that areas with more disturbance had less vegetation cover, and that vegetation community diversity and landscape integrity were more robust in protected coastal areas. Plant communities in protected areas were more homogenous and closely associated with species endemic to boreal dunes from similar regions (Byrne & McCann, 1993; Hogan & Brown, 2021; Ollerhead et al., 2013; Tissier et al., 2013; Walker et al., 2017). Specific coverage of endemic dune species (e.g., *Ammophila breviligulata*) is an indicator of ecological robustness and is therefore important to habitat suitability for beach-nesting birds (Environment and Climate Change Canada, 2012; Power et al., 2022; Tarr et al., 2010), making these sites pivotal to broader ecological prosperity in Atlantic Canada. Simultaneously, there were notable differences in plot communities between coastal dunes in the northeast, west, and southwest, due to regional factors and/or differences in the circumstances driving disturbance in each area. The findings from our research point to several potential implications for future dune landscape management in Newfoundland, to protect ecological diversity, prevent loss of vegetation cover, and preserve landscape stability over time. We discuss the potential mechanisms of our findings, as well as their broader implications for management in greater detail below.

2.4.2 Vegetation cover and disturbance characteristics

Across all transverse dune coastlines in Newfoundland, we found that substrate disturbance was linked to scarcity in vegetation cover. Disturbed areas had a greater incidence of vegetation loss, evidenced by sparse vegetation cover on the primary foredune and/or large (>10m^2) or more frequent blowouts containing little to no vegetation cover. In the southwest region, dune scarping also contributed to a loss of vegetation cover. This pattern is likely the result of the combined effects of both natural and anthropogenic disturbance on Newfoundland's dune coastlines. Substrate disturbance, regardless of the driving cause, has been previously linked with vegetation sparseness in boreal dune systems (Walker et al., 2017). Physical disturbance disrupts root systems and inundates plant species, while storm surge can disconnect blocks of vegetation and substrate, washing them out into the ocean (Eamer et al., 2022; Nordstrom, 1994; Snow, 1984; Walker et al., 2017). In Newfoundland, human visitation (Catto, 2002), ATV use (Waight, 2014), and the impacts of storms such as tropical cyclone Fiona (September 2022) (Yarr, 2022) are the biggest contributors to substrate disturbance and the correlated dune vegetation loss. However, substrate disturbance and loss of vegetation cover were not uniform across all coastlines.

Vegetation cover was higher in protected coastal dune areas than in unprotected areas. These findings were also supported by our assessment of undisturbed substrate, which we found to be higher in unprotected areas. While this seems counterintuitive, a greater level of undisturbed substrate points to lower vegetation cover on the foredunes in unprotected beach areas. Substrate disturbance (e.g., because of trampling) is typically greater on the beach and near the incipient dune zone (Nordstrom, 1994). A higher level of undisturbed substrate points to a greater incidence of areas that are not subject to constant trampling, but which could be suffering the effects of nearby disturbance (Catto, 2002). In our research, we found that the foredunes in unprotected areas were more sparsely vegetated and therefore had more exposed undisturbed substrate. This pattern was in contrast with the dunes in protected areas, which we found to have a denser and more extensive vegetation cover as well as smaller and less frequent anthropogenic blowouts.

Overall, given the vegetation density and reduced levels of disturbance, the structural and ecological integrity of Newfoundland's coastal dune systems was greater in protected areas than in unprotected areas. This pattern is likely because protected areas are subject to stricter use guidelines (e.g., signage, monitoring, ATV prohibition) (Parks NL, 2023), limiting some types of anthropogenic disturbance on the dunes. Our findings are consistent with those of similar landscape distinctions in Atlantic Canada. For example, in PEI, vegetated dunes in coastal protected areas (i.e., PEINP) are also subject to less human disturbance (Government of Canada, 2023a) and are therefore typically in better condition than coastal dunes in unprotected areas (Catto et al., 2002). Hogan & Brown (2021) also determined that vegetated dune systems were more robust on protected coastlines in New Brunswick, with anthropogenic use being a determining factor in dune ecosystem fragmentation in unprotected areas. More broadly, these findings are also compatible with previous studies concluding the effectiveness of protected areas in preserving biodiversity and ecosystem health over time (Cooke et al., 2023; Potts et al., 2014; Virkkala et al., 2014).

2.4.3 Plant communities on Newfoundland's coastal vegetated dunes

Our NMDS ordination suggested that plots located within protected areas were similar in terms of vegetation community and were associated with several plant species, including *Ammophila breviligulata*, *Vicia sativa*, and *Juncus effusus*. In contrast, unprotected areas tended to have a greater level of dissimilarity in their plant communities and were not correlated with distinct species. While *Vicia sativa* is a non-native species in Canada (NatureServe, 2023), it is not recognized as an invasive species of concern (Canadian Food Inspection Agency, 2017; Invasive Species Centre, 2023). *Ammophila breviligulata* and *Juncus effusus* are endemic to boreal dunes and can be found on transverse dune coastlines across other parts of Atlantic Canada (Byrne & McCann, 1993; Hesp et al., 2013; Hogan & Brown, 2021; Tissier et al., 2013). One reason for this could be that dune systems in unprotected regions are subject to greater anthropogenic disturbance and integration with other varieties of nearby substrate (e.g., rock, grass), thereby increasing the likelihood of atypical species establishment in the dune area. This phenomenon was particularity noticeable in unprotected areas along the northeast coast, which had undergone extensive human modification as a result of local tourism (see for e.g., Lumsden Beach Company, 2023). While dunes located along these beaches hosted endemic *Leymus mollis* (Gagné & Houle, 2002), there were also species commonly associated with disturbance, such as *Trifolium pratense, Poaceae, Taraxacum officinale* (common dandelion), and *Potentilla fruticose* (shrubby cinquefoil) (Dwire et al., 2006; Francis et al., 2012). This distinction in the plant communities between protected and unprotected areas maintains our previous conclusion that dune system integrity is more robust along protected coastlines. This conclusion is also supported by previous studies by Aretano et al. (2017) and Lucrezi et al. (2014), who determined anthropogenic disturbance to be a contributing factor in atypical species establishment on coastal vegetated dunes.

