

Dynamic Coastal Dune Restoration and Spatial-Temporal Monitoring at the
Wickaninnish Dunes, Pacific Rim National Park Reserve, British Columbia, Canada.

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B.Sc. Trent University, 2005

M.Sc. University of Guelph, 2007

A dissertation submitted in partial fulfillment of
the requirements for the degree of

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Supervisory Committee

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Abstract

This dissertation presents the results of a multi-year interdisciplinary study of a dynamic coastal dune ecosystem restoration effort in Pacific Rim National Park Reserve in British Columbia, Canada. The research is the result of a collaboration with Parks Canada Agency (PCA) who, under the Species at Risk Act (SARA), are mandated to restore habitat for SARA listed species within the dune complex. In response, PCA committed to, and implemented, a dynamic dune ecosystem restoration program that involved widespread removal of invasive vegetation (*Ammophila* spp.), transplanting of native vegetation, introduction of an endangered species, and volunteer programs to prevent re-growth of *Ammophila*. A comprehensive monitoring program was developed with PCA and undertaken by the author and PCA collaborators from start of the project in Summer 2008 to Fall of 2012. This dissertation is the product of independent research by the author carried out under the supervision of the advisory committee and does not reproduce written materials prepared for, or by, PCA. The dissertation consists of three separate journal manuscripts (the first two published by completion of the dissertation) that stand alone as independent investigations but are structured here to provide a natural progression of research findings and allow for an overall synthesis of ideas and broader contributions of the research.

The dune restoration program afforded an opportunity to review restoration trends and methods and implement a strategy and monitoring protocols based on leading edge science. Accordingly, the first manuscript, Chapter 2, summarises recent trends in coastal dune restoration, discusses relevant research surrounding beach-dune morphodynamics and coastal dune activity, and reviews preliminary data from the

project. The study identifies usable control data for the project and builds the criteria for assessing the project as a whole.

The second manuscript, Chapter 3, presents and analyses the core data obtained for the dissertation - 5 years of geomorphic monitoring from detailed land surveys with 3 years of analysis of beach-foredune-transgressive dune sediment budget responses derived from aerial LiDAR surveys. This chapter identifies several trends in the dune systems' response to restoration that, with reference to the indicators developed in Chapter 2, suggest improved levels of dynamism in the landscape.

Finally, Chapter 4 (manuscript 3), extends the findings of the restoration study and utilises the rich data set obtained from the restoration program to develop a dynamic mapping technique that better conveys the spatial-temporal morphodynamic behaviour of dune ecosystems. The study comments broadly on the potential to apply these data and techniques to the study of disturbance events in beach-dune systems. The dissertation is concluded (Chapter 5) with an overall summary of key research objectives and contributions, and presents recommendations for future research.

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Dedication

I dedicate this dissertation to my parents who gave me so much and wanted to see me finish.

1.0 Introduction

Coastal dune systems are unique natural environments located at the land-sea interface. They act as a natural buffer between land and sea and provide a wealth of ecosystem services, flood and storm protection, rare habitat, and areas for recreation. The threats to beach-dune systems and sandy coastal ecosystems are well known as we face climate change related sea-level rise and ever increasing pressure on coastal lands (Martinez and Psuty, 2004; Nordstrom, 2008, Martinez et al., 2013; Malavasi, 2016). Other threats, such as invasive species and over-stabilisation of dune landscapes, are more recently being addressed (Martinez et al., 2013; Arens, 2013; Konlechner and Hilton 2014). In some, mostly temperate coastal areas, trends in dune restoration are shifting to promote dune dynamism and enhanced morphodynamics (Walker et al., 2013; Nordstrom, 2008). Typically, this has been achieved through widespread removal of stabilising vegetation, particularly on the foredune, and frequently targeting invasive and non-native dune species.

The Wickaninnish Dunes are located within Pacific Rim National Park Reserve (PRNPR) near Ucluelet, British Columbia on Vancouver Island. This is the site of the first dynamic coastal dune restoration in Canada. Dunes at Wickaninnish Beach support a number of native plant species that are adapted to survive in nutrient poor dune soils and under conditions of salt spray and sand scour. The predominant species are American dune (wildrye) grass (*Elymus mollis*), beach morning glory (*Convolvulus soldanella*), beach carrot (*Glehnia littoralis*), and yellow sand verbena (*Abronia latifolia*). Dominant species on the foredune, however, are the introduced American and European beach (marram) grasses (*Ammophila breviligulata* and *A. arenaria*,

respectively). In the transgressive dunes, vegetation succession has led to encroachment by native Kinnikinnick (*Arctostaphylos uva-ursi*) and Sitka spruce (*Picea sitchensis*). The invasive *Ammophila* (predominantly *A. arenaria*) is of particular concern for its aggressive expansion on foredunes, reduction of ecosystem biodiversity, and ability to significantly alter foredune sediment budgets and morphodynamics (e.g., Wiedemann and Pickart, 1996, 2004; Hesp, 2002; Hilton et al., 2005). At this site, *Ammophila* has displaced the native dune grass community and reduced habitat for a variety of dune species including Silky beach pea (*Lathyrus littoralis*) and Pink sand verbena (*Abronia umbellata var breviflora*), which are listed as threatened and endangered, respectively, in the Canadian Species at Risk Act (SARA).

It is hypothesized that dense *Ammophila* colonization of the foredune has reduced sand supply to the transgressive dunes at Wickaninnish resulting in increased vegetation colonization and a loss of 28% in active sand surface area from 1973 to 2007 (Heathfield and Walker, 2011). As in other areas of the Pacific Northwest, foredunes vegetated with *Ammophila* spp. tend to have a steeper and taller morphology that limits landward sand transport, compared to foredunes vegetated with the native *Elymus mollis*, which are typically lower, more hummocky, and offer more landward sand transport pathways (Cooper, 1958; Wiedemann and Pickart, 1996; Wiedemann, 1998). Although a detailed account of pre-invasion conditions at the site is not possible, the aforementioned work of others in the region (Washington and Oregon, see Cooper, 1958) as well as in other temperate dune systems around the world (e.g. New Zealand, see Hilton, 2005) provide analogous case studies to aid in understanding the pre-invasion landscape.

PRNPR is legally obligated under SARA to develop a recovery strategy for Pink sand verbena and a 5-year dynamic restoration program was implemented by PCA in fall 2009. The treatment method involved mechanical removal of invasive *Ammophila* and later successional colonizing species, namely Sitka Spruce (*Picea sitchensis*) and Kinnikinnick (*Arctostaphylos uva-ursi*), from a 3-km stretch of foredune using a backhoe and bulldozer. Ongoing monitoring for the project includes an examination of species recovery and PCA maintains a manual pulling program for *Ammophila*.

Approaches to dynamic ecosystem restoration differ, but usually involve some type of disturbance to the foredune (where present) and removal of targeted vegetation. Beyond the intended restoration goals and related research, these projects provide opportunities to better understand the nature of, and responses to, large scale-disturbances, such as wave erosion or overwash events, on coastal foredunes and dunefields. Disturbance types and processes in coastal dunes have been discussed in great detail in the literature (see summary by Hesp and Martinez, 2007) and dune research has consistently highlighted the complexity of disturbance processes in coastal dune environments (e.g. White, 1979; Ehrenfeld, 1990; Garcia-Mora et al., 1999; Stallins and Parker, 2003; Forey et al., 2008; Miller et al., 2010, Pardini et al., 2015, etc.). However, only a relatively small number of studies have examined the geomorphological impacts of large scale foredune disturbance on landward dunefields (e.g., Van Boxel, 1999; Arens, 2013; Konlechner et al., 2014, 2015; Eamer et al. 2013; Darke et al., 2016) while research on dune vegetation changes following disturbance is better represented (Hayden, 1995; Miller et al., 2010, 2015; Malavasi et al., 2013, 2014;

Garcia-Mora; Gonzalez-moreno 2013; Pardini et al., 2015; Vecchio et al., 2015; Cheplick, 2017). However, comprehensive long-term (interannual) studies are lacking.

Widespread destruction of vegetation may occur naturally following large storm scarping or overwash events, but it is rare that appropriate monitoring protocols are in place beforehand to assess the impacts of these disturbances on landward dunefields through time. An increasing number of dynamic restoration programs have been implemented that seek to restore the disturbance regime of the landscape and promote dune dynamism using a variety of intentional disturbances such as vegetation removal (frequently involving invasive species, e.g. Pickart, 2013), foredune notching (to promote blowout development, e.g. van Boxel, 1999), or the creation of larger scale blowouts and mini-transgressive dunes (Arens et al., 2004, 2013). These restoration efforts provide an opportunity to study disturbed dune landscapes and better understand disturbance responses in natural environments given that monitoring programs are frequently in place to assess restoration effectiveness. Moreover, with the accessibility of new surveying and data processing technologies it is has become possible to acquire detailed records of landscape change at a wide range of spatial and temporal scales. By harnessing these technologies and utilising the data in new ways in will become easier to develop the tools necessary to understand and forecast dune processes in response to a range of disturbance types and other environmental forcings. The restoration case study at Wickaninnish dunes was an excellent opportunity to begin pursuing research of this nature.

The overarching goals of the dissertation are as follows:

1. To review the state of the science surrounding coastal-dune systems and better situate dynamic dune ecosystem restoration efforts within current geomorphic understanding.
2. To use a robust data set, collected during the dune ecosystem restoration program, to assess the impacts of invasive grass removal on the overall beach-dune system. This objective is two-fold and includes comment on the effectiveness of the restoration effort as well as the insights gained for future dynamic restorations.
3. To develop better techniques for assessing the responses of dune systems to disturbance processes and provide examples of new methodologies, readily employable, that will aid in monitoring and understanding dune processes, particularly in response to foredune disturbance.

1.1 Dissertation Structure

This dissertation is structured around 3 distinct journal manuscripts (Chapters 2, 3, and 4) which, while independent from one another, flow in a logical sequence and provide a natural progression of research findings.

The first manuscript, Darke et al., (2013) is provided in Chapter 2 and is published in *Earth Surface Processes and Landforms*. This chapter presents the preliminary data from the early stages of the research and its primary aim was to situate the research within current geomorphic understanding and examine the data with the primary intent of informing the research to follow. The paper provided a substantial literature review, assessed the preliminary data, and developed a framework for assessing dune restoration effectiveness.

The third chapter, Darke et al., (2016) also published in *Earth Surface Processes and Landforms* builds upon the findings of the second and presents the complete set of data collected for the project. Using a three year detailed sediment budget record, 5 year cross-shore profile record, and pre and post restoration LIDAR and orthophotographs the response of the dune system is assessed. The criteria developed in the second chapter are updated and applied to comment broadly on the effectiveness of the dune restoration project using all data acquired. Insights gained for future dynamic restoration programs are discussed briefly.

The fourth chapter (in preparation for publication) moves beyond a specific focus on the restoration project and employs the data collected to develop a dynamic geomorphic mapping technique and present more detailed landscape and landform scale assessments of the dune systems response to foredune disturbance. The disturbance, in this case, was the removal of invasive vegetation from the foredune but the application of the techniques elsewhere, to more broadly strengthen research on dune responses to disturbance, is discussed. By collecting data at these types of spatial-temporal scales we can begin to monitor and understand the morphodynamics of dune landscapes in more detail and in ways that may allow for the improvement of multi-scale system modelling.

The fifth and concluding chapter summarizes the overall findings of the combined research and not only addresses the state of the science with regards to dynamic dune restoration but comments more broadly on the study of beach-dune systems and the future need to develop more robust spatial-temporal monitoring techniques (Walker et al., 2017).

2.0 Monitoring considerations for a dynamic dune restoration project: Pacific Rim National Park Reserve, British Columbia, Canada.

This chapter has been peer-reviewed and published previous to the release of this dissertation, as follows:

Ian B. Darke, Jordan B.R. Eamer, Hawley E.R. Beaugrand and Ian J. Walker. 2013. Earth Surface Processes and Landforms. 38 (9): 983-993. [DOI: 10.1002/esp.3380](https://doi.org/10.1002/esp.3380)

2.1 Abstract

Historically, management of coastal dune systems has most commonly involved artificial stabilisation in order for coastal areas to be more easily controlled and modified for human benefit. In North America, the introduction of invasive grasses, namely European and American (marram) grasses (*Ammophila spp.*) has been one of the most successful strategies used for stabilising drifting sands in coastal areas. Recent research has demonstrated, however, that stabilisation of coastal dunes often leads to reduced landform complexity and resilience, as well as declines in species diversity. More 'dynamic' restoration efforts have emerged over the past 20 years that encourage dune mobility and aeolian activity in order to provide an overall more resilient biogeomorphic system. In North America, in general, there is very little research relating restoration methods and outcomes to geomorphic responses despite the fundamental importance of sedimentary processes and dune morphodynamics in broader ecosystem function. This paper aims to better situate dynamic dune restoration within current geomorphic understanding. A brief review of key terms and concepts used in the emerging field of dynamic dune restoration is provided and these are expanded to include geomorphologic considerations. This discussion provides context for a recently initiated restoration effort in Pacific Rim National Park Reserve, British Columbia, Canada. At this site European Marram Grass, coupled with a warming climate and

increased precipitation in recent decades, is thought to be largely associated with a rapid decline in aeolian activity, system stabilisation and accelerated ecological succession. The response of the dune system to mechanical removal of *Ammophila* is discussed at a preliminary level and based on these results a research framework for the broader monitoring effort is presented. Recommendations for improving treatment methodologies are provided to aid future restoration projects of this nature.

List of key words: coastal dune dynamics, habitat restoration, disturbance, invasive vegetation, restoration monitoring

2.2 Introduction

Historically, coastal populations have viewed the mobility of active sand dunes as a nuisance or threat to human interests. However, it has long been recognized that coastal dunes provide a buffer from the ocean and protect coastal areas from flooding during storms. As such, coastal dune systems have been subject to intense stabilisation efforts to enhance flood protection and wave erosion defense (e.g., Hillen and Roelse, 1995; Arens et al., 2001; Arens et al., 2004; Grootjans et al., 2002; Mascarenhas and Jayakumar, 2008). Aside from this protective role, they have been viewed to hold little socio-economic value and therefore they have been modified, stabilised or completely levelled for a variety of reasons including: urban and recreational development (e.g., Riksen et al., 2006), forestry and agriculture (e.g., Riksen et al., 2006, Van Der Meulen and Salman, 1996) and groundwater storage and recharge (e.g., Arens et al., 2004; Arens and Geelen, 2006; Terlouw and Slings, 2005). In areas where coastal dunes have been cleared or are overused, stabilising methods have been used to re-establish dune forms and restore their buffering capacity (e.g., Gómez-Pina, et al. 2002; Rozé and Lemauviel, 2004).

Over the last three decades, however, researchers have recognized that past stabilisation efforts have led to a loss of landform dynamics, complexity and resilience, which entails various ecological impacts such as declines in early successional floral species and a corresponding loss of species richness and diversity (e.g., Grootjans et al., 2002; Arens et al., 2004; Hilton et al., 2005; Nordstrom, 2008). In response, some dune restoration efforts have shifted toward the re-establishment of process-response dynamics in dune systems. Although this approach remains unconventional, more dune restoration projects are seeking to increase system complexity by reactivating aeolian sand transport and dune mobility in order to encourage more dynamic landforms and associated ecosystems (Rozé and Lemauviel, 2004; Van Der Meulen et al., 2004; Arens and Geelen, 2006; Nordstrom, 2008).

Research examining the process-response morphodynamics of dune systems to dynamic restoration efforts is emerging but data collection is primarily ecological, focusing on soil and vegetation changes (Van Boxel et al. 1997, Ketner-Oostra and Sykora, 2000, Grootjans et al., 2002, etc.). Isolated studies of geomorphic and/or sediment budget responses exist but have focused primarily on the expansion of active sand surfaces with only indirect or qualitative measures of aeolian activity and landscape change (Arens et al., 2004; Arens, 2005; Wondergem, 2005; Arens and Geelen, 2006). More robust measures of significant geomorphic change are needed to better assess the success of, or refinements to, restoration objectives.

2.2.1 Research Purpose and Objectives

The purpose of this paper is two-fold. First, this work presents preliminary case study results on morphodynamic responses to mechanical removal of vegetation

(*Ammophila* spp.). Mechanical vegetation removal is being used by Parks Canada Agency (PCA) as a restoration treatment within a foredune-transgressive dune complex in Pacific Rim National Park Reserve (PRNPR) on the west coast of Vancouver Island, British Columbia, Canada. Second, these results are used to provide discussion on and determine specific geomorphic measures of landscape response. These measures will be used to develop a research framework which will assess dynamic restoration efforts in these coastal dune systems. The specific research objectives are:

1. To better situate dynamic restoration efforts within current geomorphic understanding.
2. To review and discuss preliminary data following the first round of mechanical vegetation removal.
3. To utilise the preliminary data to inform the ongoing monitoring and develop a more robust research framework for assessing the response of the dune system to restoration efforts.

2.2.2 Research Context and Terminology

Dynamic dune systems are those within which contemporary aeolian processes take place as opposed to stabilised dune systems where aeolian processes are absent or found at low levels (Nordstrom, 2008). Dune mobility, which refers to the ability of dune forms to migrate under aeolian processes, is generally considered to be a function of the competence of the wind regime, frequency of precipitation and the extent of vegetation cover (Lancaster, 1988; Arens et al., 2004; Tsoar, 2005; Nield and Bass, 2008).

Stable dunes or those trending towards stabilization will return to a dynamic state following a disturbance to the vegetation cover. As Hugenholtz and Wolfe (2005) note, longer-term dune activity is cyclical and tends to alternate between active and stable states following climatic perturbations or other disturbances. Biophysical disturbances are a constant in coastal dune systems and play an important role in determining foredune structure and species assemblages. Generally, a disturbance is defined as any discrete event which results in biomass reduction and mortality (Grime, 1979; Rykiel, 1985; Pickett and White, 1985). However, in a biogeomorphic context it seems appropriate to define it as any discrete event that disrupts community and landform structure changing available resources and altering morphodynamics. The disturbance regime of a coastal foredune complex has a large influence on system dynamism, which is defined here as the collective manifestation of all extrinsic and intrinsic processes and the manner in which energy and material flow through the system (Doody, 2001; Nordstrom 2008).

Dune systems that have been subject to anthropogenic stabilisation are often resistant to all but the most extreme natural disturbances and, as a result, have disrupted natural processes, with reduced complexity and may not experience periodic activation cycles (Nordstrom, 2008). Therefore the re-establishment of the natural disturbance regime and activation-stabilisation cycles is increasingly being noted as a critical component of dune restoration projects which seek to restore lost ecosystem services (Nordstrom, 1990, 2008, 2011). Planned disturbances, in the form of vegetation removal, have recently been used in dune restoration projects to increase aeolian activity and restore system dynamism (van Boxel et al., 1997; Arens et al.,

2004). Unfortunately, a persistent challenge in coastal dune research is determining how the effects of disturbance influence foredune and community structure across space and time. Indeed, an increasing amount of research notes the complex and non-linear responses of foredune systems to disturbance events (Stallins, 2002; 2005, Stallins and Parker, 2003; Nield and Bass, 2008; Viles et al., 2008). Nonetheless, recent research examining dynamic restoration suggests that it is possible to maintain the protective role of coastal dunes while promoting early successional vegetation communities and creating an overall more resilient, as per Holling (1986), biogeomorphic system (De Raeve, 1989; Hillen and Roelse, 1995; Doody, 2001; Helsenfeld et al., 2004).