In addition to our evaluation of dune plant communities according to region and protected areas status, we also found that coverage of *Ammophila breviligulata* was greater in protected areas. This finding follows our previous trend of assessment, and is likely due to a combination of three discussed factors: (a) vegetation cover was greater in protected areas, correlating with a greater coverage of *Ammophila breviligulata*; (b) disturbance was greater in unprotected areas, leading to a decrease in *Ammophila breviligulata* establishment along those coastlines; and (c) the vegetation communities in unprotected areas were more often associated with atypical disturbance-type species, resulting in a more heterogeneous plant community and a subsequent decrease in *Ammophila breviligulata* coverage as a percentage of total groundcover. Regardless of the driving cause behind this difference, this finding has implications for Newfoundland's broader coastal dune ecosystem. *Ammophila breviligulata* is one of the most common plant species endemic to boreal coastal dunes, making it a key species in determining ecosystem robustness (Byrne & McCann, 1993; Ollerhead et al., 2003; Tissier et al., 2013). Robust dune ecosystems (i.e., those with a lesser incidence of anthropogenic disturbance and vegetation sparseness) are the most ideal habitat for the endangered Piping Plover, which nests along Atlantic Canadian dune coastlines from April to mid-October (Environment and Climate Change Canada, 2012; Power et al., 2022; Tarr et al., 2010). Sparse *Ammophila breviligulata* coverage is both a result and an indicator of disturbance; a decline in ecosystem integrity combined with an increase in disturbance has been shown to have deleterious effects on the population, physical health, and behaviors of the Piping Plover during breeding season (Boyne et al., 2014; Tarr et al., 2010). The difference in *Ammophila breviligulata* coverage that we found between protected and unprotected beaches reinforces the lack of uniformity in the integrity of Newfoundland's coastal dune systems and points to potential gaps in suitable Piping Plover and other beach-nesting shorebird habitat across the island. Given that Newfoundland has a very limited number of vegetated dune coastlines, this finding is of particular concern to wildlife conservation initiatives.

2.4.4 Implications for future landscape management

The results from our research show that in Newfoundland, transverse dune complexes located in unprotected areas displayed reduced ecological and landscape integrity when compared with those in protected areas. In general, unprotected coastlines were more disturbed, had less vegetation cover, and were more likely to have suffered some loss of landscape integrity, all of which could have potentially detrimental effects on ecological prosperity. Currently, few vegetated dune coastlines are under the protection of a governmental or conversation organization. Given the relative rarity of these landscapes in Newfoundland, additional protected areas could be established to maintain habitat, biodiversity, and landscape integrity. On the ground, human disturbance (e.g., dune trampling, ATV use) exacerbates storm-driven erosion features (e.g., dune scarping, wind blowouts), accelerating vegetation loss and dune disintegration (Catto & Catto, 2009). Under the projected impacts of climate change (Finnis, 2013), coastal dunes in unprotected areas may suffer additional losses to ecosystem prosperity under the current anthropogenic disturbance regime.

Further to the implementation of additional protected areas, current protected coastlines could benefit from extra ecological and morphological support. We found that within protected areas, higher levels of substrate disturbance also equated with a loss of vegetation cover. This loss means that the creation of protected areas themselves are not the sole factor in the maintenance of ecosystem integrity. Land use also has an important influence on dune integrity (Aretano et al., 2017), and thus should be considered in the ongoing management of existing protected areas. Our in-situ field observations evidenced extensive anthropogenic use of landscapes inside of some protected areas, with few preventative measures in place and limited enforcement by conservation marshals (Appendix II). Dune beach visitation and use within these protected areas is likely the result of their designation as provincial parks, which offer less security than other categories of provincial protected areas (The Government of Newfoundland and Labrador, 2023b). Protected sites located on the west coast in Gros Morne National Park were an exception to this trend and did not suffer from the same level of ongoing anthropogenic use. Notably, these sites also had the highest level of protection status and the most resources for ongoing site protection given their outreach and enforcement team's abilities to conduct education and compliance monitoring. One way to mediate this issue would be to change the status of some or, ideally, all provincial park dune landscapes to an area type that offers more protection, such as a wilderness or ecological reserve. This change would be particularly important for protected areas located on the southwest coast, which have been identified as a priority for Piping Plover habitat (Environment and Climate Change Canada, 2012).

Regardless of protected areas status, all of Newfoundland's vegetated dune coastlines are subject to some level of anthropogenic disturbance. Outside of our two sites in Gros Morne National Park, we found evidence of ATV or motor vehicle usage at every research location, despite the presence of signage disallowing such activities in provincial parks (Figure 2.4.1). To protect dune landscapes into the future, additional action by conservation marshals and protection agencies is needed, including: the enforcement of existing policies and signage in protected areas; the implementation or improvement of protected areas infrastructure; and the application of public outreach and/or education initiatives. Currently, Newfoundland's protected dune areas are not up to par with comparable landscapes in other regions of Atlantic Canada. PEI, which has an extensive tourism economy based off of their dune coastlines (The Government of Prince Edward Island, 2020), could serve as a model system for Newfoundland's management of their vegetated dune landscapes.

Figure 2.4.1: Images of ATV and motor vehicle tracks, adjacent to signage prohibiting off-road vehicle use in dune protected areas on Newfoundland's southwest coastline.

The management and conservation of vegetated coastal dune systems in PEI has been comprehensive and ongoing since the establishment of PEINP in 1937 (Catto et al., 2002; George et al., 2021; Mathew et al., 2010; Ollerhead et al., 2003). The dune landscapes in PEI are consequently more robust and subject to less anthropogenic disturbance when compared with those in Newfoundland (Government of Canada, 2023a). Due to the regional morphology, bathymetry, and weather conditions, PEI's coastal dunes are generally much larger (see for e.g., Ollerhead et al., 2013; Walker et al., 2009), and also see much more tourist activity during the peak (April to October) season (Government of Canada, 2023a; The Government of Prince Edward Island, 2020). However, despite these differences in regional tourism and geomorphology, many of PEINP's landscape conservation measures could be scaled down for application in the context of Newfoundland's provincial parks.