The EuroSION project defined coastal resilience as “the inherent ability of the coast to accommodate changes induced by sea level rise, extreme events and occasional human impacts, whilst maintaining the functions fulfilled by the coastal system in the longer term” (European Commission, 2004). Thus while coastal dune restoration projects have traditionally focused on biodiversity and other ecological benefits it is also important to note that dynamic dunes are cheaper to maintain than fixed dunes and are more resistant to erosion given their ability to gradually migrate landward or seaward under aeolian processes (Helsenfeld et al. 2004; Nordstrom, 2008). Davidson-Arnott (2005) provides a conceptual model of the response of sandy shorelines to sea-level rise which supports this notion by considering the broader dynamics of beach-dune systems and in doing so provides a geomorphic rationale for dynamic restoration practices. Despite progress in this area it remains difficult to convince natural resource managers of the benefits of dynamic systems when coastal

infrastructure and shoreline protection considerations often far outweigh the ecological aspects of dune management or geologic timescale coastline migration, particularly on highly developed coastlines (De Raeve, 1989; Doody, 2001; Helsenfeld et al., 2004; Nordstrom, 2008).

In summary, dune restoration efforts that seek to restore species diversity and ecological resilience need to utilise current geomorphic understanding and must recognize biogeomorphic interconnections (Viles et al., 2008). In particular, it is important to consider the morpho-ecological state of the dune systems, as per Hesp (2002), as this provides insights into the current trajectory of the system and may aid in determining if restoration treatments are necessary. Thus, in addition to traditional ecological criteria a successful dynamic restoration project will include consideration of dominant geomorphic processes (e.g., the entrainment, transport and deposition of aeolian sediment) and morphodynamic responses (e.g., dune migration, blowout formation, extension of parabolic dunes), and will ensure rejuvenation of periodic landscape activation-stabilisation cycles (i.e., dynamism; Arens and Geelen, 2006; Kooijman, 2004; Nordstrom, 2008; Van Der Meulen et al., 2004).

2.3 Study Area and Restoration Case Study

2.3.1 Study Area

The dune systems being restored back large areas of Wickaninnish beach inside PRNPR, B.C., Canada. The study site is near Ucluelet, B.C. on the west coast of Vancouver Island, (Figure 1). Wickaninnish Beach is the most southern in a series of meso-tidal beaches spanning the 10 km length of Wickaninnish Bay. Combers and Longbeach to the North are highly dissipative while Wickaninnish beach is an

intermediate bar and trough beach, all beaches within the bay have a SW aspect (Figure 2). A nearly continuous foredune ridge is established along the entire shoreline of Wickaninnish Bay and is fronted by an incipient dune field. Due to regional tectonic uplift along the Cascadia Subduction Zone offshore of Vancouver Island, the study area is experiencing a drop in relative sea level of -0.9 mm a^{-1} (Wolynec 2004; Mazzotti et al. 2008) which, combined with high onshore sand supply, assists in dune maintenance and progradation at the site (Beaugrand, 2010; Heathfield and Walker, 2011). Dunes on Wickaninnish Beach are part of a series of transgressive dune fields which range in size from small to extensive and are at various stages of ecological succession.

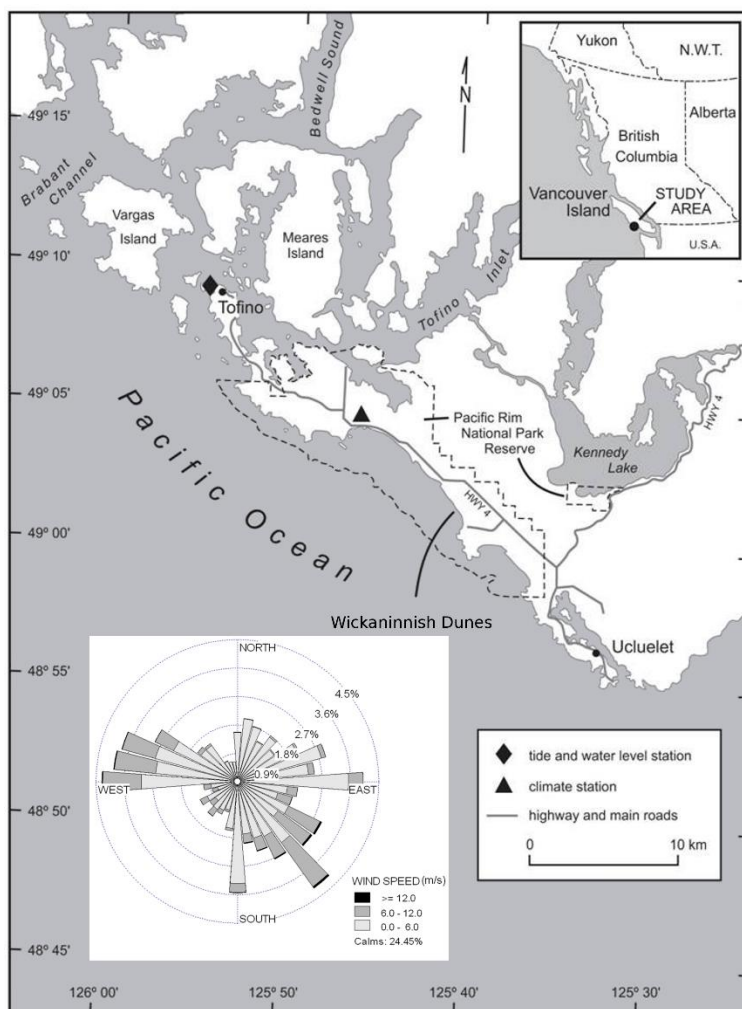


Figure 1. Study area showing the nearby town of Ucluelet and the climate station from which meteorological data were derived in Beaugrand (2010). Note the inset wind rose diagram depicting the bi-modal wind regime.

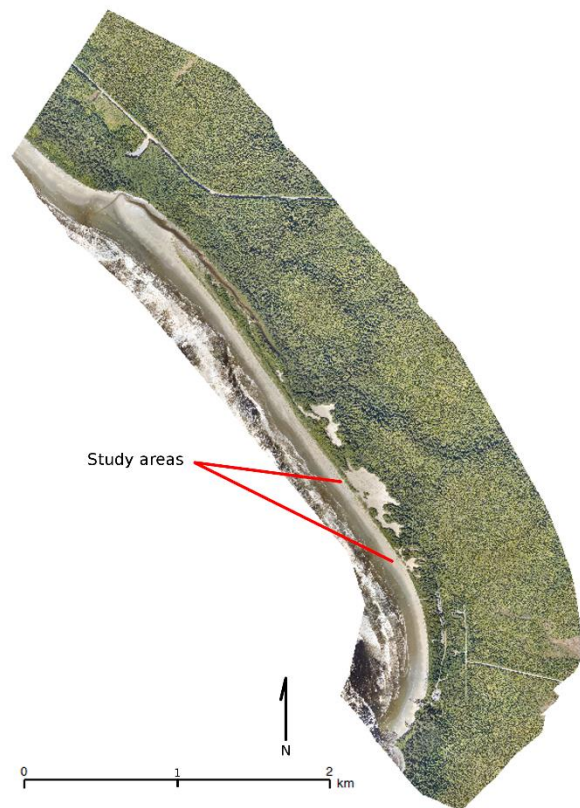


Figure 2. Digital airphoto of the study area and surrounding region.

The wind regime is highly competent and seasonally bimodal; see inset wind rose in Figure 1 (Beaugrand, 2010). These conditions allow for active foredune building and some ongoing mobility in the transgressive dunes. The alignment and geomorphology of erosional blowouts and depositional lobes within the dune complex does suggest a dominant transport vector from the WNW driven by summer wind events. This reflects the influence of high seasonal precipitation during the winter months and a seasonally controlled north-westerly alignment of the transgressive dune complex persists. The beaches are subject to a seasonally variable, energetic wave regime (Beaugrand, 2010). Foredune erosion and scarping do occur frequently along

Wickaninnish Beach although rebuilding via sand ramp development and incipient dune growth, often in the presence of large woody debris, occurs rapidly (Heathfield and Walker, 2011).

2.3.2 Case Study: Restoration of the Wickaninnish Sand Dunes, PRNPR

Dunes at Wickaninnish Beach support a number of native plant species that are adapted to survive in nutrient poor dune soils and under conditions of salt spray and sand scour. The predominant species are American dune (wildrye) grass (*Elymus mollis*), beach morning glory (*Convolvulus soldanella*), beach carrot (*Glehnia littoralis*), and yellow sand verbena (*Abronia latifolia*). Dominant species on the foredune, however, are the introduced American and European beach (marram) grasses (*Ammophila breviligulata* and *A. arenaria*, respectively). In the transgressive dunes, vegetation succession has led to encroachment by native Kinnikinnick (*Arctostaphylos uva-ursi*) and Sitka spruce (*Picea sitchensis*). The invasive *Ammophila* (predominantly *A. arenaria*) is of particular concern for its aggressive expansion on foredunes, reduction of ecosystem biodiversity, and ability to significantly alter foredune sediment budgets and morphodynamics (e.g., Wiedemann and Pickart, 1996, 2004; Hesp, 2002; Hilton et al., 2005). At this site, *Ammophila* has displaced the native dune grass community and reduced habitat for a variety of dune species including Silky beach pea (*Lathyrus littoralis*) and Pink sand verbena (*Abronia umbellata* var *breviflora*), which are listed as threatened and endangered, respectively, in the Canadian Species at Risk Act (SARA). It is hypothesized that dense *Ammophila* colonization of the foredune has reduced sand supply to the transgressive dunes at Wickaninnish resulting in increased vegetation colonization and a loss of 28% in active sand surface area from 1973 to

2007 (Heathfield and Walker, 2011). As in other areas of the Pacific Northwest, foredunes vegetated with *Ammophila* spp. tend to have a steeper and taller morphology that limits landward sand transport, compared to foredunes vegetated with the native *Elymus mollis*, which are typically lower, more hummocky, and offer more landward sand transport pathways (Cooper, 1958; Wiedemann and Pickart, 1996; Wiedemann, 1998). Although a detailed account of pre-invasion conditions at the site is not possible, the aforementioned work of others in the region (Washington and Oregon, see Cooper, 1958) as well as in other temperate dune systems around the world (e.g. New Zealand, see Hilton, 2005) provide analogous case studies to aid in understanding the pre-invasion landscape.

PRNPR is legally obligated under SARA to develop a recovery strategy for Pink sand verbena and a 5-year dynamic restoration program was implemented by PCA in fall 2009. The treatment method involved mechanical removal of invasive *Ammophila* and later successional colonizing species, namely Sitka Spruce (*Picea sitchensis*) and Kinnikinnick (*Arctostaphylos uva-ursi*), from a 3-km stretch of foredune using a backhoe and bulldozer. This study focuses solely on geomorphic and sediment budget responses during the first year following the restoration treatment. Fore-dune re-vegetation was very minimal over the monitoring period of this study and therefore ecological responses are beyond the scope of this paper. Ongoing monitoring for the project includes an examination of species recovery and PCA maintains a manual pulling program for *Ammophila*.

2.3.3 Monitoring Sites

The dune environment being restored is very large and therefore frequent monitoring has necessitated the development of discrete monitoring areas. Firstly, four cross-shore monitoring transects (WICK1 is the southernmost, WICK4 is the northernmost) were established in August 2008 and are surveyed annually during the lowest tides of the summer months (Figure 3). Secondly, 3 topographic survey swaths (WICK1, WICK2 and WICK3/4) were established after the first round of mechanical restoration in September 2009 and are surveyed bi-monthly for generation of Digital Elevation Models (DEM's) (Figure 3). As figure 3 demonstrates the topographic survey swaths extend approximately 50 m on either side of the monitoring transect. The largest monitoring swath, WICK3/4, is intersected by two monitoring transects (WICK3 and WICK4). Once a year, the area between the WICK2 and WICK3/4 survey swaths is surveyed to provide a near complete DEM of the larger transgressive system. The topographic surveys are conducted in the same shore normal orientation as the monitoring transects and therefore capture an appreciable area of linked beach, foredune, and transgressive dune components, or geomorphic 'units', within the landscape. Within the 3-km stretch of foredune identified for treatment by PCA, the first phase of vegetation removal occurred in September 2009. The extent of vegetation removed during this period is indicated in Figure 3; note that only WICK1 and a small portion of WICK2 saw complete removal of foredune vegetation. The majority of the WICK2 and WICK3/4 treatment was conducted on the incipient dunes and lower foredune.

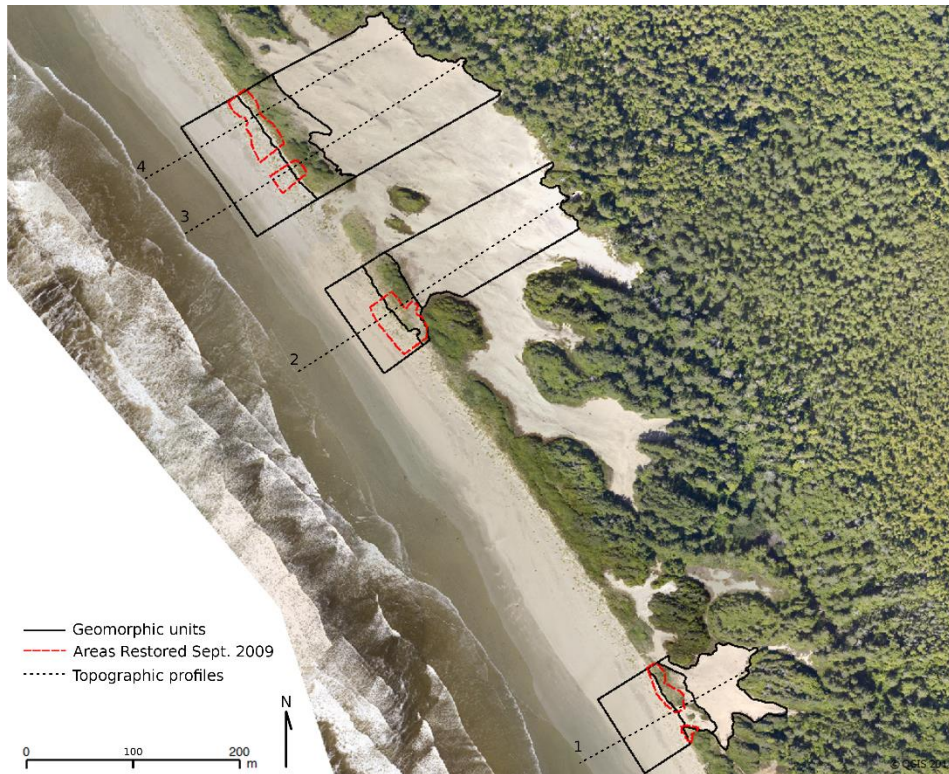


Figure 3. Finer scale image of the study areas shown in Figure 2. Superimposed are the geomorphic units for each monitoring swath, the areas where mechanical vegetation removal took place in September 2009, and the topographic cross-shore profile locations.

The WICK1 site is located to the south-eastern end of the study area in a smaller transgressive blowout complex and the entire site is discretely bound by forest. Pre- and post-restoration photographs of the site are provided in Figure 4. The site consists of approximately 75 m of fully denuded foredune, 10 320 m² of total active sand surface and a perimeter of 924 m.

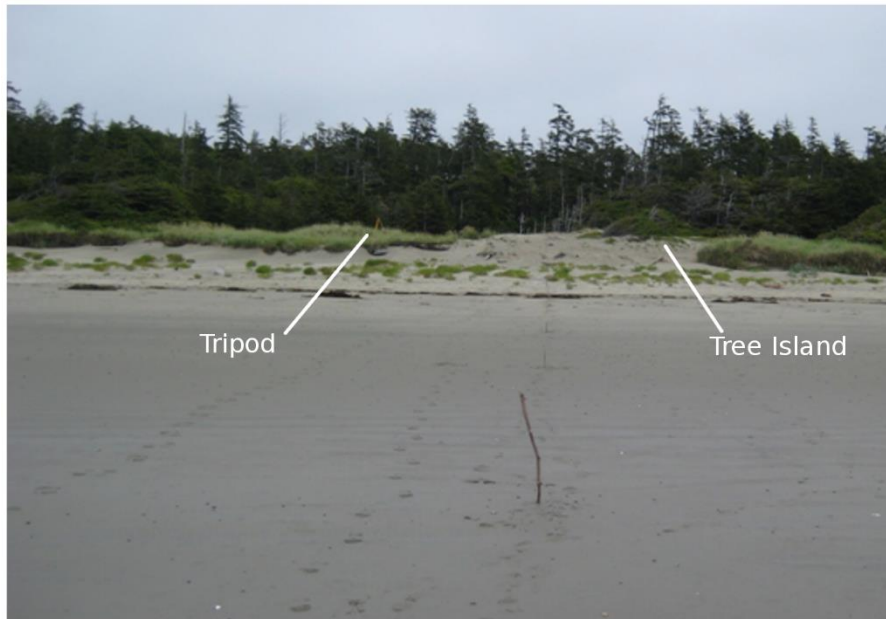


Figure 4. Photos taken immediately before (above) and after (below) mechanical vegetation removal at the WICK1 study site. Note the survey tripod for scale (~1.5 m tall) and the tree island for a common point of reference.

Sites WICK 2 and WICK3/4 exist in the larger and more open transgressive dune complex to the north of WICK 1 and are subject to appreciable lateral sand transfers and bedform migration between sites. The WICK 2 site is on the southeastern end of the larger transgressive dune field and has a total area of 17 081 m² and a total

perimeter of 1048 m. The first round of restoration treatment cleared approximately 50 m of well-developed incipient dune but only 20 m of foredune was completely denuded. The WICK3/4 site is located towards the northwest end of this larger transgressive dune complex and during the first round of mechanical removal approximately 100 m of the incipient dune and a small area of the lower foredune was cleared of vegetation. The total area of the monitoring swath is 28 072 m² and the perimeter is 1376 m.

2.4 Methods

The Parks Canada Agency mandate to restore habitat for Pink Sand Verbena is the driving force behind this project and the main objective is to free the foredune of *Ammophila* along the entire extent of the dune systems. Examining the response of the plant system is a key component of the ongoing monitoring but, as minimal vegetation re-growth occurred over the first year of monitoring and lag times in the vegetative response are considerable, there is no applicable data to present in this paper. The following paragraphs therefore focus on the techniques used for vegetation removal and the methods of analysis for the first year of geomorphic monitoring.

Vegetation removal was done using a backhoe and an excavator. The first of 3 mechanical treatments, spaced a year apart, occurred in September 2009; this initial treatment required 10 work days and completely de-vegetated 30% of foredune area selected for restoration. Manual grass pulling following the mechanical treatment is ongoing and over the one year monitoring period analysed in this study has been effective in keeping the treated areas free of *Ammophila*.

A high resolution DEM base map and digital orthophoto mosaic were developed from an airborne LiDAR survey flown prior to any mechanical vegetation removal on 27 August 2009. The vertical and horizontal accuracy of this DEM is 0.15 m and 0.01 m, respectively. Semi-monthly topographic surveys at each study site were conducted using a Topcon GTS226 laser total station for the first year following the restoration activity (September 2009 - August 2010). For each survey, the total station was resectioned into the WGS 84 Datum by commencing the survey with 3 shots to permanent control markers, which were established prior to restoration activities using a Real Time Kinematic (RTK) GPS unit. As such, points were georeferenced on collection and required no post-processing. The survey data collection strategy was a systematic nested pattern (Chappell et al., 2003) (vs. a fixed positional grid of recurrently surveyed points) that captured detailed coverage of significant features and slope inflection points with grid densities of 0.04 to 0.09 points m⁻² and vertical accuracies (closing errors) of 0.04 to 1.65 cm. These results are compared to the LiDAR reference dataset.

In order to estimate sediment volume exchanges, each site was subdivided into three geomorphic units: beach, foredune, and transgressive dune (see Fig. 3). This approach is similar to that used in France by Anthony et al. (2006, 2007), although in that study only two geomorphic units (beach and dune) were used. The beach geomorphic unit represents the sediment source for the system including all sediment brought to the beach through wave action given that frequent bathymetric data in the nearshore is unavailable. The perimeter of the beach unit was defined by the seaward limit of the survey and on the landward margin it was defined by the seaward extent of foredune vegetation. The foredune geomorphic unit can be both depositional and

erosional and both conditions should be captured in the mass balance. The perimeter of this unit was defined by the extent of foredune vegetation. The transgressive dune geomorphic unit includes all dune areas landward of the foredune vegetation and is bound by the surrounding forest vegetation. This geomorphic unit is the sediment sink for the system and is therefore a net depositional area, although landward inputs into the transgressive dune appeared minimal in the years preceding the project.

After each survey, the volumetric change at each site is calculated for the three geomorphic units relative to the initial LIDAR survey and this allows net volumetric change to be plotted over time starting from the LIDAR baseline. Post processing for the generation of DEM's is done using a robust geostatistical approach as outlined in detail by Eamer et al. (2013). This methodology allows for user selected best-fit model parameters and, using kriging, generates the DEM surface based on the unique statistical signature found within the discrete landscape units. Volumetric and elevation change detection between the monthly surveys and the baseline LIDAR survey was done by importing DEM's into a Geomorphic Change Detection Software package (Wheaton et al., 2010a). This software was developed for morphological sediment budgeting and determines errors associated with the change detection process allowing for identification of statistically significant change.

2.4.1 Control Data

Effective monitoring of the restoration effort is complicated by difficulties in acquiring relevant control data given that time constraints did not permit robust monitoring of the site prior to vegetation removal. Moreover, little is known about the site prior to *Ammophila* invasion given that no usable air photos exist for vegetation and

landform analysis and personal communications with long-time residents do not provide sufficient descriptions. As noted in section 3.0, a high resolution orthophotograph and LIDAR survey were conducted prior to any mechanical removal and serves as a baseline to all subsequent surveys. While this baseline survey does not provide a detailed assessment of volumetric variability prior to restoration it nonetheless provides a good assessment of landscape scale morphology and vegetation patterns prior to restoration. Moreover, the timing of restoration treatments has allowed for some temporal control of volumetric variability. As opposed to the WICK1 site, which experienced complete denudation of the foredune in the first treatment, the WICK3/4 site only received a small amount of vegetation removal on the incipient dune and lower foredune stoss slope. Foredune dimensions are highly comparable across all sites (see section 4.1) and allow for comparative analysis. Given that 30 metres of heavily vegetated foredune existed behind the small mechanically treated patch at WICK3/4, it is unlikely that this initial treatment has had a large impact on the beach-dune sediment budget. Indeed, a prime objective of this study is to determine if the initial monitoring data at this site has utility as control data for the ongoing project. Finally, the four year record of cross-shore topographic profiles includes several years of pre-restoration surveys and, as discussed in Section 4.1, is therefore useful in providing some form of temporal control.

2.5 Results

2.5.1 Cross-shore topographic profile changes

The four cross-shore topographic profiles surveyed within the restoration area between 2008 and 2011 provide a simple indication of sedimentary responses times to

the restoration treatments (Figure 5). Complete mechanical removal of foredune vegetation occurred at the WICK1 site in September 2009, in September 2010 for sites WICK3/4, and in September 2011 for WICK2. At each site complete denudation of the foredune using bulldozers and a backhoe occurred over a five day period. In general, following mechanical treatments a slight lowering and widening of the foredune is observed and rapid sediment accumulation occurs landward of the foredune in the year following treatment. Vertical gains and losses at various locations along the foredune profile are summarised in Table 1. This ongoing record provides some context to inform the analysis of volumetric change observed in the DEM's and presents one form of control data for the ongoing study.

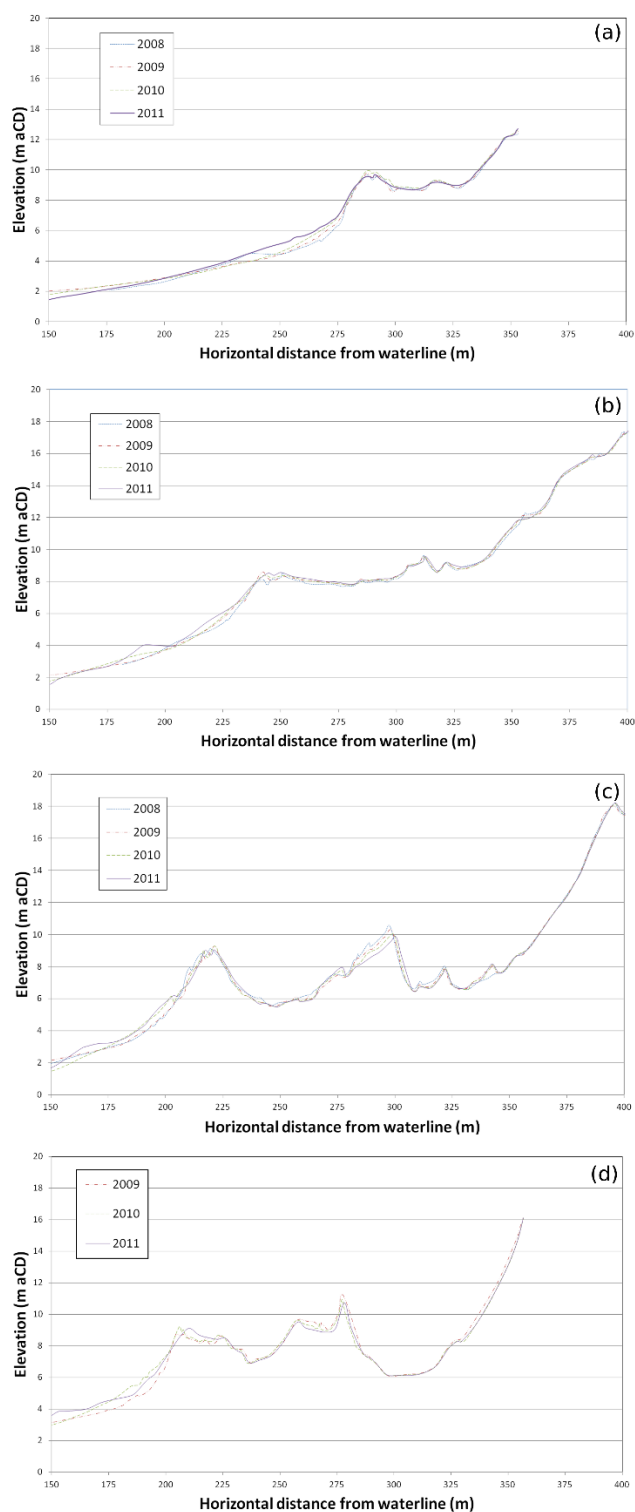


Figure 5. Topographic cross-shore profiles for WICK 1 (a), WICK2 (b), WICK3 (c), and WICK4 (d) showing four surveys and thus three full years of surface change at three of four sites (issues with the 2008 WICK4 profile rendered the data unusable). Locations for each profile are shown in Figure 4.

Table 1. Summary of important foredune surface changes, based on topographic profiles. Shore normal changes refer to prograding (seaward) migrations (+) and retreating (landward) migrations (-). Vertical changes refer to accretion (+) or erosion (-).

Change (m a ⁻¹)	WICK1		WICK2		WICK3		WICK4	
	Shore normal	Vertical	Shore normal	Vertical	Shore Normal	Vertical	Shore Normal	Vertical
Incipient dune	4.00	0.22	2.78	0.27	1.98	0.29	2.38	0.28
Foredune stoss slope	0.38	0.10	0.70	0.13	-1.06	0.19	~0	~0
Foredune lee slope	~0	0.12	-2.64	0.11	-0.40	0.13	0.60	-0.09

2.5.2 DEM landscape Response

A time series showing the statistically significant, area-normalized volumetric changes measured at each site over the first year of monitoring is provided in Figure 6. For each site, volumetric changes in the three geomorphic units are displayed relative to the LIDAR baseline DEM. A corresponding change detection map is provided for the three monitoring swaths in Figure 7 and indicates the statistically significant surface changes observed at the end of the first monitoring year. For each monitoring swath the net annual volumetric changes, calculated using the GCD software, are listed by geomorphic unit in Table 2. For an in-depth examination of the WICK1 site see Eamer et al. (this issue), but details of the seasonal volumetric change and annual surface change are summarised in figures 6a and 7a respectively.

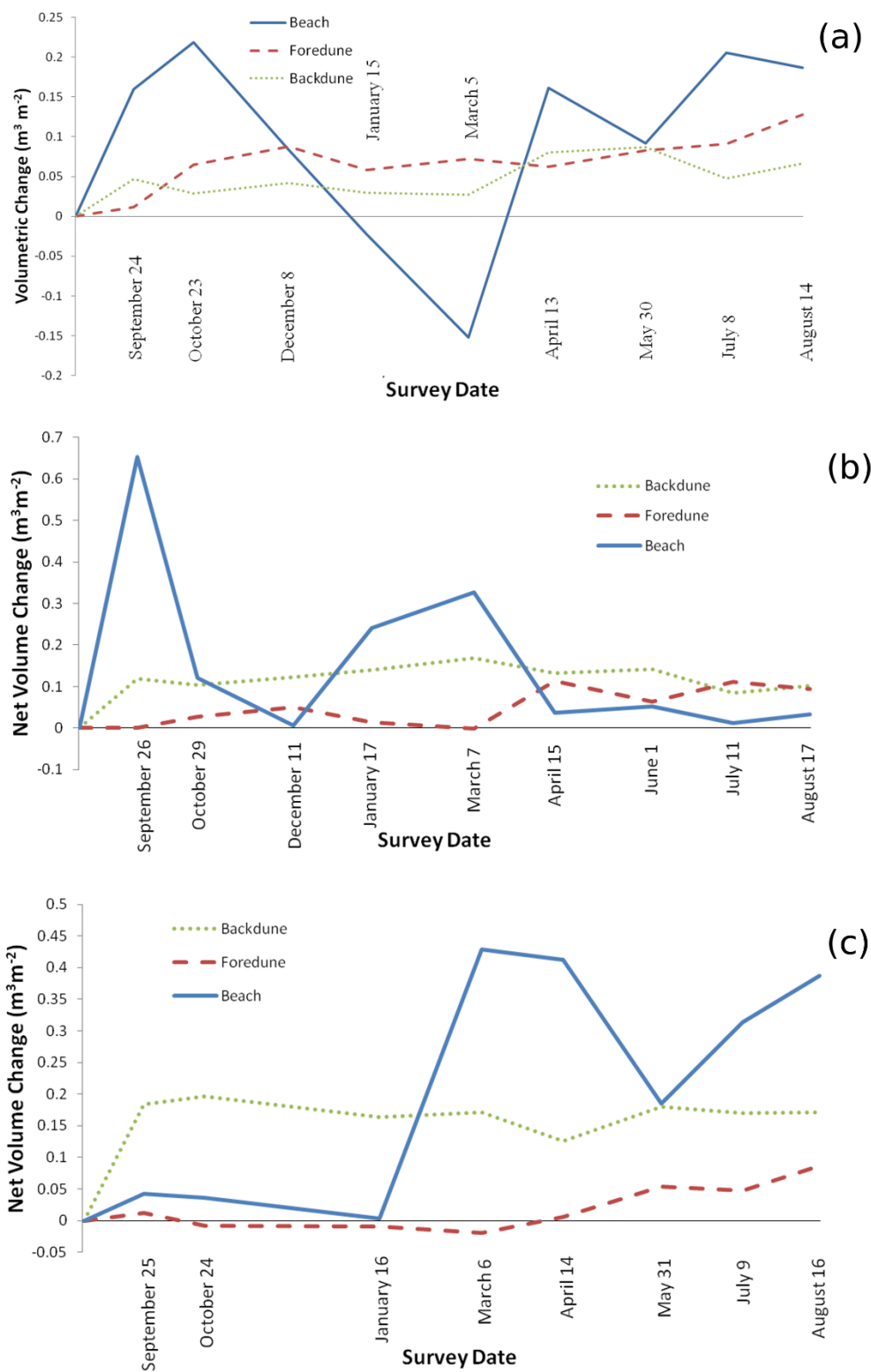


Figure 6. Area-normalized volumetric results determined to be statistically significant based on the GCD methodology described in Wheaton (2010a).

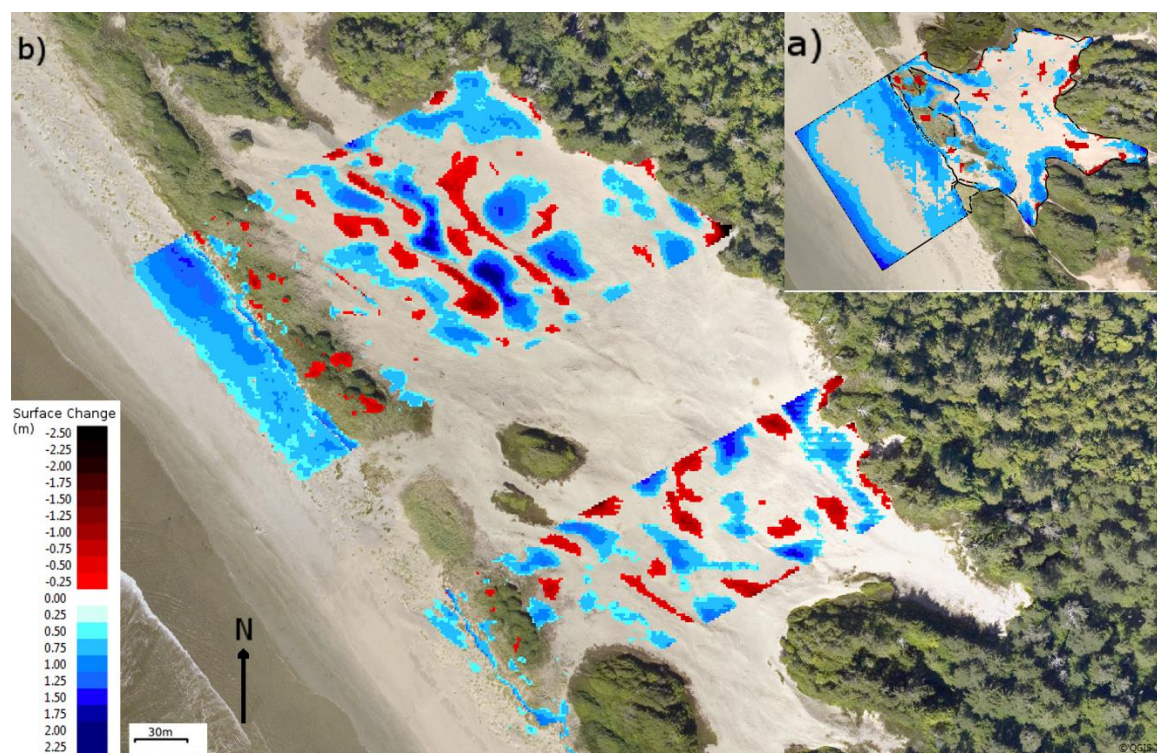


Figure 7. Statistically significant surface change detection maps for the three monitoring swaths at the end of the first year of restoration monitoring. Note that the smaller and discrete WICK1 site is inset (figure 7a) while the WICK2 and WICK3/4 site are displayed in the main image (figure 7b).

Table 2. Statistically significant sediment volume changes determined using the GCD methodology (Wheaton et al., 2010a). Area-normalized values ($\text{m}^3 \text{m}^{-2}$) provide an effective depth of average sediment accretion (+) or erosion (-) within each unit, analogous to vertical changes reported in Table 1.

	Annual net volumetric change (LiDAR baseline to August 14, 2010 survey) in m^3 and area-normalized ($\text{m}^3 \text{m}^{-2}$)		
Geomorphic Unit	WICK1	WICK2	WICK3/4
Beach	834 (0.187)	128 (0.0326)	2689 (0.387)
Foredune	200 (0.128)	191 (0.0934)	402 (0.0860)
Backdune	284 (0.0663)	1135 (0.102)	2819 (0.171)
Total	1318 (0.381)	1454 (0.228)	5910 (0.644)

Volumetric change in the beach unit of the WICK2 swath gained a maximum of $0.65 \text{ m}^3 \text{m}^{-2}$ in September. No sediment losses were observed in the beach with

reference to the LIDAR baseline but after considerable gains in September, sediment losses began in October and reached a maximum in December with only a slightly higher volume of sand, $0.006 \text{ m}^3 \text{ m}^{-2}$, observed. Net change in beach volume over the full year shows a slight gain of $0.03 \text{ m}^3 \text{ m}^{-2}$. The foredune unit of WICK2 gained a maximum of $0.11 \text{ m}^3 \text{ m}^{-2}$ for the April 2010 survey. Maximum erosional losses in the foredune were in March 2010, with a very slight loss of $-0.001 \text{ m}^3 \text{ m}^{-2}$. Net volumetric change in the foredune from the Lidar baseline to the August 2010 topographic survey shows a slight increase of $0.09 \text{ m}^3 \text{ m}^{-2}$. The transgressive dune unit of WICK2 gained a maximum of $0.17 \text{ m}^3 \text{ m}^{-2}$ in March, 190 days after the LIDAR baseline survey. No loss in volume was recorded in the transgressive dune over the one year record but the lowest gain, $0.08 \text{ m}^3 \text{ m}^{-2}$, was measured in July, 315 days after the LIDAR survey. Net volumetric change in the transgressive dune unit over the first year was $0.1 \text{ m}^3 \text{ m}^{-2}$.

In the substantially larger WICK3/4 monitoring swath the beach unit gained a maximum of $0.43 \text{ m}^3 \text{ m}^{-2}$ in March. No loss in beach sediment was observed for any of the surveys but the minimum gain in beach volume over the LIDAR baseline was $0.003 \text{ m}^3 \text{ m}^{-2}$ in January. Net change in beach volume over the first year of monitoring was $0.39 \text{ m}^3 \text{ m}^{-2}$. The foredune unit gained a maximum of $0.086 \text{ m}^3 \text{ m}^{-2}$ right at the end of the first year monitoring period in August 2010. Therefore net volumetric change in the foredune over the first year is represented by this maximum gain. The maximum loss of foredune sediment, $-0.02 \text{ m}^3 \text{ m}^{-2}$, occurred in March. The transgressive dune unit experienced a maximum gain of $0.196 \text{ m}^3 \text{ m}^{-2}$ in October, with minimum gains of $0.125 \text{ m}^3 \text{ m}^{-2}$ in April. Net change in the transgressive dune for the year shows a gain of $0.171 \text{ m}^3 \text{ m}^{-2}$.