There are four measures currently implemented by PEINP that we suggest for enactment in Newfoundland's protected areas: (a) boardwalks or steps confining beach access to one area; (b) bar-and-wire fencing creating a physical barrier between the beach and dune

Figure 2.4.2: Examples of conservation infrastructure in PEI National Park, including: a) boardwalks for beach access; b) bar-and-wire dune fencing; c) signage educating about piping plover habitat; and d) a placard explaining the citizen science #Coastie program.

zones; (c) educational and prohibitional signage to discourage dune trampling; and (d) public outreach campaigns encouraging locals and tourists to become conservators of vegetated dune coastlines (Figure 2.4.2) (Government of Canada, 2023a). We understand that regional differences in land use and the limited availability of financial and personnel resources are potential barriers to the enactment of these measures. Combining the results from our field observations with our knowledge of conservation practices in PEI, we therefore recommend the following measures for implementation in Newfoundland's vegetated dune protected areas:

- the implementation of signage, ground-level boardwalks, or rock bordering to confine pedestrian access to one pathway through the primary foredune;
- additional enforcement preventing and/or sanctioning ATV and motor vehicle use;
- the placement of bar-and-wire fencing between the beach and dune zones for the first 50m on both sides of the designated primary beach entry point;
- updating existing signage to include educational material about the vegetated dune landscape and its importance in terms of habitat provisioning and ecological prosperity;
- adding signage to encourage walking on the wetted beach and discourage dogs during peak shorebird nesting season (April to mid-October);
- starting Parks NL social media campaigns to highlight the rarity and importance of coastal vegetated dune systems in Newfoundland, and to encourage locals to become landscape conservators (e.g., the Coastie Initiative) (Government of Canada, 2023b).

Combined, these measures would decrease disturbance and provide additional protection to Newfoundland's vegetated dune systems, thus maintaining landscape integrity, conserving endangered bird habitat, and preserving ecological functioning into the future.

2.5 Conclusions

Through our research, we developed an improved understanding of the relationships between protected areas status, ecological robustness, and landscape integrity in Newfoundland's vegetated coastal dune ecosystems. Across all our research sites, we found that areas with a higher incidence of substrate disturbance also had a lower total vegetation cover. This correlation was different when accounting for protected areas status, with unprotected regions displaying a significantly higher level of substrate disturbance and sparseness in vegetation cover. We determined that dune ecosystem robustness and landscape stability were thus better in protected areas. When evaluating plant communities, we noted that dunes in unprotected areas had a greater variety of species and were more likely to host atypical or disturbance-type species. The plant community in protected areas was conversely more homogenous and associated with species endemic to boreal dunes (e.g., grasses, sedges, salt-tolerant species). Combined with our conclusion that total *Ammophila breviligulata* cover was higher in protected areas, we determined that dune systems in protected areas were more ecologically robust and should be a target for future conservation initiatives.

Despite our findings highlighting the greater ecosystem robustness in protected areas, we assert that the management of dunes in existing protected areas is insufficient to overcome the combined effects of anthropogenic disturbance and increasing occurrence of storm events under climate change. If circumstances remain the same, the current and projected future disturbances may result in landscape disintegration, decreasing the quality of wildlife habitat and increasing community vulnerability to storm events. To better protect coastal dune ecosystems, we recommend that: new protected areas be established in currently unprotected regions; existing protected areas be converted to wilderness or ecological reserves; and landscape management procedures be updated in accordance with those from a more robust and effective management system, such as that of PEINP. The protection of Newfoundland's coastal vegetated dune systems is imperative to the conservation of wildlife habitat, the protection of coastal communities, the management of beach tourism, and the maintenance of the landscape for its intrinsic value to people and wildlife alike.

2.6 References

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Chapter 3: Summary, qualitative findings, and conclusions

3.1 Summary of quantitative findings

In Newfoundland, boreal coastal dune systems account for a relatively small portion of all shoreline ecosystems. The morphological dynamics that contribute to their genesis are specific, limiting them to coastal areas with gently sloping bathymetry and fine sediment flux (Catto, 2002). Vegetated dunes serve a variety of structural and ecological purposes, including the provision of endangered shorebird habitat, hosting endemic plant species, coastal protection during storm events, as well as human aesthetic use and appreciation. Despite their diverse significance, most vegetated dune systems remain unprotected or fall within provincial park areas that fail to provide adequate protection for their coastal ecosystems. Little previous research has been conducted to evaluate the status of vegetated dune coastlines in Newfoundland, leading us to an opportunity to contribute ecological, morphological, and disturbance-related knowledge to this limited field of study. The ongoing and projected future effects of climate change warrant the urgent increase in the study and increased protection of Newfoundland's rare coastal sand dunes.

Here, we developed a study to evaluate the plant communities and disturbance features on Newfoundland's transverse dune shorelines, including those near Lumsden in the northeast; near Burgeo and Channel-Port aux Basques in the southwest; and near Stephenville Crossing and Gros Morne National Park in the west. Assessing a wide geographic range of vegetated dunes inside and outside of protected areas allowed us to evaluate potential differences in ecological and morphological factors when accounting for both protected areas status and research area (i.e., northeast, west, or southwest). Our results indicate several potential links between vegetation cover, level of disturbance, vegetation community, and protected areas status.

Across all coastal areas, we found that substrate disturbance was linked to a scarcity in vegetation cover, likely resulting from prolonged physical disturbance over time, which disrupts root systems and causes fragmentation of sediment blocks (Eamer et al., 2022; Nordstrom, 1994; Walker et al., 2017). In Newfoundland, physical disturbance of coastal areas is most commonly associated with human visitation (Catto, 2002), ATV use (Waight, 2014), and post-tropical storms (Yarr, 2022). Vegetation cover was denser in protected areas than in unprotected areas, which displayed a greater incidence of exposed substrate and anthropogenic blowouts.

Within our analyses, we also noted potential links between vegetation community and protected areas status. Protected areas tended to be more closely associated with endemic dune species such as *Ammophila breviligulata* and *Juncus effusus*, which are important markers of dune ecosystem robustness (Byrne & McCann, 1993) and thus may indicate habitat suitability for beach-nesting shorebirds (Environment and Climate Change Canada, 2012; Tarr et al., 2010). In contrast, unprotected areas tended to be associated with a higher incidence of plant species that are atypical to the dune ecosystem, such as *Poaceae*, *Taraxacum officinale, Trifolium pratense*, and *Potentilla*. We determined that this observed effect may be the result of increased anthropogenic disturbance in unprotected areas, where human traffic and the movement of sediments for infrastructural development may serve as a vector for atypical species establishment on the foredune. Our assessment of the vegetation community between protected areas reinforced our earlier conclusion that both ecological and landscape integrity were higher in protected dune areas.