The surface change detection maps allow for visualization of three dimensional statistically significant surface changes in the beach-dune system for one year of data following the initial restoration treatment. When the change detection map is overlaid on the pre-restoration orthophoto, as it is in Figure 7, the locations of vertical gains and losses align well with erosional and depositional components of existing landforms. As such new depositional features, associated with the restoration treatment are easily identified. This is most apparent at the WICK1 site as new depositional features form just landward of the foredune and in small areas of the transgressive dune geomorphic unit where they did not exist before. Although erosional and depositional features are captured in the change map of the WICK2 and WICK3/4 site there is no indication that new depositional features arise.

2.6 Discussion

The results presented here from the four year record of two-dimensional cross-shore topographic profiles and the one year record of detailed three-dimensional volumetric and geomorphic responses provides insight into early responses of the foredune-transgressive dune complex to mechanical removal of vegetation. The extent of restoration treatment varied between the monitoring sites and accordingly so did the morphologic responses. Photographs taken looking south and in the lee side of the foredune are provided for all 3 monitoring swaths and demonstrate the varying levels of foredune denudation and transport corridor creation (Figure 8). However, the variable responses allow for some initial conclusions regarding treatment methodology, issues of scale and system reaction times. Moreover, these contrasting responses have highlighted several indicators of favourable geomorphic responses and are used to

present a research framework for the ongoing monitoring effort. Most notably, the confirmation of control data at the WICK3/4 site based on minimal vegetation removal and an unresponsive transgressive dune geomorphic unit is a key finding to inform the ongoing project. The following section summarizes general volumetric and geomorphic responses to vegetation removal at each site and implications for ongoing restoration monitoring.

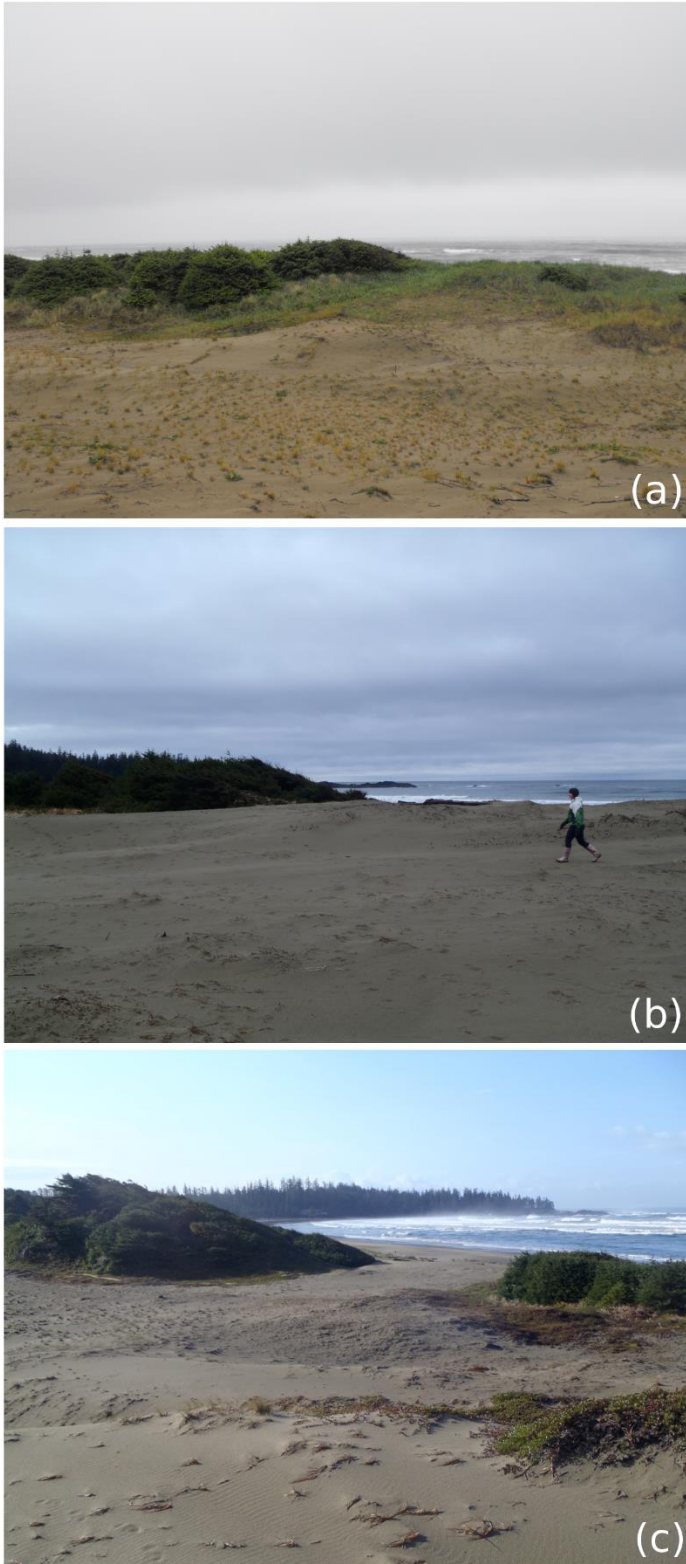


Figure 8. Photos of the lee side of the restored foredune at WICK3/4 (a), WICK1(b), and WICK2(c). Note how a complete opening of a transport corridor between the beach and transgressive dune complex that is present at WICK1 is not present at the other two sites.

2.6.1 Geomorphic and volumetric responses to vegetation removal

A detailed analysis of the WICK1 geomorphic and volumetric responses is provided in Eamer et al. (2013) but the general outcome of the first year of monitoring is nonetheless summarized here.

This WICK1 site has demonstrated the most pronounced volumetric and geomorphic responses to the first round of mechanic treatments (Figure 6a, Figure 7a). Perhaps analogous to a foredune overwash event, the near complete vegetation removal resulted in a large scale geomorphic activation. Between the August LIDAR survey and the first post vegetation removal survey in October 2009 there is some immediate volumetric change due to sediment reworking in the treatment process. However, beyond this change sediment volumes in the transgressive dune remain quite stable throughout the winter. Beginning in March 2010 drier conditions and consistent onshore wind increase aeolian activity and drive a positive mass balance in the transgressive dune geomorphic unit (Table 2) and development of new depositional features just landward of the foredune (Figure 7 a). Evidence of an expanding active sand surface has been observed where large amounts of newly accumulated sediment have transgressed onto established vegetation (Figure 9). The transgressive dune geomorphic unit at this site is bound by forest vegetation on all sides and, as such, provides a spatially discrete entity for quantifying and describing significant volumetric and morphological responses to the restoration treatment. Given that it is a smaller, discrete site that experienced complete vegetation removal there are already strong indicators of enhanced sedimentation with the associated benefits to system function.



Figure 9. Expansion of the active sand surface at WICK1 in the form of extension of a depositional lobe in the transgressive dune complex onto established vegetation downwind.

In contrast to the WICK1 site, the foredune at WICK3/4 saw minimal vegetation removal and, as such, no large pulse of sediment was driven by the dominant northwest winds into the transgressive dune in the active aeolian season following the initial treatment. The initial restoration treatment at this site is perhaps more representative of a small wave scarping event where no lasting changes to system dynamics and foredune structure are likely to result. Within the WICK3/4 monitoring swath no new depositional features are observed landward of the foredune, as they were at the WICK1 site (Figure 7). Instead there is continued lateral transfers of sediment and migration of transgressive features, i.e. parabolic dunes, which existed within the transgressive dune geomorphic unit prior to restoration activities.

Examination of the area normalized volumetric changes over the one year record (Figure 6c) shows an initial gain of $0.2 \text{ m}^3 \text{ m}^{-2}$ in the first manual survey following the LIDAR baseline and a total variability of only $0.05 \text{ m}^3 \text{ m}^{-2}$ for the remainder of the

manual surveys in the first year. Given the typically low aeolian activity of August and September it seems unlikely that such great accumulations could occur in one month. The topography of the backdune unit of the WICK3/4 swath is the most undulating of all sites (Figure 5 c and d), therefore it is likely that errors in the LIDAR generated DEM's in such a high relief environment and subsequent comparisons to manually generated DEM's is responsible for such rapid change. Ignoring this initial volumetric gain the remainder of the monitoring period shows minimal volumetric variability and no further gains. Furthermore, no indicators of active surface expansion have been observed. Examination of the cross shore monitoring transects (Figure 5 c and d) supports the idea of ongoing geomorphic change, i.e. upwind deflation and downwind deposition on the parabolic dune, unrelated to restoration activities. However, the vertical and horizontal change on a major parabolic dune between 2010 and 2011 is the most pronounced and may be an indication of the restoration response to a second round of mechanical treatment in September 2010 which completely denuded the foredune.

The WICK2 monitoring swath does not exhibit conclusive evidence of enhanced sedimentation in the first year of monitoring volumetric change but some possible indicators are emerging. Recall that a small area (20 metres) of foredune was completely denuded at this site and examination cross-shore profiles between 2009 and 2011 (Figure 5b) does indicate that vertical accretion is occurring. Vertical gains in the foredune lee are small but are most pronounced in 2011 two years after the restoration treatment (Table 1). This may suggest that reaction times to the treatment will be longer for larger sites particularly when there are no discrete shore normal boundaries and landward sediment inputs through restoration corridors may move laterally, outside of

the monitoring area. Note that a spike in the sediment volume of the transgressive dune geomorphic unit is observed in March 2010 but this gain is quickly lost as the sediment moves laterally outside of the monitoring swath. Some indications of an expanding sediment surface have been observed as newly liberated sediment is largely driven into a downwind tree island and some dieback of this vegetation is occurring.

Examination of the volumetric change time series for the WICK2 transgressive dune unit indicates an initial gain of $0.12 \text{ m}^3 \text{ m}^{-2}$ in the first manual survey following the LIDAR baseline but a total variability of only $0.05 \text{ m}^3 \text{ m}^{-2}$ for the remainder of the monitoring period (Figure 6b). Although this initial increase is less drastic than that observed for WICK3/4 it could also be indicative of problems in comparisons between the LIDAR DEM and the manually generated DEM in a high relief environment. Given the minimal variability that follows for the remainder of the monitoring period it appears that no true indication of a positive mass balance in the transgressive dune geomorphic unit is present. To summarize, the available volumetric change record and annual change map do not demonstrate a clear restoration response but the cross-shore monitoring transect from 2011 and some anecdotal evidence of surface expansion suggests that the area is beginning to respond to restoration. It would appear this site is at an intermediate stage in the restoration process between the non-responsive WICK3/4 site and the highly responsive WICK1 site.

When examining the volumetric and topographic variability in the foredune and beach units of WICK2 and WICK3/4 it is believed that this is largely governed by natural processes. Although some initial changes associated with reworking of sediment during the restoration process causes some initial variability as well. This is particularly true for

WICK2 which saw a massive gain, $0.65 \text{ m}^3 \text{ m}^{-2}$, of sediment on the beach in September but a rapid loss, $0.55 \text{ m}^3 \text{ m}^{-2}$, in the subsequent October survey (Figure 6b). As with WICK1 variability in beach volumes can also largely be attributed to seasonal changes in beach steepness and ongoing migration of beach cusps. Although foredune gains are comparable across all sites, only WICK1, demonstrates a consistent trend of accretion for the monitoring record (Figure 6). This is not surprising as complete denudation at the WICK1 site caused considerable reworking of sediment and foredune rebuilding was observed (Eamer et al., 2013).

2.6.2 Implications for ongoing research and restoration monitoring

Recent research has highlighted the importance of aeolian sediment transport and geomorphic processes in dune restoration efforts seeking to increase system dynamism and restore lost ecosystem services. Based on the monitoring results collected in the first year following restoration treatments, several easily identifiable indicators of favourable geomorphic processes and improved system dynamics have been established. The contrasting observations from the discrete WICK1 site versus the larger WICK2 and WICK3/4 sites in the open transgressive system supports the use of these indicators given that several of the criteria are already being met at WICK1. Thus, five key indicators of increased dynamism and enhanced morphodynamics are defined as follows:

- 1) A positive mass balance in the transgressive dune geomorphic unit.
- 2) Increased variability in the sediment mass exchange within, and between, geomorphic units.

- 3) Greater geomorphic diversity and accelerated evolution in landscape features, i.e., adjustments in form or fragmentation of the foredune, blowout development, extension of parabolic dunes, and creation of new depositional landforms.
- 4) An increase in the total area of mobile sediment available for deflation by wind.
- 5) An increase in levels of aeolian sediment transport in the transgressive dune geomorphic unit.

Preliminary data to relate to these indicators has been presented but the ongoing record is critical to assess the longer term response and perhaps success of the restoration effort. Most notably, the scheduled 3 year record of geomorphic and volumetric change will provide a better assessment of the response of the system to vegetation removal. Alterations to the sediment mass exchange between, and within, geomorphic units as well as landscape scale morphologic impacts will be more evident when examining the system on a multi-year scale. This is particularly important for the WICK3/4 site, which given the minimal vegetation removal in the first round of restoration treatments, has been identified as a control site and provides a one year record of pre-restoration geomorphic change rates and sedimentation trends. Additional monitoring data, primarily focusing on vegetative changes and meteorological conditions, will be available for the second and third year of monitoring to complement the ongoing record of geomorphic change from the topographic surveys.

2.6.3 Future research and restoration monitoring

Subsequent mechanical treatments to the foredune will occur in September 2010 and September 2011 completing the intended 300 m extent of vegetation removal

designated by PCA. However, the monitoring program for the dune restoration effort is still expanding, topographic surveys have been ongoing and research activities will continue until August 2013.

In order to assess increases in active sedimentation and gather a more complete understanding of the landscape scale morphologic and ecologic responses a follow up DEM and high resolution digital orthophoto mosaic will be generated from a second airborne LIDAR survey, scheduled for September 2012. Moreover, in June 2010 a meteorological station was installed in the transgressive dune of the WICK3/4 site collecting a continuous record of wind speed and direction, atmospheric pressure, temperature, precipitation and sediment transport (from an in-situ saltation probe). The LIDAR DEM's and orthophotographs will provide several comparative parameters for assessing the overall system response and the meteorological data adds context to the geomorphic monitoring by accounting for year to year variation in conditions which influence aeolian activity.

Of course, given that the plant system, and biogeomorphic feedbacks between landforms and vegetation, will greatly influence the longer term response of the system to vegetation removal it is too early to draw conclusions on the overall system response. Therefore, future analysis will utilise the digital orthophotography, hyperspectral data sets and photogrammetry applications to gather additional ecological data and aid in determining the overall system response. Throughout the monitoring record of the current study the treated areas of foredune remained largely denuded and the untreated areas remained heavily covered primarily with Marram grass (*Ammophila spp.*), Sitka Spruce (*Picea sitchensis*) and Kinnikinnick (*Arctostaphylos uva-ursi*).

Based on analysis of monitoring data at Wickaninnish some recommendations for future restoration treatments utilising mechanical removal methods can be made. Firstly, the spatial extent of vegetation mechanically removed should be sufficient to allow for a complete transport corridor into a landward transgressive complex. Moreover, in open transgressive systems subject to lateral transfers, removal needs to occur over a sufficient alongshore extent to allow for lag times in sediment accumulation and a greater area of dispersal, i.e. longer reaction times (as per Allen, 1974).

Secondly, there needs to be ample consideration for the direction of dominant transporting winds. If vegetation removal cannot be conducted over large and continuous stretches of foredune, as with a 'process management' approach (Riksen et al., 2006), the most strategic discrete location should be identified to maximize sediment delivery into the transgressive system, i.e. a 'pattern management' approach (Riksen et al., 2006) should be employed. At Wickaninnish, for example, a small portion of foredune was denuded within the WICK2 monitoring swath in September 2009. However, the location of this denuded area was at the southern end of the monitoring swath and with respect to the northwest winds of the dry spring and summer seasons a large tree island was immediately downwind of the denuded section. As such landward sediment delivery from the beach and foredune was largely directed into an adjacent tree island and minimal benefits resulted from this vegetation removal.

Finally, based on the monitoring results following the first round of restoration it appears that removal of incipient vegetation or partial removal of foredune vegetation is ineffective for stimulating active sedimentation and the associated benefits to system function unless repeat treatments, clearing the remainder of the foredune, follow

promptly. Foredune recovery from mechanical or natural disturbance occurs rapidly (Eamer and Walker, 2010; Heathfield and Walker, 2011) as does vegetation re-growth, this is particularly true for *Ammophila* (Wiedemann and Pickart, 1996; Hesp, 2002), and therefore it may be better to avoid treatment all together until complete denudation is possible. Thus when faced with time or budgetary constraints a pattern management approach is better suited as the most strategic area, however small, can be selected for complete denudation and will maximize aeolian delivery of sediments into the transgressive dune.

2.7 Conclusions

This paper has provided a discussion on specific geomorphic monitoring considerations for coastal dune restoration projects which seek to create a more dynamic and resilient biogeomorphic system. An ongoing dynamic restoration case study has been introduced and preliminary results obtained over the first year of restoration monitoring have been presented. The small and discrete WICK1 monitoring site was the only site to experience complete vegetation removal and exhibits a direct restoration response. In contrast, the WICK2 and WICK3/4 sites, which are situated within a larger and more open transgressive dune complex, experienced less of a vegetation disturbance and are yet to demonstrate a clear restoration response.

Although preliminary, the results have nonetheless been useful in identifying a control site for the project and specific indicators of favourable geomorphic responses which may act to enhance system dynamism in the long term. Based on these results, a research framework for monitoring the restoration effort has been developed and it is grounded in current geomorphic understanding. Finally, some insights into treatment

methodologies have been gained and future dune restoration projects of this type can draw from this experience to maximize benefits of vegetation removal.

3.0 Beach-dune sediment budgets and dune morphodynamics following coastal dune restoration, Wickaninnish Dunes, Canada

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3.1 Abstract

The results from three years of surveying and monitoring a dynamic foredune and dunefield restoration effort on Vancouver Island, Canada is presented. Complete removal of foredune vegetation occurred in three phases spaced a year apart in an effort to control invasive *Ammophila spp.* The collection of airborne LIDAR, orthophotographs, and bi-monthly topographic surveys provided a means to quantify and examine sediment budgets and geomorphic responses. Three survey swaths, corresponding with each phase of vegetation removal, were established to provide detailed topographic coverage over the impacted beach, foredune, and dunefield landscape units. The swath corresponding with the first phase of removal recorded a positive sediment budget of $1.3 \text{ m}^3 \text{ m}^{-2}$ after 3 years. A control swath, with data collected for a year prior and two years following removal, exhibited a distinct pulse of sediment delivery into the dunefield unit with a maximum gain of $0.03 \text{ m}^3 \text{ m}^{-2}$ pre-removal compared to $0.11 \text{ m}^3 \text{ m}^{-2}$ post-removal. Vegetation analysis zones, associated with each of the three swaths, demonstrate a range of vegetation responses due to variation in the vegetation removal and subsequent re-invasion or removal methods employed. The first site to be cleared of vegetation, received ongoing invasive re-growth control, and three years following removal vegetation cover dropped from 57% in 2009 to 13% in 2012 (-44%). An adjacent site was cleared of vegetation two years later (only 1 year of

recovery) but experienced rapid *Ammophila* re-invasion and percent cover changed from from 61% in 2009 to 26% in 2012 (-35%). The data presented provides insights for improving the application of sediment budget monitoring in dynamic restorations and discusses the potential for detailed spatial-temporal survey data to improve our understanding of meso-scale landscape morphodynamics following foredune disturbance. Overall, the vegetation removal treatments reduced the extent of invasive grass and increased dunefield mobility and dynamic activity.

3.2 Introduction

Dynamic restorations seeking to reactivate stabilising coastal dunefields are on the rise. Most common on both developed and undeveloped coasts of temperate regions, they are frequently driven by the need to control or eliminate invasive species. Recent research examining restoration approaches in a variety of habitats note that the re-establishment of ecosystem processes and flows of material and energy in dynamic systems may be a more important indicator of ecological resilience across scales, rather than fixed or target states (e.g., Conroy et al., 2003; Nordstrom, 2008; Murray et al., 2009; Beetchie et al., 2010; Martinez et al., 2013). Moreover, newer research in coastal dune environments highlights the importance of beach-dune sediment budgets and foredune dynamics in allowing sandy coasts to gradually adapt to rising sea-levels (e.g. Davidson-Arnott, 2005; Arens et al. 2013; Keijsers et al. 2015). In response, there has been increased consideration of geomorphic processes in dune ecosystems and restoration objectives now stress the need for dynamic, often unpredictable, behaviour in restored habitats (e.g., Nordstrom, 2008; Feagin et al., 2005, 2010). Such 'dynamic' dune restoration efforts are commonly associated with efforts to protect rare or

threatened species (e.g., Pye et al., 2014; De Raeve, 1989; Pickart and Sawyer, 1998; Pickart, 2013; Doody, 2001, 2013; Arens et al., 2001; 2004; 2005; 2006; 2013; Grootjans et al., 2001; 2002; 2013; Zarnetske, 2012; Martinez et al., 2013). In North America's Pacific Northwest, the introduction and subsequent spread of the invasive grass, *Ammophila arenaria* (aka European beachgrass or marram), has provided an impetus for such dynamic restorations. The rapid naturalisation and spread of the species has been well documented in the region and elsewhere (Cooper, 1958; Buell et al., 1995; Wiedemann and Pickart, 1996; Lubke and Hertling, 2001; Hilton et al., 2005, 2006; Doody, 2013, Konlechner, 2009; Hayes and Kirkpatrick, 2012; Seabloom et al., 2013). Research in recent decades indicates significant ecological and morphological impacts following its introduction, primarily an accelerated vegetation stabilisation of sandy areas and foredune building. This is mostly an issue for coastal dunes in temperate latitudes such as in North America's Pacific Northwest (e.g., Seabloom and Wiedemann, 1994; Wiedemann and Pickart, 1996, 2004; Wiedemann, 1998; Zarnetske et al., 2010; Seabloom et al., 2013), and New Zealand (e.g. Hilton et al., 2005; Hesp and Hilton, 2013).

Interactions between airflow, sediment transfers, and vegetation that drive landform and habitat dynamics within coastal dunes have been the topic of recent dune restoration literature (e.g., Zarnetske et al., 2012; Petersen et al., 2011; Martinez et al., 2013, Nordstrom, 2008; van Boxel, 1999). A group of recent studies in the Netherlands (eg. Arens et al., 2013; Grootjans 2013;) and more recently in New Zealand (Hesp and Hilton, 2013; Konlechner et al., 2014, 2015) and the USA (Pickart et al., 2013; Seabloom et al., 2013) have examined changes to vegetation coverage and large scale

erosion/deposition patterns as well as vulnerabilities to wave overtopping. However, few studies have quantified or monitored sediment budget responses and related morphodynamics within coastal beach-dune systems following restoration actions. Often, such research lacks detailed and/or frequent topographic surveying datasets to examine sediment budgets and morphodynamic responses and, more generally, to characterise meso-scale beach-dune interactions (e.g. Sherman and Bauer, 1993; Delgado-Fernandez and Davidson Arnott, 2011). Calculations of sediment budgets are a key approach for meso-scale inquiry, which involves quantifying the balance of sediment added to or removed from various components of the beach-dune system including sediment inputs (sources) and outputs (sinks) within and between landscape units (i.e., beach, foredune, dunefield). Many studies have conceptualised coastal sediment budgets, but without quantifying volumes (e.g. Bowen and Inman, 1966; Komar, 1976; Bray and Hooke, 1995; Cooper and Pethick, 2005) and others have attempted to estimate volumes indirectly based on cross-shore profiles (e.g. Davidson-Arnott and Law, 1996; Arens, 1996; Arens, 2013, Ollerhead et al., 2013). Broader sediment budget approaches, using true volumes, have been more commonly applied to river restoration efforts to assess physical habitat changes (e.g., Jacobson et al., 2009; Merz et al., 2006; Kondolf, 2000). These studies demonstrate the importance of capturing linked components of the geomorphic system at both the reach and watershed scale.

In addition, the detailed surveying needed to monitor sediment budgets at the landform to landscape scale generates rich geospatial data that can be used for 3-D visualisations, which improve landscape interpretation, mapping and analysis (Mitasova

et al., 2012). Repeat surveys used to estimate sediment budgets include a temporal dimension that extends interpretation into a fuller spatial-temporal (4-D) domain, thereby improving our ability to more effectively detect morphodynamic changes related to sediment budget responses (James et al., 2012). Results presented here are interpreted as a means to explore restoration responses at the often overlooked meso-scale, and to provide preliminary data from which to explore a more complete morphodynamic assessment of the Wickaninnish beach-dune system.

This paper presents results from 3 years of geomorphic monitoring and sediment budget (volumetric change) analysis following removal of invasive *Ammophila* spp. in an effort to restore dynamic habitat for native and endangered species within a coastal foredune and transgressive dune system on the west coast of Vancouver Island, British Columbia, Canada. Details of the restoration objectives, rationale and methods are outlined in Chapter 2, see Darke et al. (2013) which reviewed preliminary data, guiding the current study and informing the ongoing restoration project. The criteria for assessing restoration effectiveness was presented in Walker et al. (2013), which defined six key indicators of geomorphic effectiveness including: 1) increased aeolian activity (sand transport, erosion, deposition), 2) enlarged active sand surface areas, 3) a positive sediment budget, 4) increased dune morphodynamics, 5) improved geomorphic diversity, and 6) enhanced geomorphic resilience. The current study implements these criteria using data collected from a 3-year period of topographic surveys and evaluates seasonal to interannual landscape morphodynamics and sediment budget responses as a means to assess project effectiveness. The specific research objectives include:

- 1) To identify landscape (meso-scale) morphodynamic changes recorded from repeat topographic surveys over a three-year observation period and compare interpretations derived from traditional 2-D cross-shore profiles vs 3-D digital elevation models (DEMs);
- 2) To quantify and interpret sediment budget responses from three separate study swaths that capture 3-D sediment exchanges between linked beach, foredune and transgressive dunefield landscape units;
- 3) To explore the potential for meso-scale topographic survey data to improve understanding of beach-dune interactions.
- 4) To assess the geomorphic effectiveness of the implemented restoration treatment against pre-determined success indicators.

3.3 Regional Setting

The study area is located within Pacific Rim National Park Reserve near the village of Ucluelet on the west coast of Vancouver Island, British Columbia, Canada (Figure 10). Wickaninnish Beach is an intermediate, meso-tidal beach with longshore bar and trough morphology (per Wright and Short, 1984) located at the south end of the 10 km long Wickaninnish Bay with a southwest aspect to the open Pacific Ocean (Figure 11). An established foredune ridge exists along most of the shoreline of Wickaninnish Bay and several areas are backed by small transgressive dunefields, such as the Wickaninnish Dunes complex. The Cascadia Subduction Zone is located just offshore of Vancouver Island and, as a result, the study area experiences tectonic uplift and a net drop in relative sea level of approximately -0.9 mm a^{-1} (Wolynec 2004; Mazzotti et al. 2008). This, combined with a high onshore sand supply, assists in dune

building and shoreline progradation rates approaching 1 m a^{-1} in the study area (Beaugrand, 2010; Heathfield and Walker, 2011).

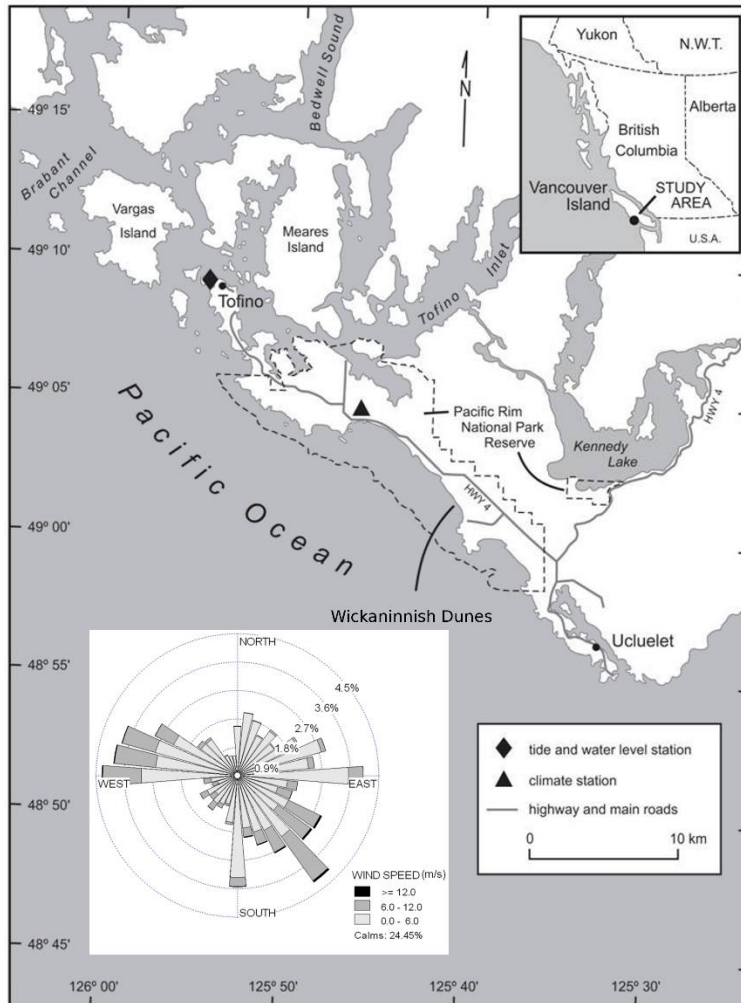


Figure 10. The Wickaninnish dunes study site on the west coast of Vancouver Island, Canada with annual wind rose inset.

The wind regime in the region is highly competent and seasonally bimodal (see Figure 10, Beaugrand, 2010), which allows for active foredune building and some mobility of landward transgressive dunes. The dominant mode in the regime is from the SE and is typically associated with intense winter storms with high precipitation. The alignment and geomorphology of erosional blowouts and depositional lobes within the dune complex, however, suggests a dominant transport vector from the WNW, which

aligns closely with the secondary (summer) mode in the wind regime (Figures 10 and 11). Beaches in the study area experience a seasonally variable, energetic wave regime and beach erosion and foredune scarping occur frequently with approximately 2.8 erosive events per year (Heathfield et al., 2013). Despite this erosive activity, dune rebuilding from sand ramp development and incipient dune growth, often in the presence of large woody debris, occurs rapidly (Heathfield and Walker, 2011; Heathfield et al. 2013).

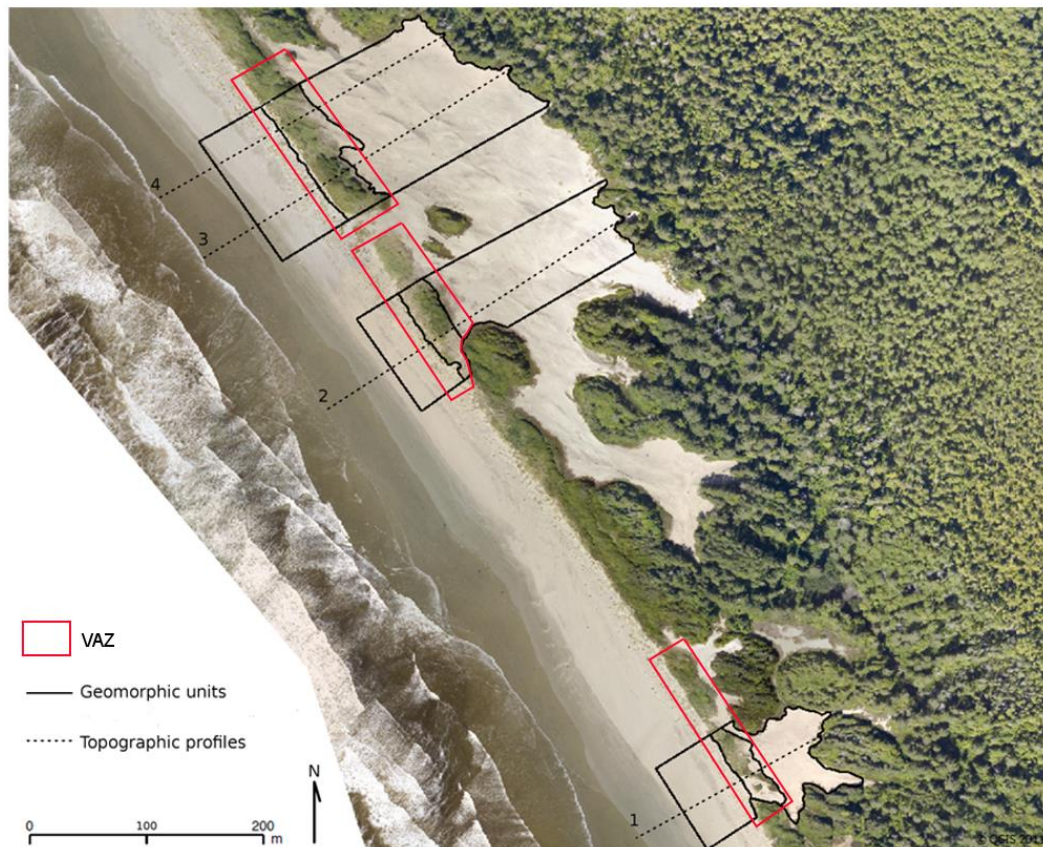


Figure 11. The locations of the four cross-shore profiles: WICK 1-4, the three corresponding topographic monitoring swaths separated by landscape unit: WICK1, WICK2 and WICK3/4, and the three corresponding vegetation analysis zones (VAZ's) indicated by the red boxes. The WICK1 site was cleared of vegetation in September 2009, WICK3/4 in October 2010, and WICK2 in October 2011.

At this study site, *Ammophila* spp. (*A. breviligulata* and *A. arenaria*) has displaced the native foredune plant community, which is dominated by dune wildrye

grass (*Elymus mollis*) and includes a variety of other pioneer species of conservation interest, including Grey beach pea vine (*Lathyrus littoralis*, provincially listed) and Pink sand verbena (*Abronia umbellata* var *breviflora*), which is red-listed in the Canadian Species at Risk Act (SARA) (Page et al., 2011). Since the early 1970s, there has been a rapid decline in active sand surface area (-28% from 1973 to 2007, Heathfield and Walker, 2011). It is believed that dense *Ammophila* spp. (primarily *A. arenaria*) colonization of the foredune has reduced sand supply to such a degree that aeolian processes are only operating locally within the landward transgressive dunefield, resulting in accelerated vegetation stabilisation. Although a detailed account of pre-invasion conditions is unavailable for this site, previous work in the Pacific Northwest region (e.g., Cooper, 1958; Buell et al., 1995; Wiedemann and Pickart, 1996; Wiedemann, 1998; Pickart, 2013) and in other temperate dune systems in the world (e.g., New Zealand, see Hilton, 2005; Hesp and Hilton, 2013; Konlechner, 2015) provide analogous case studies to aid in understanding the pre-invasion landscape.

3.4 Methods

3.4.1 Topographic data and orthophotography

One year prior to restoration activities at the site, four cross-shore topographic monitoring profiles were established there for unrelated coastal erosion monitoring in the region (Figure 11). These were surveyed annually during summer low tides between August 2008 and July 2012. This five year record from the profiles provides some limited data on landscape change in the years leading up to foredune vegetation removal. More importantly, the geomorphic responses interpreted from these traditional 2-D profiles were contrasted against interpretations derived from detailed 3-D DEMs

(described below). Each profile extends from the lower beach to the top of the precipitation ridge backing the transgressive dune complex with locations spread evenly throughout the designated restoration area.

The restoration driven monitoring began when a bare earth DEM base map of the entire Wickaninnish Dunes system was derived from airborne LIDAR flown on August 27, 2009, just prior to the initial vegetation removal treatment in September 2009. Following this, three survey swaths, associated with each phase of mechanical removal, were established to extend coverage approximately 50 m on either side of the pre-existing cross-shore profiles. The largest swath, WICK3/4 (28 072 m²), was established around two profiles (WICK3 and WICK4), while smaller swaths WICK2 (17 081 m²) and WICK1 (10 320 m²) encompassed only their respective monitoring profiles (Figure 11). Surveying of these swaths was completed in order to monitor sediment budget and morphodynamic responses associated with the restoration program and began just following the first round of mechanical vegetation removal in September 2009. These were surveyed approximately bi-monthly until February 2012 and amounted to twenty surveys in total. Combined, the three swaths cover 55 473 m² of the dune complex. Each swath was separated into three linked landscape units: beach, foredune, and transgressive dunefield, with the intention of monitoring and interpreting how sediment moved through the various components of the landscape. The transgressive dunefield landscape unit in the WICK3/4 swath was identified as a control site given that the timing of vegetation removal allowed for monitoring to occur for a year prior to the clearing of foredune vegetation and two years following. As such the foredune remained a net sink for beach sediments during the first year of monitoring as

confirmed in Darke et al. (2013).

To complete the monitoring a final DEM was generated from a second airborne LIDAR flight on September 17, 2012. Survey point densities on the LIDAR surveys were 1.13 points m^{-2} . In comparison, survey point densities on all manual surveys varied between 0.04 and 0.13 points m^{-2} . Some improvement was achieved in the second and third years of monitoring by using an RTK DGPS that, given the increased speed at which survey points were collected, allowed for higher density surveys. Digital orthophoto mosaics of the study site were also captured simultaneously with each LIDAR survey and provide a high-resolution aerial view of the dune system prior to, and following, restoration treatments (Figures 15 and 16). These digital snapshots were primarily used to calculate changes in vegetation cover (described below) but were important for the overall examination of landscape changes.

3.4.2 Geomorphic and volumetric change detection

To assess changes in geomorphology and sediment budgets, DEMs derived from both the 20 manual survey datasets and the two LIDAR flights were compared using a vertical change detection method, described below. Essentially, each interval DEM from the swaths was compared against the initial (pre-restoration) LIDAR DEM. Related research has explored novel techniques for DEM generation and change detection (see Eamer et al., 2013; Eamer and Walker, 2013; Walker et al., 2013). For this study, a simplified approach was adopted for repeatability across datasets of varying point density. The method involved standard kriging of all survey data and a more conservative and consistent assignment of error in all change detection

calculations. Accordingly, the magnitude of change is likely under-estimated, but the variability across the volumetric change time series may be viewed with confidence. Additionally, the aforementioned research generated DEMs and interpolated survey data on a landscape unit basis, adjusting the variogram model based on the unique geostatistical signature within each unit (Eamer et al., 2013). In the current study, however, the interpolation process was held constant and extended several metres beyond the boundaries of the survey swaths so as to avoid observed edge effects.