Overall, we determined that vegetation coverage and landscape integrity were higher in protected areas because of the stricter use guidelines limiting anthropogenic disturbances (Parks NL, 2023). While this finding does correspond with other assessments of the net-positive effect of protected areas on ecological and landscape integrity (Cooke et al., 2023;

Potts et al., 2014; Virkkala et al., 2014), Newfoundland's protected dune areas were still subject to a concerning level of disturbance. Stricter use guidelines, the implementation of new management techniques, the development of additional protected areas, and/or the conversion of existing provincial parks into wilderness or ecological reserves would all contribute to the improvement of landscape integrity and ecological functioning in vegetated dune systems across the island.

3.2 Qualitative findings

3.2.1 Qualitative sampling methods

In conjunction with our quantitative data collection in Newfoundland, we also made several qualitative observations at each of our research locations as well as at six vegetated dune beaches in PEI. Research locations in PEI were chosen based on accessibility given a limited timeframe window for data collection, but met the criteria previously outlined for the Newfoundland sites (see Methods, Chapter 2). Of the PEI locations, four were in PEINP (Brackley, Cavendish, Dalvay, and Greenwich Beaches) and two were in unprotected coastal areas (Blooming Point and Thunder Cove Beaches), all featuring transverse dune complexes. Methods of observational data collection were not invasive (i.e., we did not disturb the dune vegetation or morphology) and were conducted with the appropriate permissions from staff at Parks NL, PEINP, and Gros Morne National Park. Qualitative data collection was performed concurrently with the quantitative data collection in July 2023 in Newfoundland (see Chapter 2) and was performed across a five-day period in August 2023 in PEI. Observations were performed by the same researcher (Power) to ensure consistency between locations.

At each study site, we first ranked the location by the extent of overall disturbance, by placing it on a scale from zero to three. Here, a score of zero would indicate no observed disturbances, while a score of three would indicate a highly disturbed system (e.g., pervasive dune scarping, evidence of extensive anthropogenic use, the presence of multiple large blowouts in the primary foredune). We also noted all visible infrastructure (e.g., garbage cans, boardwalks, signage) and landscape developments (e.g., parking lots, trailer parks) at each location. Conspicuous blowouts in the primary foredune, as well as their estimated size (in meters) and nature of formation (natural or anthropogenic) were also recorded. We then made notes about any impactful human or wildlife activities that were ongoing during data collection. We ended our observational assessment of each location by taking photographs of notable disturbance features, infrastructures, developments, or other unexpected but pertinent site characteristics (Appendix II).

3.2.2 Results from observations in Newfoundland

We observed two types of co-occurring infrastructural and disturbance-related factors, that were pervasive across our study sites in Newfoundland. Generally, sites with peripheral anthropogenic developments (i.e., parking lots, roads, RV parks, playgrounds, construction zones, residential or business-related building developments) also displayed a greater amount of anthropogenic disturbance (extent of disturbance = 3), while sites with small-scale informative or operative infrastructure (i.e., signage, washrooms, access boardwalks, beach safety infrastructure, garbage cans, park or picnic benches) displayed less anthropogenic disturbance (extent of disturbance ≤ 2). Protected areas regulations limit the extent, type, and number of developments that can occur within their domain (The Government of Newfoundland and Labrador, 2023), while activity within unprotected areas may only be constrained by municipal bylaws. Frequently, we found that unprotected dune areas were exploited for tourism in a way that failed to prioritize the integrity and longevity of the coastal ecosystem. Direct disturbance of the primary foredune was infrequent. Apart from Lumsden North Beach (Figure 3.2.1), anthropogenic developments were located outside of the primary foredune area. However, the unrestricted presence and expansion of large-scale human developments in coast-adjacent areas invariably increases and encourages beach

Figure 3.2.1: An image of signs positioned on top of the vegetated foredune at Lumsden North Beach.

activities (e.g., trampling, ATV use, campfires, litter), which when chronic, may lead to disturbance and fragmentation of the dune landscape. There were six study sites that we found to have likely suffered additional disturbance from proximity to human developments: Lumsden North Beach, Lumsden Back Beach, Cape Freels North Beach, Cape Freels South Beach, Grand Bay East Beach (Figure 3.2.2), and Stephenville Crossing Beach.

In contrast, informative or operative infrastructures are more commonly associated with protected areas, as these structures are in place to guide human activity, thereby conserving the dune system. These structures also enhance the aesthetic value of the landscape by highlighting positive interactions and limiting negative interactions between people and the ecosystem. For example, garbage cans provide receptacles for litter, park benches encourage appreciation of the landscape, and signs both discourage and inform about prohibited activities. While these measures are not always completely effective, we found

Figure 3.2.2: Images of beach infrastructures (a) and dune vegetation (b) at Grand Bay East Beach. This beach is accessible by car from Channel-Port aux Basques and is situated adjacent to urban developments (shown in the background of both photos). Due to chronic anthropogenic disturbance, Grand Bay East Beach demonstrated sparse vegetation cover and considerable landscape disintegration.

that these types of infrastructures, combined with restrictions on development, limited some disturbance in the dune system. Specifically, we found that sites with designated pathways for beach access, clear signage outlining regulations, staff monitoring, or that were isolated from extensive human development, typically had lower disturbance scores. Four of our study sites employed restrictions and infrastructures effectively to limit anthropogenic disturbances to the vegetated dune complex: Gros Morne Shallow Bay Beach (Figure 3.2.3), Gros Morne Western Brook Pond Outlet Beach, Rocky Barachois Outlet Beach, and Sandbanks Provincial Park Beach.

3.2.3 Results from observations in Prince Edward Island

Our assessment of dune systems in PEI led us to a better understanding of the ongoing relationships between landscape disturbance, protected areas status, regional culture, infrastructure, and tourism. In contrast to our findings in Newfoundland, patterns of anthropogenic disturbance on the dune landscape were similar between protected and

Figure 3.2.3: Images of the boardwalk (a) and signage informing about endangered shorebirds (b) at Gros Morne Shallow Bay Beach. Enforcement of parks regulations appeared to be effective at this location. There was little evidence of human disturbance and vegetation cover on the primary foredune was tall and dense.

unprotected beaches in PEI (Figure 3.2.4). While unprotected dune systems appeared to display more anthropogenic disturbance (i.e., evidenced by the presence of blowouts and vegetation loss), the difference between those located in protected and unprotected areas was marginal from an observational perspective. Dunes located at Blooming Point and Thunder Cove Beaches were intact and did not appear to have suffered extensive landscape fragmentation outside of the main path of entry. While regional differences in morphology impede our ability to directly compare the coastlines of Newfoundland and PEI, unprotected dunes in PEI appeared to demonstrate a greater level of ecological and landscape integrity than any of those found in Newfoundland, regardless of protected areas status.

Dependance on the dune landscape to promote regional tourism (The Government of Prince Edward Island, 2020), stricter protected areas regulations, cultural differences in coastal land use, and more effective infrastructures are all factors that likely contribute to the comparative sparseness of anthropogenic disturbance on dune systems in PEI. Rather than

Figure 3.2.4: Photographs of vegetation cover in protected (a) and unprotected (b) coastal areas in Prince Edward Island. Image (a) was taken inside of Prince Edward Island National Park, while image (b) was taken at Blooming Point Beach. Patterns of vegetation cover were similar between protected area types. Note that the extensive dune scarping (visible in both photos) was a result of storm overwash damage incurred during Hurricane Fiona in September 2022.

each operating independently, these factors work in tandem to facilitate a public understanding for the need of dune ecosystem conservation. In turn, this increased public awareness affects both the types of human activities and the types of infrastructures built on the landscape. In PEINP, the most popular beaches (i.e., Cavendish, Brackley, Greenwich) featured many robust infrastructures that limited or otherwise controlled human use of the landscape, including boardwalks and/or stairs for beach access; washrooms; garbage and recycling bins; bar-and-wire dune fencing; signage informing about dune conservation and parks regulations; and picnic tables. Signs and placards were large, artistically pleasing, and provided easily understood information about the ecological and financial ramifications of anthropogenic dune disturbance (Figure 3.2.5). These types of signs were pervasive throughout both protected and unprotected dune areas. As a result of increased citizen awareness, as well as of social media initiatives promoting ecological conservation

Figure 3.2.5: An image of placards and garbage disposal infrastructure at Cavendish Beach in Prince Edward Island National Park. Visitor information signage was extensive throughout the park and educated about prohibited beach activities (e.g., dune trampling, campfires, dogs).

(Government of Canada, 2023), visitor adherence to protective regulations appeared to be much higher in PEI than in Newfoundland. Repeated trampling of the vegetation did not appear to be ongoing and at the time of visitation, there was no evidence of ATV or motor vehicle usage on any vegetated dune beaches in PEI. Within PEINP, strict fines are also in place prohibiting dogs on dune beaches during shorebird breeding and migration season (April to mid-October), and visitors seemed to adhere to those guidelines. It is evident through our observation of coastal dune systems in PEI that cultural importance and pride in landscape preservation is a significant motivating factor in the implementation and adherence to dune ecosystem protection. Newfoundland, which generally does not share the same pervading understanding of the dune landscape, and which does not rely upon vegetated dune tourism for economic prosperity, fails to provide an adequate level of protection to its own dune coastlines.

3.3 Study limitations

As with any scientific study, ours was also subject to certain limitations. One major limitation of our research was the timeframe in which we had to perform data collection. Resulting from restricted time, personnel, and resources, our data were collected across a two-month period in the summer of 2023. The information that we engaged with as part of this work was thus limited to the conditions of each study site at one moment in time. Ideally, we would have collected data across multiple seasons and years, to develop a more robust understanding of dune landscape disturbance and vegetation communities over time. The constraint of visiting each site once also meant that we were not present during the flowering time of all species present. For some species, like *Poaceae*, inflorescences are vital for species-level identification. More frequent visits would have allowed us to identify some species that currently are just grouped at the genus or family level. A long-term study such as this was beyond the scope of what could be accomplished during a Master's project. The limiting scope of this project also restricted the geographic area in which we could collect our data. Given that few studies of this nature had been previously performed in Newfoundland, we opted to visit more research sites and try to cover as much geographic space as possible. This also meant that we had to limit our data collection to one beach per study site, despite the presence of many adjacent dune beaches in some areas. Ideally, we would have laid additional transect lines and/or visited multiple beaches per research site, to develop a more detailed understanding of how patterns of disturbance may change within adjacent locations.

Finally, at three of our sites (Gros Morne Shallow Bay Beach, Gros Morne Western Brook Pond Outlet Beach, and Rocky Barachois Outlet Beach), we estimated the vegetation communities and groundcover assessments of some plots located on the vegetated dune. At

Shallow Bay, we observed shorebirds hiding in the dense and tall dune vegetation and made the decision to estimate some plots to avoid trampling individuals and/or nests. At Western Brook Pond Outlet, the presence of *Heracleum sphondylium* (common hogweed) made it dangerous for researchers to climb the vegetated foredune. Similarly, the slope and height of the vegetated foredune at Rocky Barachois Outlet also precluded the direct assessment of vegetation and groundcover plots. We prioritized researcher and wildlife safety throughout our fieldwork and used all possible tools at our disposal (e.g., binoculars, plant identification programs, cameras) to perform the most accurate assessment given the present hazards at these three locations.

3.4 Future study suggestions

Through our research, we sought to provide a comprehensive overview of the current vegetative and disturbance-related conditions on Newfoundland's vegetated dune coastlines. Given the limited number of previous studies conducted in this area, there are multiple future research opportunities that could build upon or derive from our study's framework. As we previously discussed, this project was conducted within a limited timeframe. A potential future study could expand upon our research by collecting vegetative and disturbance-related data across multiple seasons and years. This type of study would provide greater insight into dune system dynamics in Newfoundland and could lead to conclusions about coastal dune recovery after tropical cyclone events. Repeated surveys have led to a deeper understanding of dune restoration in PEI (George et al., 2021; Ollerhead et al., 2013), which in turn has informed human intervention in dune restoration initiatives (CBC News, 2021). Developing an understanding of the annual geomorphic dynamics of vegetated dune systems in Newfoundland would provide intricate context for use in future coastal management initiatives.