Each survey dataset was gridded into raster format using linear kriging in the 3-D mapping software, Surfer™ (v. 8.01), and cropped to match the landscape units defined for each monitoring swath (Figure 11). Next, volumetric changes were calculated on a landscape unit basis using the Geomorphic Change Detection (GCD) software (Wheaton et al., 2010), which identifies statistically significant surface elevation changes, calculates associated volumetric changes, and quantifies associated errors. In addition, the software also generates DEMs of Difference (DoDs). GCD assessment runs were conducted on all survey intervals within defined landscape units, and two final GCD runs (WICK1 and surrounding area, WICK2-3/4 and surrounding area) were completed using the two larger LIDAR surveys (August 2009, September 2012) only. This was completed using the same GCD parameters but, given the greater extent of the LIDAR DEMs, cropping was completed using larger polygons capturing more of the landscape. The DoDs provided from these final GCD runs of the entire landscape provided good landscape scale visualisations of erosion and deposition patterns. Furthermore, survey data collected within a subsection of the WICK3/4 survey swath was used to generate a series of 3-D surface visualisations using the Surfer™

software. The surfaces provided a visual record of changes within an isolated area that were compared against changes recorded in the DoDs and cross-shore profiles.

All GCD simulations were conducted using a 95% confidence level threshold with a uniform vertical DEM error of 15 cm for the LIDAR surveys (per stated maximum error in related data acquisition reports) and 5 cm for all manual surveys (stated maximum errors for the total station and RTK instruments used were 0.5 cm and 2 cm respectively). Closing errors on manual surveys ranged from 0.2 cm to 2.1 cm and, therefore, the combined maximum instrument error and maximum closing error resulted in a value within the limits of the selected 5 cm error value.

3.4.3 Meteorological data and sediment transport thresholds

To provide an environmental context for the interval survey data, precipitation and 12-hour daily wind records were obtained from Environment Canada's Tofino airport weather station (ID number: 1038204), located approximately 9km from the study site. Total monthly precipitation was calculated by summing the daily totals over the 3 years from archived records. The threshold velocity for aeolian sediment transport was calculated using Bagnold's (1941) formula:

$$u_{*t} = A \sqrt{\frac{(\rho_p - \rho_a)gd}{\rho_a}} \quad (1)$$

where A is an empirical coefficient (0.08 for impact threshold); ρ_p is the density of quartz sand particles ($2.65 \times 10^3 \text{ kg m}^{-3}$); ρ_a is air density (1.22 kg m^{-3}); g is gravitational acceleration (9.81 m s^{-2}); and d is mean sand grain diameter at the study site ($1.74 \times 10^{-4} \text{ m}$). The resulting threshold velocity was estimated to be 0.154 m s^{-1} and, to relate it

to the elevation of the wind measurements ($Z = 10$ m), the threshold normal velocity $V_{t(z)}$ was determined using the method of Hsu (1974):

$$V_{t(z)} = \frac{u_*^*}{k} \ln\left(\frac{Z}{Z_0}\right) \quad \text{if } Z > Z_0 \quad (2)$$

Where $V_{t(z)}$ is impact threshold normal velocity at height Z (10 m); U_*^* is impact threshold shear velocity from Eq. 1 (0.154 m s^{-1}); k is von Karman's constant (0.4); Z_0 is a roughness coefficient ($5.82 \times 10^{-6} \text{ m}$) equivalent to $d/30$. From this, the calculated threshold normal velocity in the study region was approximately 5.53 m s^{-1} .

3.4.4 Vegetation Removal

The strategy developed by Parks Canada Agency for improving habitat at the Wickaninnish Dunes site was to remove *Ammophila spp.* and any established late-successional species from the foredune so as to improve and expand favourable dynamic habitat for Pink sand verbena. The restoration treatment involved three phases of mechanical removal to clear the foredune of vegetation followed by targeted hand pulling to limit re-growth. These three phases of removal were spaced along the foredune and corresponded with each of the three survey swaths described above (WICK 1, 2, and 3/4). WICK 1 was treated in September 2009, WICK3/4 was cleared second in October 2010, and WICK2 was cleared last in October 2011 (Figure 11). Mechanical removal was completed with a backhoe and an excavator as well as controlled burning of small trees and bushes (Figure 12). Hand pulling of *Ammophila* regrowth, primarily at the WICK1 site, was undertaken by PCA staff and volunteers sporadically throughout the five-year period of study, and efforts continue on an ad-hoc basis.



Figure 12. Photograph depicting the mechanical removal of foredune vegetation at the study site.

3.4.5 Vegetation Analysis Zones

Figure 11 indicates the location of three separate vegetation analysis zones (VAZs) used for assessing vegetation changes to the foredune region associated with each monitoring swath. These were spaced along the foredune in conjunction with their respective topographic survey swaths. Analysis within these zones is limited to a simple vegetation presence/absence assessment between the pre- and post-restoration orthophotographs. This was completed using a standard supervised classification calculation in QGIS. Training sites were easily identified within each VAZ to distinguish between active sand surface area and vegetated surface area and the percentage of vegetation cover within each VAZ was calculated from both August 2009 and September 2012 orthophotographs.

3.5 Results

3.5.1 Cross-Shore Topographic Profiles

Topographic change data from the four 2-D cross-shore monitoring profiles (Figure 11) over the five year period of observation are shown in Figure 13. The WICK1 and WICK2 profiles demonstrate an overall accumulation of sediment while the more northern profiles, WICK3 and WICK4, are more variable with substantial areas of sediment loss and/or bypassing. Sediment loss landward of the foredune on these more northern profiles primarily reflects the presence of erosional deflation surfaces associated with migrating parabolic dunes and blowouts in this area of the dunefield. At these sites, some lateral movement of sediment across the shore-normal profiles occurs within the transgressive dunes.

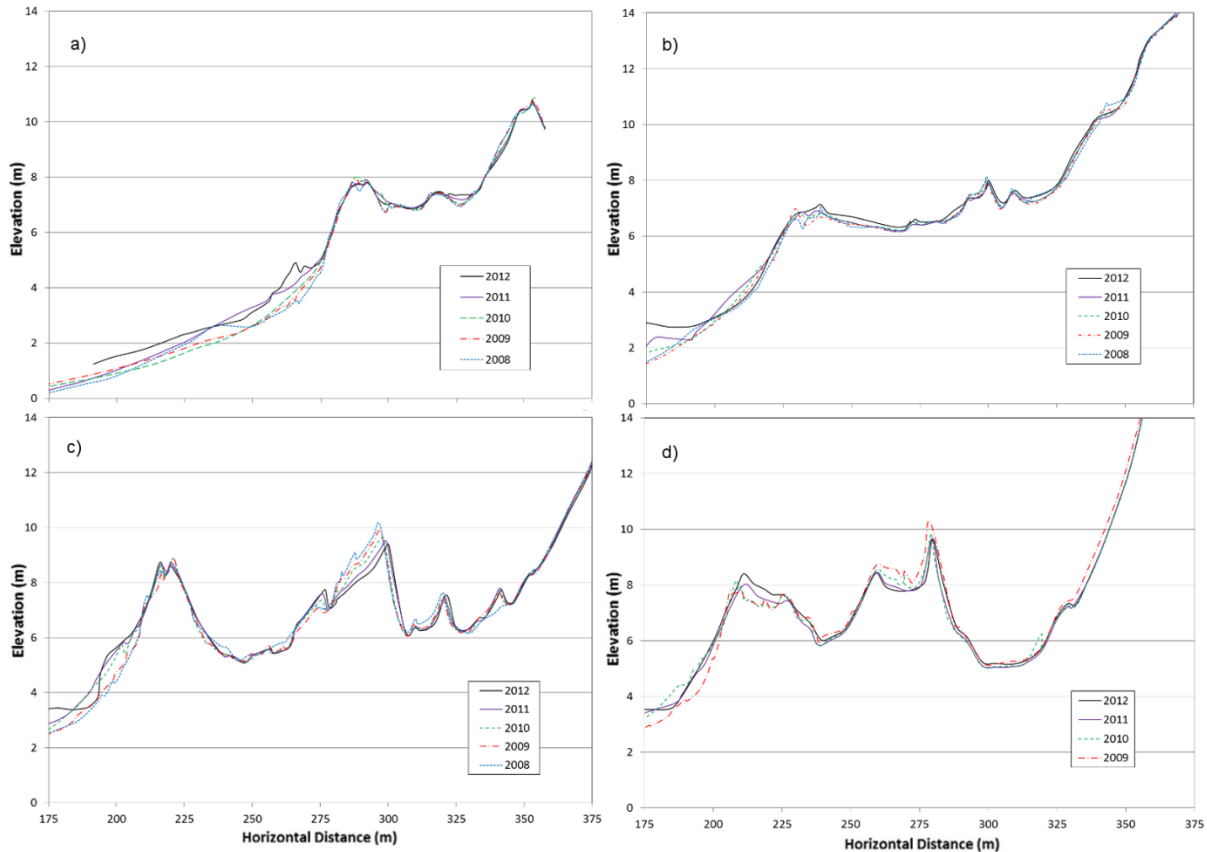


Figure 13. Annually surveyed cross-shore profiles: a) WICK1, b) WICK2, c) WICK3, and d) WICK4.

At the WICK1 site the foredune crest shifts landward by approximately 3 m, is reduced in height by 0.2 m, and accumulations at the base of the precipitation ridge are 0.5 m. At the WICK2 site the crest shifts landward by approximately 8 m and increases in height by 0.3 m. Accumulations at the base of the precipitation ridge are minimal (approximately 0.1 m) but the swale in the lee of the foredune experiences a vertical gain of approximately 0.3 m consistently over a 15 m distance landward of the foredune. The WICK3 profile demonstrates little change in foredune morphology but landward shows consistent lowering of a parabolic dune deflation basin by approximately 1 m over the study period and a landward shift of the corresponding depositional lobe of

approximately 2 m, mostly within the first year following foredune vegetation removal. Finally, the WICK4 profile demonstrates approximately 1 m of vertical growth on the foredune and approximately 1 m of lowering in the deflation basin of a landward parabolic dune, but the remaining areas of the profile show minimal change.

In general terms, the profiles indicate a landward shift of the foredune crest and ongoing growth of the incipient foredune and upper backshore in response to the ample sediment supply to the beach and competent wind regime for aeolian transport. Changes landward of the foredune appear to reflect the ongoing migration of transgressive dune features as well as considerable accumulations of new sediment in depositional lobes and transverse dunes. Of course, the timing of vegetation removal strongly influenced the observed responses. For example, at the WICK1 site (Figure 13a), sediment accumulates immediately landward of the foredune in the first two years following treatment. In the third year, however, deposition migrates away from the foredune with observed increases in accumulation at the landward extent of the profile. The WICK2 site (Figure 13b), in contrast, was the last to experience complete removal of vegetation and sediment accumulation immediately landward of the foredune was still observed in the final 2012 profile.

3.5.2 Three dimensional surfaces and DEMs of Difference (DODs)

As a supplement to the WICK3 and WICK4 cross-shore profiles, a sequence of 3-D surfaces are provided (Figure 14) that captures a key portion of beach, foredune and landward transgressive dunes within in the broader WICK3/4 survey swath. These DEMs provide a more detailed visualization of foredune and dunefield morphological changes throughout the study period. For example, the 3-D surfaces and 4-D DODs

better capture and visualize the overall flattening of the foredune crest, that was not observed to the same degree in the 2-D profiles, which miss prominent peaks along the foredune ridge that were subsequently flattened during the mechanical vegetation removal. Interpretation of the cross-shore profiles alone indicate only slight crestal rounding and/or landward extension (e.g., Fig. 13 a, b, d) and migration of the parabolic dunes. Furthermore, the 3-D surfaces and DODs confirm that trailing ridges, blowouts and parabolic dunes rapidly accumulate sediment and migrate in the dominant southeasterly direction following mechanical clearing of foredune vegetation.

Figures 15 and 16 provide broader landscape scale change (DOD) maps and vantage photos of responses within the northern WICK 2, 3/4 sites and smaller southern WICK 1 site, respectively, as derived from change detection of the LiDAR DEMs between August 2009 and September 2012. Select photographs are indicated within the landscape and a vertical change scale is provided with red hues indicating erosion and blue hues indicating deposition. These additional maps present a broad overview of landscape change to help situate the sediment budget records captured within them. Heavy machinery activity at these sites resulted in a general flattening of the foredune crest and landward extension of the foredune (Figures 14, 15, 16, and 19). A new blowout, partially initiated by heavy machinery, with a corresponding depositional lobe extending from it (Figure 15a and 15d) developed towards the north end of the WICK3/4 foredune. Along the southeastern margins of the transgressive dunefield, localized erosion was evident along steep seaward facing slopes of the precipitation ridge, rapid migration of a prominent transverse dune occurred, and significant accumulations of sand at the forest margins was also clearly visible in the DODs.

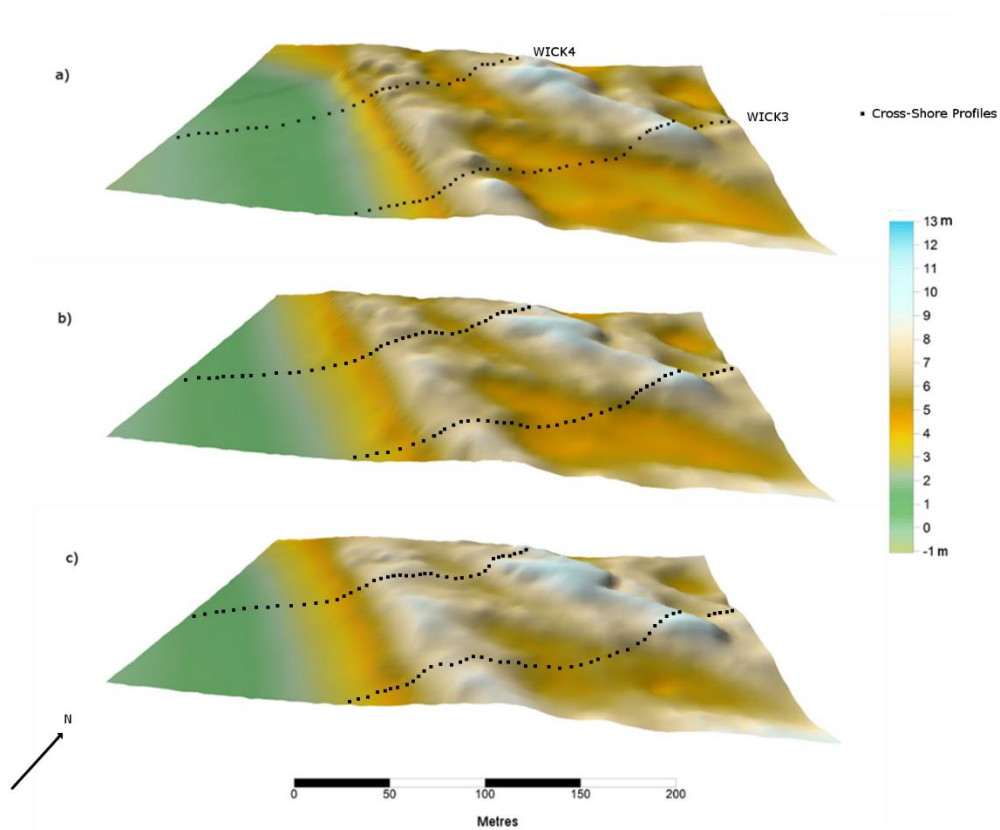


Figure 14. A sequence of 3-D surfaces generated from three separate survey DEMs in: a) September 2009, b) October 2010 (two weeks after foredune vegetation removal) and c) February 2012. The area captures the beach, foredune and two parabolic dunes in the WICK3/4 swath. The locations of the WICK3 and WICK4 cross-shore profiles are indicated with black dots.

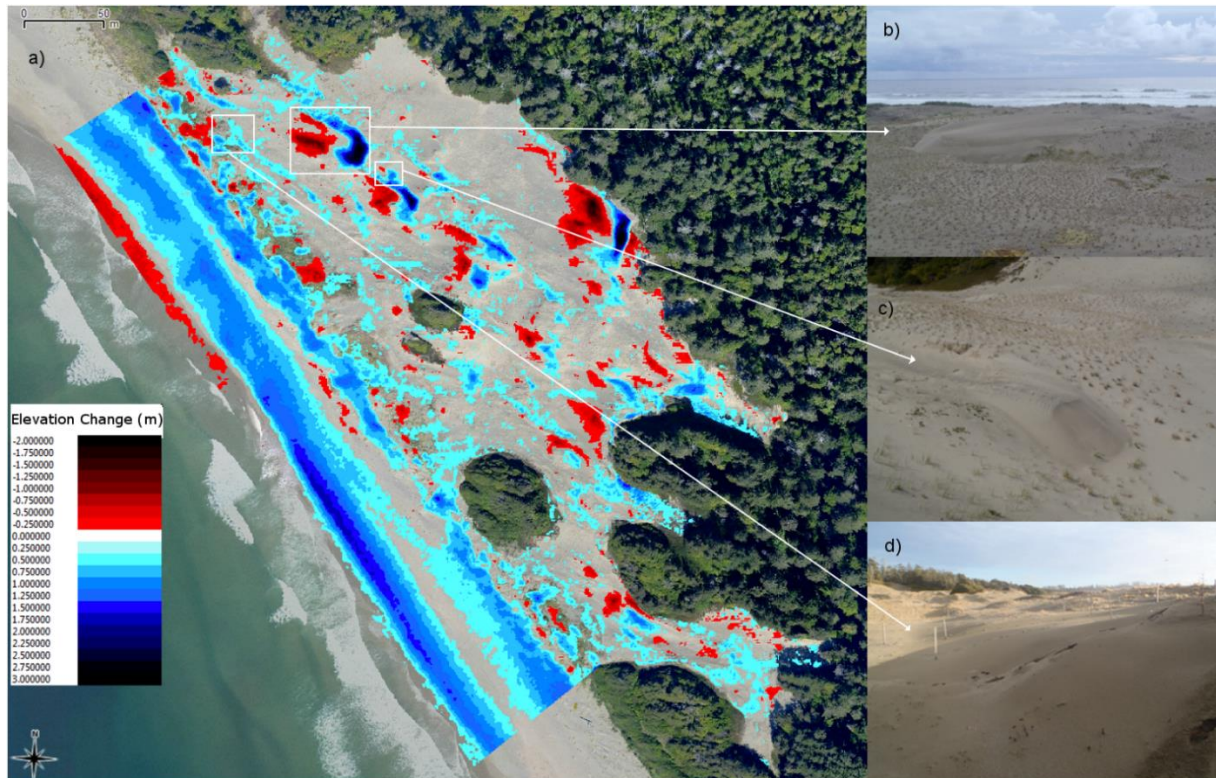


Figure 15. The larger WICK234 beach-dune system with the GCD DEM of Difference (DOD) generated from the August 2009 LIDAR to September 2012 LIDAR simulation overlain on the 2012 orthophotograph.

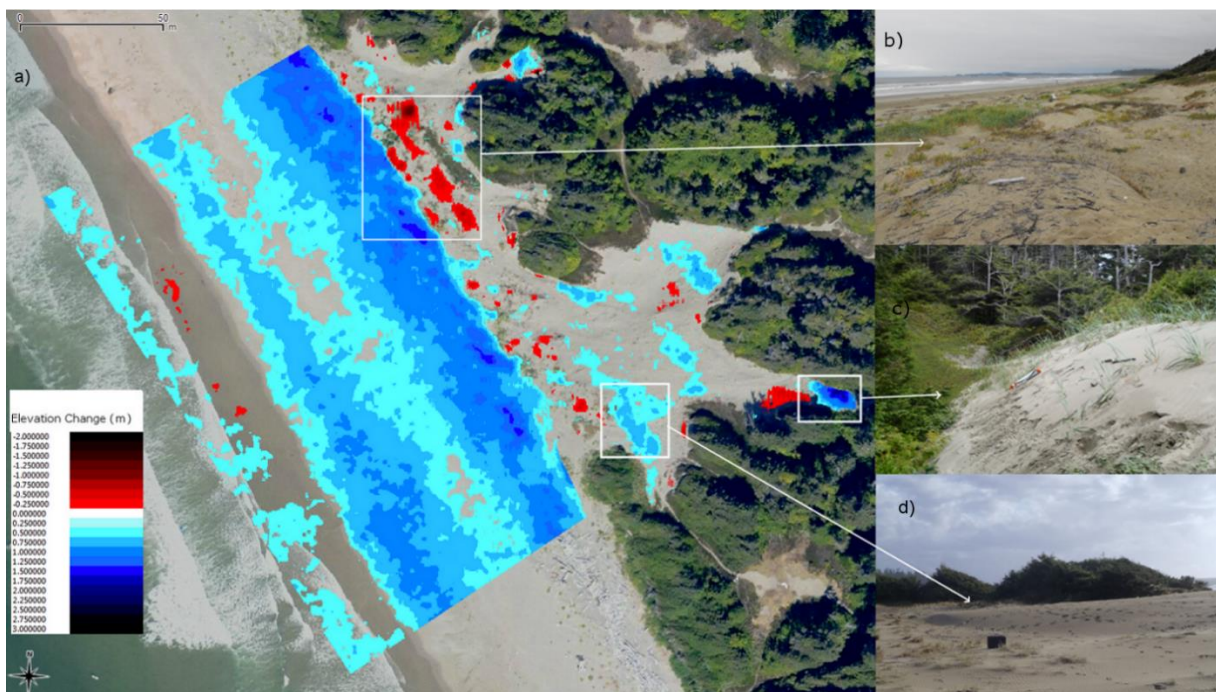


Figure 16. The smaller WICK1 beach-dune system with the GCD DEM of Difference (DOD) generated from the August 2009 LIDAR to September 2012 LIDAR simulation overlain on the 2012 orthophotograph.

3.5.3 Sediment budget responses within beach, foredune, and transgressive dunefield landscape units

A time series of area-normalized volumetric changes within each landscape unit over the study period is presented for each site in Figures 17 and 18. Additionally, Table 3 provides a summary of values for each site at the end of the observation period. For the WICK1 site, data are shown for all three landscape units (Figure 17a) and for just the foredune and transgressive dune units (Figure 17b) for ease of interpretation of these sink components.

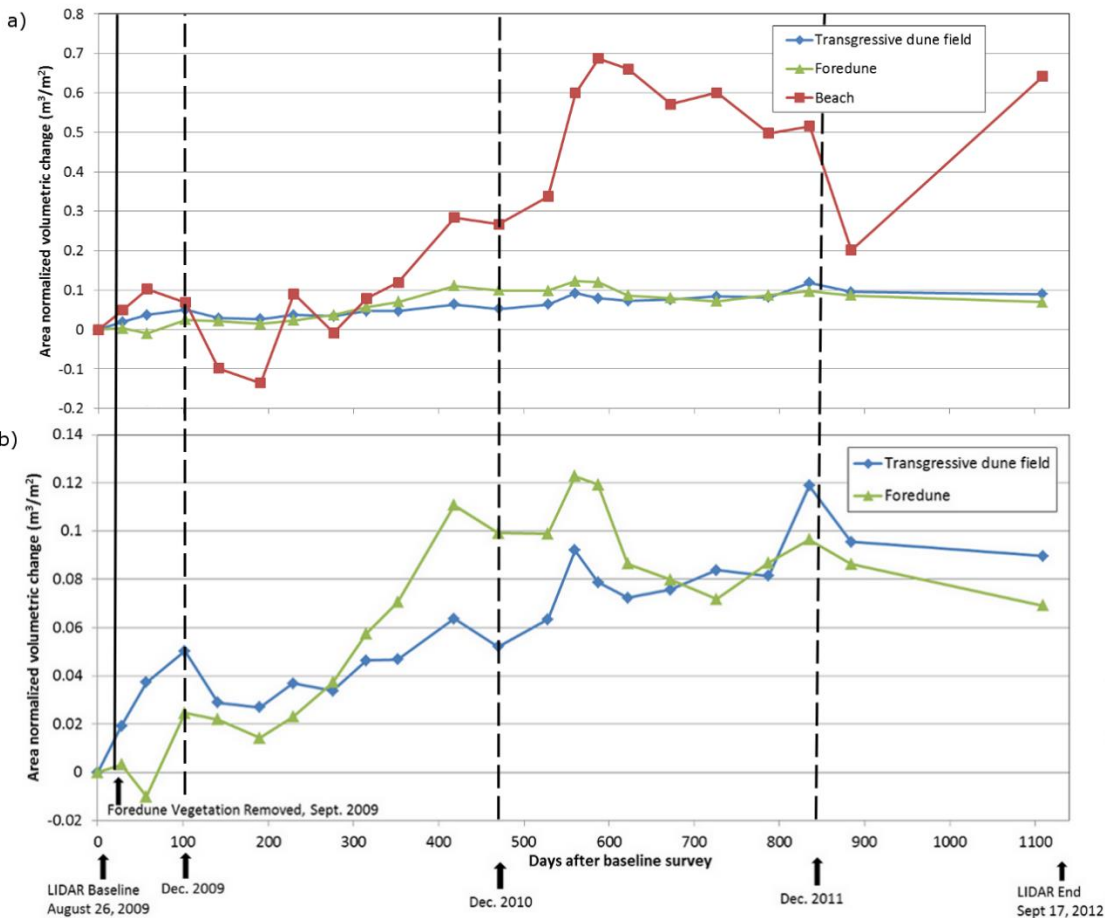


Figure 17. The WICK1 area normalized volumetric time series: a) with all three landscape units, and, b) with just the transgressive dunefield and foredune landscape units. When viewed on a separate scale there is a notable coupling between volumetric fluctuations in the beach and the landward foredune and transgressive dunefield components of the system. Solid vertical lines represent the time of vegetation removal and dashed vertical lines indicate December of each year to aid seasonal interpretations.

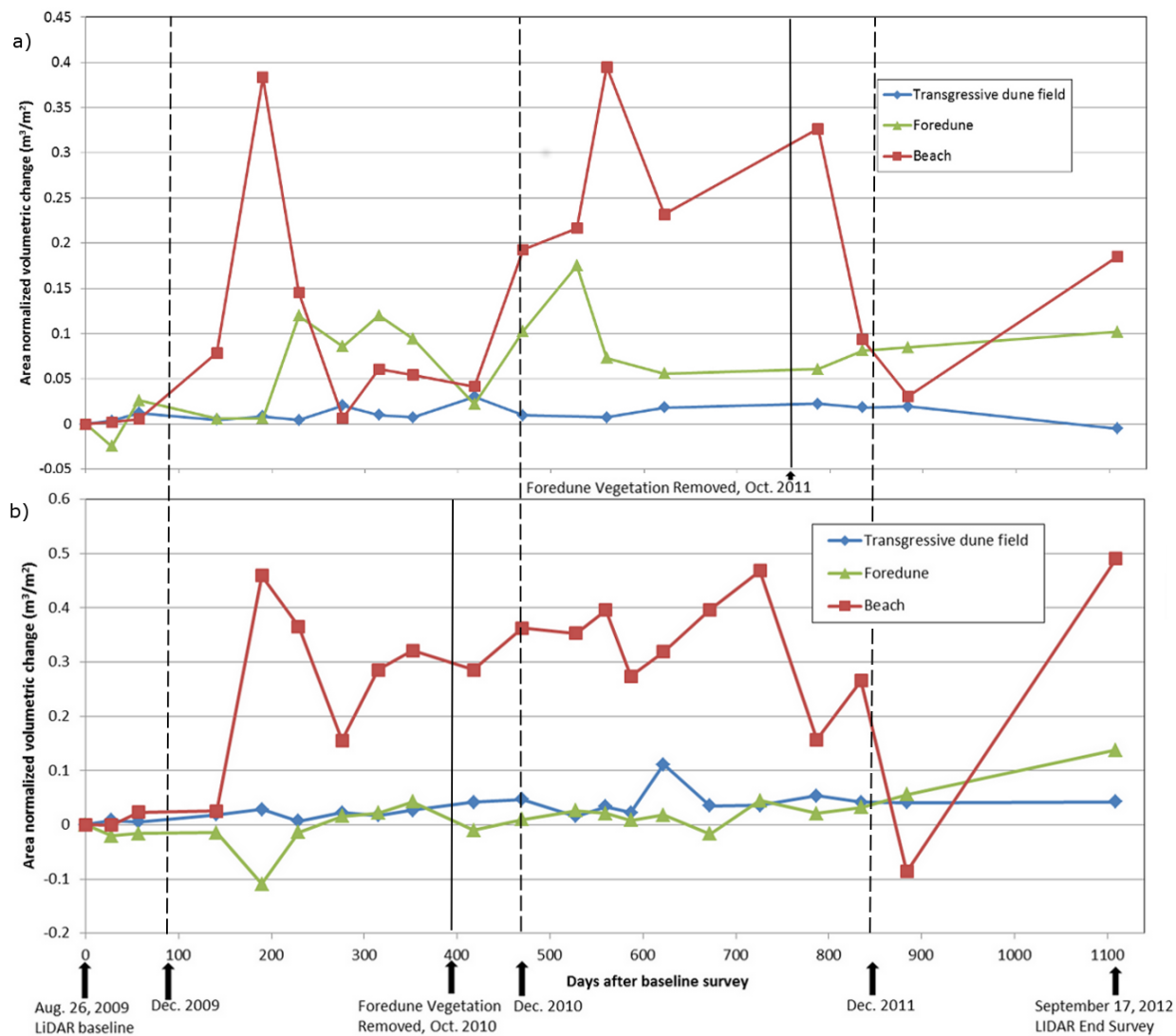


Figure 18. The WICK2 area normalized volumetric time series with all three landscape units presented. b) The WICK3/4 area normalized volumetric time series with all three landscape units presented. Solid vertical lines represent the time of vegetation removal and dashed vertical lines indicate December of each year to aid seasonal interpretations.

Table 3. Summary of erosional, depositional and net volumetric changes in each landscape unit for all three monitoring swaths at the end of the three year monitoring period (August 2009 to September 2012).

		Total volumes (m ³) and area normalized volumes (m ³ m ⁻²) of erosion, deposition and net change at the end of the three year monitoring period		
Landscape Unit		WICK1	WICK2	WICK3/4
Beach	Erosion	0 (0)	-7.7 (-0.002)	-76.1 (-0.011)
	Deposition	2866.7 (0.641)	736.4 (0.187)	3480.2 (0.501)
	Net change	2866.7 (0.641)	728.6 (0.185)	3404.1 (0.49)
Foredune	Erosion	-24.5 (-0.016)	-57.1 (-0.028)	-96.3 (-0.021)
	Deposition	132.7 (0.085)	265.7 (0.13)	741.4 (0.159)
	Net change	108.2 (0.069)	208.6 (0.102)	645.1 (0.138)
Transgressive dunefield	Erosion	-63.2 (-0.014)	-236.7 (-0.021)	-312.3 (-0.019)
	Deposition	447.7 (0.104)	182.5 (0.016)	1003.5 (0.061)
	Net change	384.5 (0.09)	-54.2 (-0.005)	691.2 (0.042)
Total	Erosion	-87.7 (-0.008)	-301.5 (-0.018)	-484.7 (-0.017)
	Deposition	3447.1 (0.334)	1184.6 (0.069)	5225.1 (0.186)
	Net change	3359.4 (0.326)	883.1 (0.052)	4740.4 (0.169)

The cumulative, area-normalized volumetric change in the transgressive dunefield unit of each monitoring swath is presented in Figure 19, which allows for comparisons of sediment budget responses in the landward sink component across the three sites, each of which experienced different timing and extent of restoration treatments. The WICK1 site exhibited the greatest change in normalized sediment

volumetric change and most rapid accumulation rates, followed by WICK3/4, which experienced approximately half of the area-normalized accumulation and a distinct change in the accumulation rate following the restoration treatment. The WICK2 site experienced the least accumulation and the rate of accumulation was fairly consistent over the three-year period. The cumulative normalized volumetric changes for WICK1, WICK2 and WICK3/4 at the end of the three-year record were 1.3, 0.65, and 0.19 $\text{m}^3 \text{m}^{-2}$, respectively.

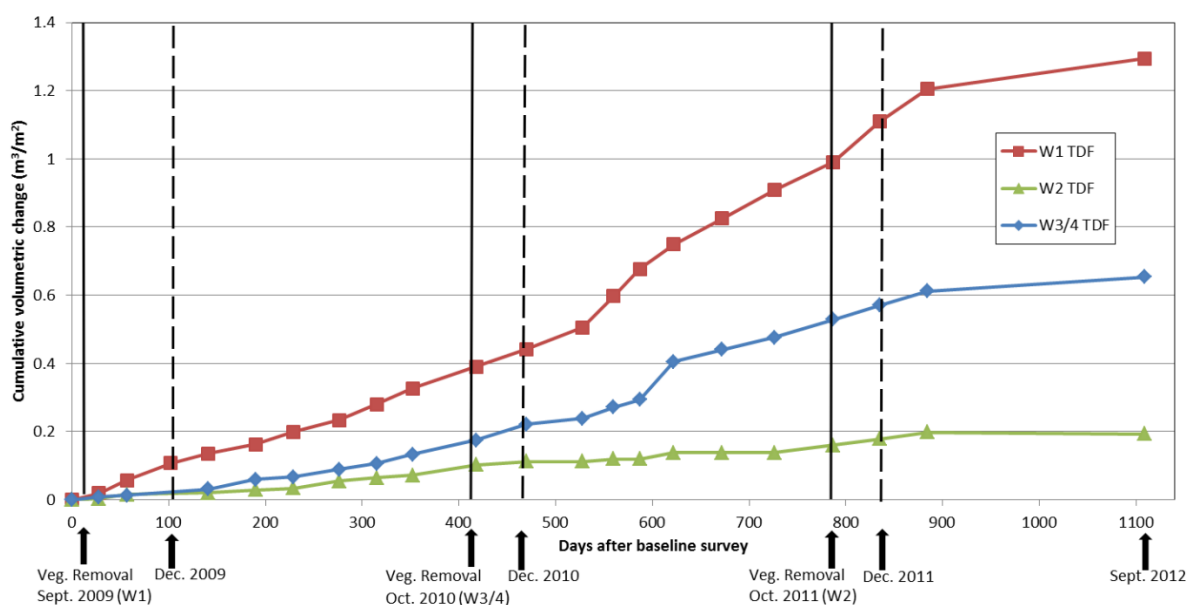


Figure 19. Area normalized cumulative volumetric change for the transgressive dunefield landscape unit of all three monitoring swaths. Solid vertical lines represent the time of vegetation removal and dashed vertical lines indicate December of each year to aid seasonal interpretations.

3.5.4 Meteorological Variability

Data from the Tofino airport weather station were used to assess some of the year to year variability in the potential aeolian activity driving the observed volumetric and morphological changes. Figure 20a displays a time series of area-normalized volumetric changes from the WICK3/4 transgressive dunefield control site, and in part b of the figure the total monthly rain (mm) and hours per month above the threshold

velocity, $V_{t(z)}$ of 5.53 m s^{-1} . These data provide an (albeit limited) proxy for transport- and supply-limiting conditions during the study period. The data demonstrate expected annual variability in precipitation and winds above threshold and no anomalous records exist to suggest that the sediment budget and geomorphic responses were not primarily associated with vegetation removal.

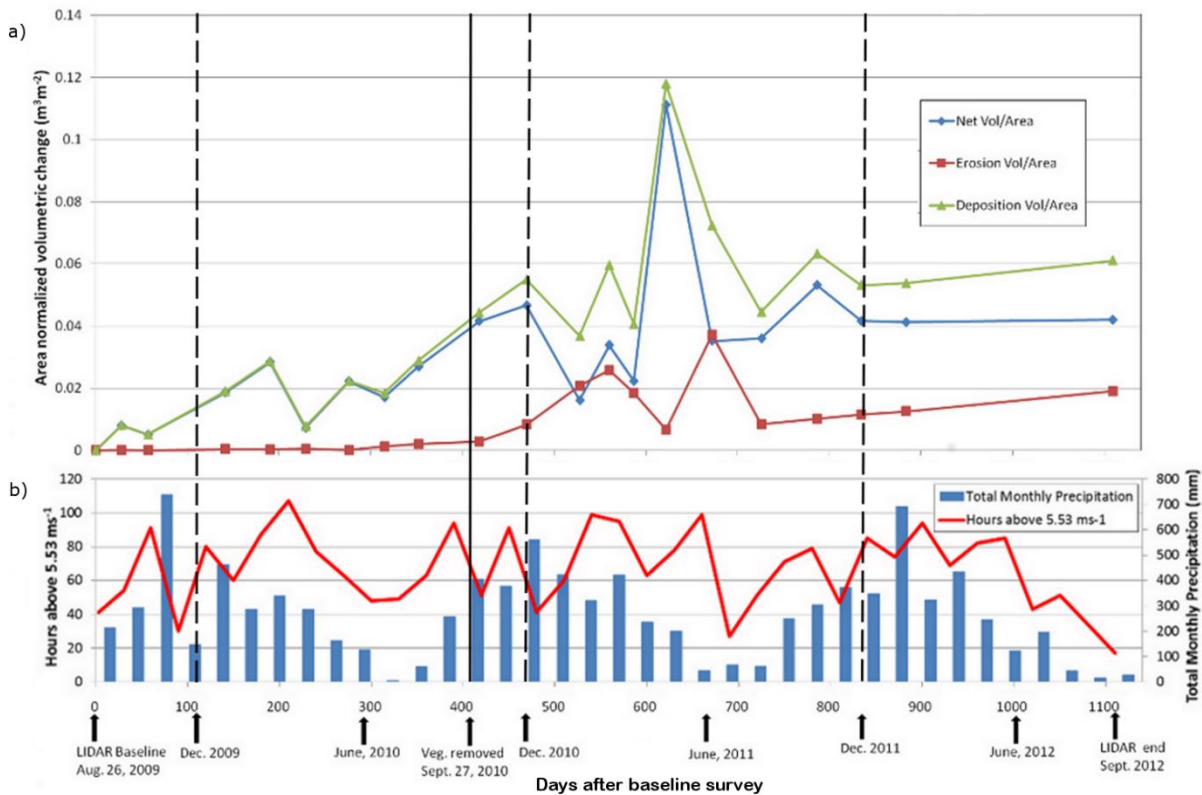


Figure 20. a) The Wick3/4 Transgressive dunefield landscape unit displaying area normalized net volumetric change, area normalized erosional volumes, and area normalized depositional volumes and b) the monthly total precipitation and hourly observations a above 5.53 m s^{-1} (the threshold normal velocity at 10m and calculated based on mean grain size) provided for context. Solid vertical lines represent the time of vegetation removal and dashed vertical lines indicate December of each year to aid seasonal interpretations.