While the evaluation of non-native and native species was outside the scope of this study, our results suggest that disturbance in the dune area may be related to the propagation of non-native or atypical plant species on the vegetated foredune. In their previous assessment of the impact of ATV use on dune vegetation in New Brunswick, Hogan & Brown (2021) found that ATV use on vegetated dune coastlines was linked with non-native species establishment, pointing to humans as a potential vector. We therefore suggest that a future study focus on the potential relationships between anthropogenic disturbance and non-native species establishment on Newfoundland's vegetated dunes. Future research in this area would determine whether dune species communities are at risk in near human developments and would provide additional scientific evidence to support the establishment of new or more robust protected areas.

We did not interact with remote sensing imagery as part of our research; however, few updated and/or repeated aerial surveys of Newfoundland's dune coastlines have been conducted. A future study could focus upon creating, updating, and evaluating a comprehensive image inventory of vegetated dune areas, ideally over multiple years, to develop a great understanding of landscape change over time. We previously discussed that limitations on our time, personnel, and resources restricted the geographic area that we could survey at each study site. Remote sensing imagery of the dune landscape would facilitate the assessment of each study area at a macroscale and provide additional information about patterns of disturbance across individual sites. In previous studies of coastal dune dynamics, aerial surveys have captured dune system fluctuations through time and across large areas of space (Balduzzi et al., 2014; Eamer et al., 2022; George et al., 2021; Mathew et al., 2010; Mountney & Russell, 2006; Ollerhead et al., 2013). An updated and comprehensive inventory of dune imagery in Newfoundland would fill knowledge gaps on dune migration, system recovery, drivers of disturbance, and patterns of vegetation establishment, all of which can inform land management, use, and protection.

3.5 Conclusions

The results from our study suggest that Newfoundland's unprotected dune areas are subject to extensive anthropogenic disturbance and are at risk for additional landscape fragmentation and vegetation loss over time. While dune systems in protected areas demonstrated a greater level of landscape integrity and vegetation cover, they were still in relatively poor condition when compared to those that were visually assessed in PEI. It is evident that the existing set of conditions and regulations in Newfoundland's protected dune areas are insufficient to provide adequate protection to the landscape over time. Despite regulations disallowing vegetation trampling and the use of motorized vehicles in protected dune areas, we found abundant evidence that these activities were ongoing at many of our protected research locations. These circumstances are in direct contradiction with the Government of Newfoundland and Labrador's protected areas strategies and guiding philosophies (The Government of Newfoundland and Labrador, 2023).

To combat future anthropogenic disturbance, we recommend the stricter enforcement of regulations in existing protected areas; changing some or all protected dune areas from provincial parks to wilderness or wildlife reserves; the establishment of infrastructures like those used in PEINP in Newfoundland's protected dune areas (e.g., bar-and-wire fencing, educational and/or informational signage, restricted pathways for beach access); and the establishment of social awareness campaigns to improve public understanding about the need for dune conservation. There is an abundant need to improve local pride in the vegetated dune landscape, as our case study of PEI has indicated that respect for dune ecosystem conservation can facilitate tourism and benefit local economies. In Newfoundland, the protection of coastal dune systems will become increasingly important under the projected conditions of climate change, which may amplify net disturbances to the landscape. Vegetated dune coastlines provide diverse benefits: they protect coastal communities from storm surge impacts; they provide beach nesting shorebird habitat; they enhance biodiversity; and their beaches provide a place for gathering, recreation, and appreciation of the landscape. While Newfoundland may not rely on its coastal dunes for economic prosperity, they are an important part of the homes and lives of people and wildlife. Their protection is warranted now and into the future.

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Appendix I: Outcome of generalized linear mixed models

AI.1: A generalized linear mixed model comparing i) plot level species richness with the combined effects of ii) percent disturbed substrate and iii) protected areas status with all 486 plots included across 14 research locations (2023).

```
Call:
glmmPQL(Species.Per.Plot ~ Perc.Dist.Sub*Protected.Area, random= ~1 |
Transect.ID, family=poisson, data = Plotdata)

Linear mixed-effects model fit by maximum likelihood
  Data: Plotdata
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Transect.ID

         (Intercept) Residual
StdDev: 3.162551e-05 1.205794

Variance function:
 Structure: fixed weights
 Formula: ~invwt

Fixed effects:  Species.Per.Plot ~ Perc.Dist.Sub * Protected.Area

                                  Value  Std.Error  DF   t-value p-value
(Intercept)                   0.4706703 0.08303250 478  5.668507  0.0000
Perc.Dist.Sub                -0.0141212 0.00180109 478 -7.840375  0.0000
Protected.Area1               0.2145414 0.13205388 478  1.624650  0.1049
Perc.Dist.Sub:Protected.Area1 -0.0037290 0.00298418 478 -1.249580  0.2121

 Correlation:
                              (Intr) Pr.D.S Prt.A1
Perc.Dist.Sub                -0.521
Protected.Area1              -0.629  0.328
Perc.Dist.Sub:Protected.Area1  0.315 -0.604 -0.499

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-1.1682038 -0.5179573 -0.4785280  0.5980627  3.6178047
```

AI.2: A generalized linear mixed model comparing i) plot level species richness with the combined effects of ii) percent disturbed substrate and iii) protected areas status with beach plots removed, for a total of 256 plots across 14 research locations (2023).

```
Call:
glmmPQL(Species.Per.Plot ~ Perc.Dist.Sub*Protected.Area, random= ~1 |
Transect.ID, family=poisson, data = Plotdatanobeach)

Linear mixed-effects model fit by maximum likelihood
  Data: Plotdatanobeach
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Transect.ID

         (Intercept)  Residual
StdDev: 1.326145e-05 0.9235753

Variance function:
 Structure: fixed weights
 Formula: ~invwt

Fixed effects:  Species.Per.Plot ~ Perc.Dist.Sub * Protected.Area

                                   Value  Std.Error  DF   t-value p-value
(Intercept)                    0.9364794 0.06406955 248 14.616606  0.0000
Perc.Dist.Sub                 -0.0127727 0.00142518 248 -8.962173  0.0000
Protected.Area1                0.1032768 0.10259591 248  1.006637  0.3151
Perc.Dist.Sub:Protected.Area1  0.0013139 0.00240823 248  0.545568  0.5859

 Correlation:
                              (Intr) Pr.D.S Prt.A1
Perc.Dist.Sub                 -0.488
Protected.Area1               -0.624  0.305
Perc.Dist.Sub:Protected.Area1  0.289 -0.592 -0.495

Standardized Within-Group Residuals:
       Min         Q1        Med         Q3        Max
-1.7293451 -0.9131241 -0.2845260  0.3567562  3.0996590
```

AI.3: A generalized linear mixed model comparing i) percent vegetation cover with the combined effects of ii) percent disturbed substrate and iii) protected areas status with all 486 plots included across 14 research locations (2023).

```
Call:
glmmPQL(Perc.Veg ~ Perc.Dist.Sub*Protected.Area, random= ~1 | Transect.ID,
family=gaussian, data = Plotdata)

Linear mixed-effects model fit by maximum likelihood
  Data: Plotdata
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Transect.ID

        (Intercept) Residual
StdDev: 0.001307965 25.80407

Variance function:
 Structure: fixed weights
 Formula: ~invwt

Fixed effects:  Perc.Veg ~ Perc.Dist.Sub * Protected.Area

                                 Value Std.Error  DF   t-value p-value
(Intercept)                  31.595312  2.205578 478 14.325182  0.0000
Perc.Dist.Sub                -0.314233  0.031676 478 -9.920107  0.0000
Protected.Area1              15.734950  3.751814 478  4.193958  0.0000
Perc.Dist.Sub:Protected.Area1 -0.146523  0.052537 478 -2.788947  0.0055

 Correlation:
                              (Intr) Pr.D.S Prt.A1
Perc.Dist.Sub                 -0.743
Protected.Area1               -0.588  0.437
Perc.Dist.Sub:Protected.Area1  0.448 -0.603 -0.759

Standardized Within-Group Residuals:
         Min           Q1          Med           Q3          Max
-1.834216683 -0.615549130 -0.006667087  0.126212590  2.650925886
```

AI.4: A generalized linear mixed model comparing i) percent vegetation cover with the combined effects of ii) percent disturbed substrate and iii) protected areas status with beach plots removed, for a total of 256 plots across 14 research locations (2023).

```
Call:
glmmPQL(Perc.Veg ~ Perc.Dist.Sub*Protected.Area, random= ~1 | Transect.ID,
family=gaussian, data = Plotdatanobeach)

Linear mixed-effects model fit by maximum likelihood
  Data: Plotdatanobeach
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Transect.ID

        (Intercept) Residual
StdDev: 0.001138904 24.93499

Variance function:
 Structure: fixed weights
 Formula: ~invwt

Fixed effects:  Perc.Veg ~ Perc.Dist.Sub * Protected.Area

                                Value Std.Error  DF    t-value p-value
(Intercept)                  51.59545  2.744274 248  18.801126  0.0000
Perc.Dist.Sub                -0.50178  0.041196 248 -12.180288  0.0000
Protected.Area1              17.96679  4.516679 248   3.977877  0.0001
Perc.Dist.Sub:Protected.Area1 -0.16922  0.074021 248  -2.286040  0.0231

 Correlation:
                              (Intr) Pr.D.S Prt.A1
Perc.Dist.Sub                 -0.706
Protected.Area1               -0.608  0.429
Perc.Dist.Sub:Protected.Area1  0.393 -0.557 -0.681

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.70953587 -0.09877821 -0.03280505  0.61912038  1.94123027
```

Appendix II: Site characteristics observed during 2023 vegetated dune coastline assessments

Table AII.1: List of study site characteristics, including geographic region, protected areas status, scored extent of disturbance, observed major disturbance features within the transect study area, and observed infrastructures at or adjacent to each site.

Region	Site Name	Protected Areas Status	Extent of Disturbance (0-3)	Major Disturbance Features	Infrastructures
Northeast Newfoundland	Cape Freels South Beach	Not Protected	3	Anthropogenic linear blowout (4), dune scarping (1) Total = 5	Road (dirt road for access)
	Cape Freels North Beach	Not Protected	2	Anthropogenic linear blowout (2), dune scarping (1) Total = 3	Retaining wall, playground
	Windmill Bight Municipal Park	Protected	2	Anthropogenic linear blowout (3), dune scarping (1) Total = 4	Signage, beach safety infrastructure, benches, garbage cans
	Lumsden North Beach	Not Protected	3	Anthropogenic linear blowout (5), anthropogenic built feature (2) Total = 7	Parking lot, buildings, signage, beach access infrastructure, beach safety infrastructure, benches, garbage cans, RV park

	Lumsden Back Beach	Not Protected	3	Anthropogenic linear blowout (3), anthropogenic built feature (1), dune scarping (1), wind blowout (1) Total = 6	Homes (permanent residences or summer homes), beach access infrastructure, retaining wall
	Deadman's Bay Provincial Park	Protected	2	Anthropogenic linear blowout (2) Total = 2	Signage
West Newfoundland	Stephenville Crossing	Not Protected	3	Anthropogenic deflation hallow (1) Total = 1	Signage, road (major highway)
	Gros Morne – Western Brook Pond Outlet	Protected	1	Anthropogenic linear blowout (1) Total = 1	Signage, beach access infrastructure
	Gros Morne – Shallow Bay	Protected	1	Anthropogenic linear blowout (2) Total = 2	Parking lot, buildings, signage, beach access infrastructure, benches, garbage cans
Southwest Newfoundland	Sandbanks Provincial Park	Protected	1	Anthropogenic linear blowout (1), dune scarping (1) Total = 2	Parking lot, buildings, signage, beach access infrastructure, benches, garbage cans

	Grand Bay East Beach	Not Protected	3	Anthropogenic linear blowout (6) Total = 6	Parking lot, buildings, signage, benches, garbage cans, road (residential)
	Grand Bay West Beach	Not Protected	3	Anthropogenic linear blowout (1), anthropogenic deflation hallow (2), dune scarping (1) Total = 4	Signage
	Rocky Barachois Outlet	Not Protected	2	Dune scarping (1), wind blowout (1) Total = 2	Signage, homes (cabins)
	JT Cheeseman Provincial Park	Protected	3	Anthropogenic linear blowout (1), dune scarping (1) Total = 2	Signage, road (dirt road for access)
Prince Edward Island	PEINP – Brackley Beach	Protected	2	Anthropogenic linear blowout (1), dune scarping (2) Total = 3	Parking lot, buildings, signage, beach access infrastructure, beach safety infrastructure, benches, garbage cans
	PEINP – Dalvay Beach	Protected	2	Anthropogenic built feature (2), dune scarping (1) Total = 3	Parking lot, signage, beach access infrastructure, benches, garbage cans, road (paved main road)

	PEINP – Cavendish Beach	Protected	2	Anthropogenic linear blowout (1), anthropogenic built feature (1), dune scarping (1) Total = 3	Parking lot, buildings, signage, beach access infrastructure, beach safety infrastructure, benches, garbage cans
	PEINP – Greenwich Beach	Protected	3	Anthropogenic linear blowout (3), anthropogenic built feature (1), dune scarping (1) Total = 5	Buildings, signage, beach access infrastructure, beach safety infrastructure, benches, garbage cans
	Blooming Point Beach	Not Protected	2	Anthropogenic linear blowout (3), dune scarping (1) Total = 4	Signage, road (dirt road for access)
	Thunder Cove Beach	Not Protected	3	Anthropogenic linear blowout (4), dune scarping (1) Total = 5	Signage, homes (permanent residences or summer homes)

Table AII.2: List of vegetation species identified during transect-plot assessments at each study site in Newfoundland, including geographic region and protected areas status. Species names are listed using both binomial nomenclature and common name, for clarity.

Region	Site Name	Protected Areas Status	Identified Species
Northeast Newfoundland	Cape Freels South Beach	Not Protected	*Lathyrus japonicus* (beach pea), *Leymus mollis* (American dunegrass), *Achillea millefolium* (common yarrow), *Taraxacum officinale* (common dandelion), *Senecio pseudoarnica* (seabeach groundsel), *Ligusticum scoticum* (scots lovage), *Sanguisorba canadensis* (Canadian burnet), *Bryophyta* (mosses), *Trifolium pratense* (red clover)
	Cape Freels North Beach	Not Protected	*Lathyrus japonicus* (beach pea), *Leymus mollis* (American dunegrass), *Ammophila breviligulata* (American marram grass), *Achillea millefolium* (common yarrow), *Taraxacum officinale* (common dandelion), *Senecio pseudoarnica* (seabeach groundsel), *Honckenya peploides* (sand seawort), *Poaceae* (grasses), *Trifolium pratense* (red clover)
	Windmill Bight Municipal Park	Protected	*Lathyrus japonicus* (beach pea), *Leymus mollis* (American dunegrass), *Ammophila breviligulata* (American marram grass), *Taraxacum officinale* (common dandelion), *Bryophyta* (mosses), *Cakile edentula* (American searocket)
	Lumsden North Beach	Not Protected	*Lathyrus japonicus* (beach pea), *Leymus mollis* (American dunegrass), *Juncus effusus* (soft rush), *Ammophila breviligulata* (American marram grass), *Achillea millefolium* (common yarrow), *Taraxacum officinale* (common dandelion), *Vicia sativa* (common vetch)

	Lumsden Back Beach	Not Protected	*Lathyrus japonicus* (beach pea), *Leymus mollis* (American dunegrass), *Juncus effusus* (soft rush), *Ammophila breviligulata* (American marram grass), *Achillea millefolium* (common yarrow), *Taraxacum officinale* (common dandelion), *Poaceae* (grasses), *Cakile edentula* (American searocket), *Potentila fruticose* (shrubby cinquefoil), *Argentina anserina* (silverweed)
	Deadman's Bay Provincial Park	Protected	*Lathyrus japonicus* (beach pea), *Leymus mollis* (American dunegrass), *Ammophila breviligulata* (American marram grass), *Achillea millefolium* (common yarrow), *Taraxacum officinale* (common dandelion), *Vicia sativa* (common vetch), *Senecio pseudoarnica* (seabeach groundsel), *Poaceae* (grasses), *Cakile edentula* (American searocket), *Linaria vulgaris* (yellow toadflax)
West Newfoundland	Stephenville Crossing	Not Protected	*Leymus mollis* (American dunegrass), *Ammophila breviligulata* (American marram grass), *Senecio pseudoarnica* (seabeach groundsel), *Cakile edentula* (American searocket), *Artemisia stelleriana* (hoary mugwort)
	Gros Morne – Western Brook Pond Outlet	Protected	*Lathyrus japonicus* (beach pea), *Ammophila breviligulata* (American marram grass), *Heracleum sphondylium* (common hogweed), *Rosa acicularis* (wild rose), *Taraxacum officinale* (common dandelion), *Poaceae* (grasses), *Ligusticum scoticum* (scots lovage), *Cakile edentula* (American searocket), *Mertensia maritima* (oyster leaf), *Nabalus trifoliolatus* (three-leaved rattlesnake root)
	Gros Morne – Shallow Bay	Protected	*Leymus mollis* (American dunegrass), *Ammophila breviligulata* (American marram grass), *Taraxacum officinale* (common dandelion), *Poaceae* (grasses), *Bryophyta* (mosses), *Cakile edentula* (American searocket), *Nabalus trifoliolatus* (three-leaved rattlesnake root), *Chamaenerion angustifolium* (fireweed)

Southwest Newfoundland	Sandbanks Provincial Park	Protected	*Lathyrus japonicus* (beach pea), *Ammophila breviligulata* (American marram grass), *Achillea millefolium* (common yarrow), *Poaceae* (grasses), *Ligusticum scoticum* (scots lovage), *Cakile edentula* (American searocket)
	Grand Bay East Beach	Not Protected	*Ammophila breviligulata* (American marram grass), *Taraxacum officinale* (common dandelion), *Ligusticum scoticum* (scots lovage), *Cakile edentula* (American searocket)
	Grand Bay West Beach	Not Protected	*Ammophila breviligulata* (American marram grass), *Cakile edentula* (American searocket)
	Rocky Barachois Outlet	Not Protected	*Ammophila breviligulata* (American marram grass), *Honckenya peploides* (sand seawort), *Cakile edentula* (American searocket)
	JT Cheeseman Provincial Park	Protected	*Lathyrus japonicus* (beach pea), *Ammophila breviligulata* (American marram grass), *Poaceae* (grasses)