3.5.5 Vegetation Change

Supervised classification analysis results within each VAZ are used to describe vegetation changes within the foredune region associated with the mechanical removal treatment (Table 4). The WICK1 site was the first to be cleared of vegetation, received

ongoing invasive re-growth control, and did not experience vegetation transplants.

Vegetation cover within the WICK1 VAZ dropped from 57% to 13% (-44%) by the end of the monitoring period and the foredune had a low, hummocky morphology (Figure 16b, Table 4). In contrast, the WICK2 site experienced rapid *Ammophila* re-invasion, primarily via nodal regeneration, following a site closure that restricted public access and any restoration activities in the spring following mechanical removal (Figure 21a). Percentage change within the WICK2 VAZ was -35%, dropping from 61% in 2009 to 26% in 2012. Finally, the WICK3/4 site demonstrated considerable re-vegetation in response to transplanting of the native *Elymus mollis* at the site in the spring following removal (Figure 21b). Vegetation cover in the WICK3/4 VAZ dropped by -27% from 78% in 2009 to 51% in 2012.

Table 4. Summary of vegetation presence/absence analysis completed using a simple supervised classification in QGIS. Percent vegetation cover in the three respective VAZ's are provided for the August 2009 and September 2012 orthophotographs and the percentage change between the two times is indicated.

Vegetation Analysis Zone (VAZ)	Vegetation Cover 2009 (Percent cover in VAZ)	Vegetation Cover 2012 (Percent cover in VAZ)	Vegetation Change (Percent cover in VAZ)
WICK1	57%	13%	-44%
WICK2	61%	26%	-35%
WICK3/4	78%	51%	-27%

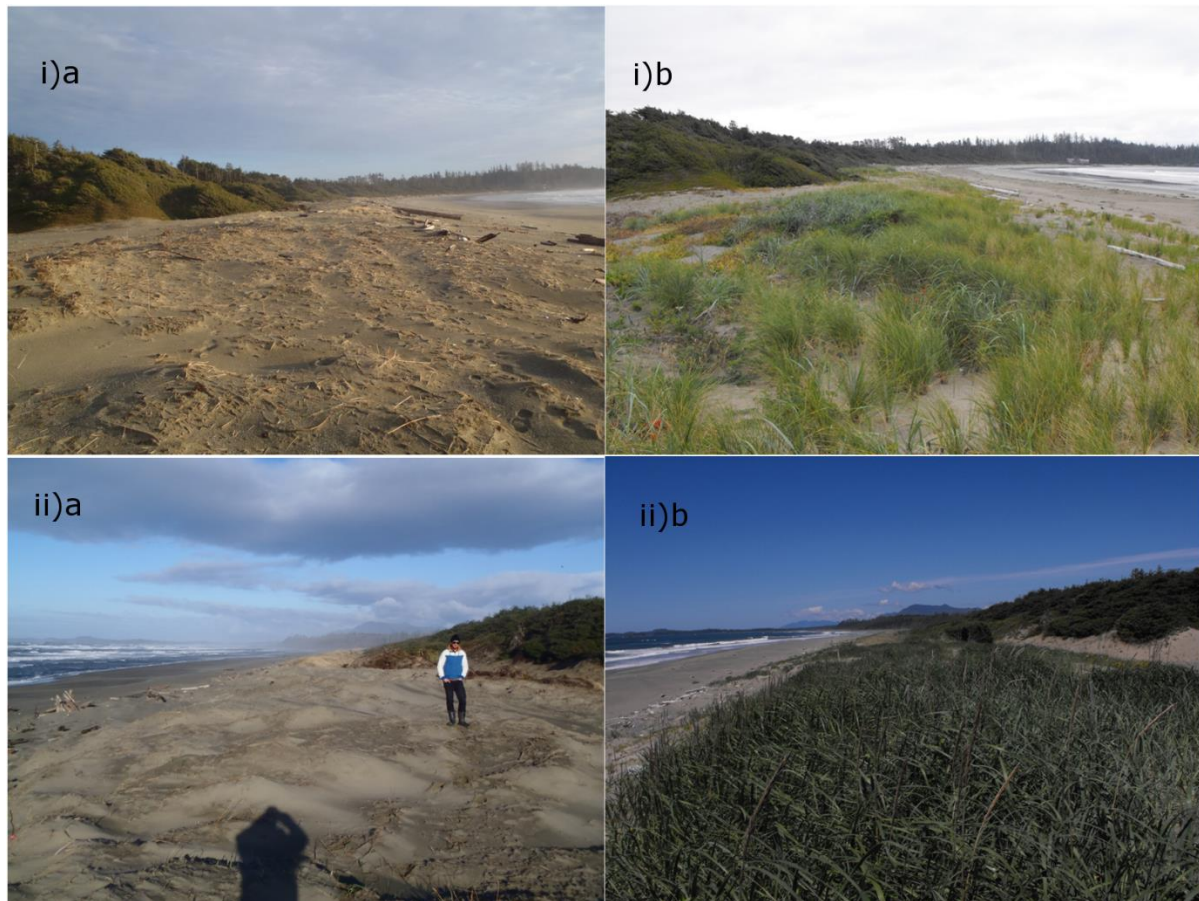


Figure 21. Vantage photographs, spaced a year apart, of the foredune at: i)WICK2 and ii)WICK3/4. Note that at both sites the foredune is completely denuded following mechanical treatment but the WICK2 site does not receive follow up hand pulling of *Ammophila* re-growth and it rapidly re-invades while the WICK3/4 site received follow-up hand pulling and *Elymus mollis* transplants resulting in considerable coverage with native grass.

3.6 Discussion

3.6.1 Characterizing sediment exchanges and morphodynamics in a coastal dune landscape

The initial surface reworking following each removal treatment was substantial as much of the *Ammophila* rhizome networks, smaller shrubs, and trees were removed. Treatments occurred in either September or October after which aeolian activity declines due to seasonal increases in precipitation and infrequent competent winds. During late fall and early winter months following each treatment, a gradual smoothing of the highly irregular, mechanically disturbed foredune terrain was observed. By the

end of the winter, a slightly more uniform foredune profile had re-established, following large storms and occasional aeolian transport events, and fewer remnants of destroyed vegetation were visible. Re-vegetation of the foredune occurred at different times depending on the extent of *Ammophila* re-growth (at WICK2, see Figure 21i) and, at the WICK3/4 site, in response to *Elymus mollis* transplants by PCA staff (Figure 21ii). In all cases, sites remained essentially denuded until late spring in the following year when annual species began to re-emerge. As drier conditions and more frequent onshore transporting winds resumed in the spring and early summer, a large pulse of the recently liberated foredune sediment, combined with enhanced supply to the beach, was delivered into the landward transgressive dune system to feed depositional areas in the dunes. In the foredune unit, re-establishing vegetation, large woody debris, and beach wrack acted as roughness elements that encouraged incipient dune development, sand ramp development and foredune rebuilding, which quickly began to limit the amount of sediment delivered into the transgressive system.

Examination of the 3-D DEMs (Figure 14) and 4-D change surface DODs (Figures 15 and 16) provides a more complete picture of foredune and transgressive dunefield dynamics than can be provided from traditional, 2-D cross-shore profiles. The ability to capture alongshore and onshore sediment transfers within the landscape and vertical accretion or deflation is imperative for assessing landscape scale morphodynamics, particularly in response to dynamic restoration efforts. These morphological and broader sediment budget responses would not be captured as effectively, if at all in some cases, using traditional cross-shore profiles.

3.6.2 Landscape scale morphodynamics and related volumetric changes

The spatial-temporal surfaces produced by the 4-D DODs highlight the evolution of geomorphic features in the landscape over three years following initial vegetation removal. In general, both erosive and depositional components of existing dunes (e.g., blowouts, parabolic dunes) activate and migrate to the southeast, which is suggestive of enhanced morphodynamics. The spatially uniform and highly conservative change detection approach used here estimates that the net volumetric change for the complete beach-dune area was +17 672 m³ (Figure 15) confirming that the entire landscape exhibited a positive sediment budget during the study period. The majority of this gain occurred on the beach (Figs. 15-19), however, and is unrelated to the restoration actions. Nonetheless, this sediment input to the beach provides an appreciable source for the dunes, which also show an overall increase in volume, which was primarily concentrated in the various depositional lobes as other partially stabilised dune areas within the transgressive dunefield. These areas remained sparsely vegetated, primarily with seashore bluegrass (*Poa macrantha*), exhibited little vertical change, and appeared to act more as sediment bypass zones where saltating sediment was not trapped but continued on to be ultimately deposited at the forest margins where their accumulations could not be detected.

The first site to be mechanically cleared, WICK1, experienced the most extensive hand pulling of *Ammophila* re-growth and no transplanting of *Elymus mollis*. As such, the foredune region remained quite hummocky with a poorly defined crest and sparse vegetation cover (Figure 16a) that, speculatively, may better represent the pre-invasion landscape given what is known about analogous dune systems elsewhere in the Pacific

Northwest (i.e. smaller, more gradual and hummocky foredunes and/or line of nebkha with lower vegetation density, cf. Cooper 1958; 1967; Wiedemann and Pickart, 1996; Wiedemann, 1998). The sites located within the larger foredune-transgressive dune system (WICK2, WICK3/4), experienced more subtle geomorphic changes. For instance, the pre-treatment foredune was much larger than at the WICK1 site (Figure 13), so a larger quantity of sediment remained post vegetation removal. Thus, re-vegetation with transplants of the native *Elymus mollis* (at WICK3/4) or from rapid *Ammophila* re-invasion (at WICK2) resulted in less pronounced changes to foredune morphology (Figure 21). Nonetheless, new blowout features along the WICK3/4 foredune and the new characteristics of the foredune at WICK1 indicate improved transport pathways through the foredune and overall increased geomorphic diversity.

In the transgressive dunefield, existing landforms evolved rapidly with relatively high rates of change in both the erosional and depositional components (Figures 14, 15, and 16). Accelerated erosion was evident in the deflation basins and steep sections of the precipitation ridge that experience flow acceleration, enhanced sand transport, and surface deflation (Figures 15 and 16). As confirmed through assessments of the various digital visualisations, large slip faces of precipitation ridges are extending into the forest edge with thinner sediment aprons fanning out over large downwind areas in the forest where vegetation dieback is expected eventually. Finally, due to the influx of sediment in the transgressive dunefield and localized vegetation mortality, new blowouts emerged (Figure 15c) with active erosional basins and depositional lobes. Previous research exploring impacts of vegetation removal on dune dynamics has not been able to chart such detailed changes to hinterland dunefields and, in this case, it is

clear at various scales that a phase of dune activation has been initiated and sustained for up to two years post-removal.

3.6.3 Beach-dune sediment budgets following vegetation removal

The WICK1 swath provided a location where the three landscape units were closely linked and a notable coupling in volumetric fluctuations between source (beach) and sink (foredune and transgressive dunefield) units was observed (Figure 17). While the degree of volumetric change differs greatly between the beach and the landward foredune and transgressive dunefield units, there is nonetheless a strong coupling in the patterns of volumetric change between source and sink components of the system. Existing models of beach dune interaction (e.g. Short and Hesp, 1982; Psuty, 1988; Sherman and Bauer, 1993; Houser, 2009; Hesp, 2012) stressed these interactions although many are somewhat limited in ability to quantify and examine the nature of such sediment exchanges. Some studies using DEMs to derive beach-dune sediment budgets exist, but they are often limited by either a small spatial extent of manual surveys (e.g. Davidson-Arnott and Law, 1996; Andrews et al., 2002; Anthony et al., 2006, 2007) or limited survey frequency of LIDAR surveys (e.g. Woolard and Colby, 2002; Saye et al., 2005).

At the WICK2 and WICK3/4 swaths, the same coupling in volumetric fluctuations between landscape units was not observed. These two survey swaths and their associated landscape units only captured portions of the larger system. Given appreciable lateral exchanges within the larger dunefield and logistical limitations with the initial (manual) survey design, the volumetric estimates in the transgressive dunefield (main sink component of the system), do not capture the full extent of the

downwind accumulation zones. This includes depositional lobes of blowouts and parabolic dunes that migrate obliquely across the survey swaths, some transverse dunes along the precipitation ridge, and some depositional slip faces at the downwind forest margin. Accordingly, the WICK2 and WICK3/4 swaths have a volumetric change record that does not illustrate clear coupling between landscape units (Figure 18). Ideally, the location of these downwind accumulation zones, especially areas vegetated or stabilising at the start of monitoring, should be anticipated and captured in surveying prior to vegetation removal, but limitations of both manual and LIDAR surveying in steep and forested terrain will, of course, dictate the boundaries of the defined landscape units.

Sediment budget responses for each of the three survey swaths within the transgressive dunefield unit show interesting patterns when examined with reference to the extent of foredune re-vegetation (Figure 19, Table 4). The rate and total accumulation of sediment within the transgressive dunefield reflect not only the timing of the restoration treatments, but also the extent to which hand pulling was conducted to prevent regrowth. For instance, the WICK1 site experienced mechanical removal at the start of the observation period and a second mechanical clearing of vegetation just to the north of the swath at the start of the second year. Moreover, given the close proximity of the site to the beach access, it received the most intensive regrowth removal program. As such, it exhibits the greatest rate of accumulation and the greatest total area normalized accumulation ($0.09 \text{ m}^3 \text{ m}^{-2}$).

The WICK3/4 swath, in contrast, was denuded of foredune vegetation at the beginning of the second year (September 2010) and shows the second highest

cumulative accumulation and rate of accumulation. At this site, *Ammophila* re-growth removal was conducted manually and *Elymus mollis*, was transplanted in early July 2011, resulting in more rapid re-vegetation (Figure 21). This re-vegetation may have slowed rates of accumulation within the transgressive dunefield after the first summer but, given the substantial size of the unit and the presence of depositional features within it, there was still considerable sediment accumulation (+691.2 m³ total or 0.042 m³ m⁻²) at the end of the study period in September 2012.

The WICK2 site exhibits the lowest rate and total area normalized volume of accumulation in the transgressive dunefield and this is attributed to the following factors. First, the site was the last site to be cleared of vegetation. Second, unlike the WICK3/4 site, it is narrow in a cross shore direction and, given the lack of depositional features within it, lateral transfers of sediment across the monitoring swath are common. Moreover, the steepest part of the precipitation ridge backs the landward edge of the monitoring swath and was highly eroded in the final year, which offset any increase in the rate of volumetric accumulations. As such, there is a net volumetric loss within the landscape unit between the February 2012 and September 2012 surveys (-54.2m³ or -0.005 m³ m⁻²).

The WICK3/4 site was the only location where it was possible to collect control data, which included a full year of monitoring prior to vegetation removal as well as the two years following. Again, it is important to note that the foredune remained denuded until the summer of the following year when *Elymus* transplants began and considerable vegetation coverage re-established on the foredune (Figure 21). Area-normalized volumetric changes within the WICK3/4 transgressive dunefield (Figure 20a) indicate a

distinct sediment pulse in May 2011 following vegetation removal in the previous September with a maximum gain of $0.11 \text{ m}^3 \text{ m}^{-2}$ vs. a maximum gain of $0.04 \text{ m}^3 \text{ m}^{-2}$ in the pre-treatment year. The 3-D DEMs (Figure 14) qualitatively support this observation as changes between September 2009 and October 2010 (vegetation removal in September 2010) are minimal compared to the changes observed throughout the rest of the record. The sediment liberated from the de-vegetated foredune, combined with enhanced delivery from the beach, drive this spike in volume as stronger and more consistent onshore winds combined with dry conditions. The subsequent loss of sediment in June and August 2011 suggests continued migration of sand outside of the survey swath and decreased delivery from the beach as vegetation cover increased on the foredune. The total monthly precipitation and hours above the calculated transport threshold presented in Figure 20b are somewhat limited as a proxy for supply and transport limiting conditions during the study but, nonetheless, do not indicate any anomalous conditions that would indicate the sedimentation patterns are not primarily related to vegetation removal.

There was also an immediate increase in the volume of erosion in the first few surveys following vegetation removal in September 2010, despite the fact that erosion volumes were negligible for the entire year prior (Figure 20a). This suggests rapid aeolian activation via enhanced deflation of sediment on the foredune as mechanical removal did not occur within the boundaries of this unit. Accordingly, the erosion record from reactivating dunefields may be the most sensitive record of changing dynamics following alterations to the foredune. Erosion volumes decrease in April and May of 2011 when the major pulse of sediment is deposited, inundating even erosive areas but,

following this inundation, erosive processes resumed and were maintained up to the end of the study period indicating some ongoing dynamic activity in the transgressive dunefield.

3.6.4 Assessing restoration effectiveness

Dynamic dune restoration programs are relatively new endeavours in North America and longer-term (interannual) monitoring data are typically lacking, and this occurs despite the acknowledged importance of follow up monitoring and appropriate goal setting in restoration projects in recent literature (e.g., Martinez and Psuty, 2004; Martinez et al., 2013; Walker et al., 2013). As a result, relatively few dune restoration efforts have monitored relevant indicator responses before and/or after restoration treatments so as to provide relevant data for developing evaluation metrics and assessing effectiveness (Lithgow et al., 2013; Martinez et al., 2013; Darke et al., 2013; Walker et al., 2013). This project explored the application of such metrics in the form of several geo-indicators that can be used to assess the effectiveness of dynamic dune restoration efforts according to Walker et al. (2013), including: 1) increased aeolian activity (sand transport, erosion, deposition), 2) enlarged active sand surface areas, 3) a positive sediment budget, 4) increased dune mobility and morphodynamics, 5) improved geomorphic diversity, and 6) enhanced geomorphic resilience (as indicated by a return to the more dynamic pre-disturbance, in this case pre-*Ammophila* invasion, state).

Indicator 1, increased aeolian activity, was observed as rapid accumulations of sediment in the transgressive dunefield (Figures 13 and 14) and an increase in erosion following vegetation removal (Figure 20a). It is widely accepted that rates of sand supply and aeolian erosion and deposition strongly influence vegetation density and

community composition (e.g., Hesp and Martinez, 2007). The increases in aeolian activity at this site suggests improved habitat conditions for the targeted species as they are gap specialists tolerant to sand abrasion and deposition which prevents the establishment of colonizer species and the associated processes of surface stabilisation.

Indicator 2, enlarged active sand surface area, was not observed during the study period although there is some indication that some limited expansion of the mobile surface will occur in the coming years. Large amounts of liberated sediment and enhanced aeolian activity have been observed to be causing vegetation dieback at the southern forest margins of the transgressive dunefield and along the precipitation ridge but, as of yet, has not expanded the active sand surface to a measurable extent (Figures 15 and 16). Expansion of the dune habitat would aid in increasing populations of threatened species by providing greater area for their establishment.

Indicator 3, positive sediment budgets, was recorded within the transgressive dunefield landscape units of the WICK1 and WICK3/4 swaths. The narrowness and lack of depositional features within the WICK2 swath likely resulted in the slightly negative sediment budget at this site and examination of the broader landscape reveals large accumulations of sediment to feed the landscape and promote dune transgression, which is favourable for targeted species and dynamic dune habitat in general.

Indicator 4, increased dune morphodynamics, was evidenced by accelerated migration of transverse, parabolic and sub-parabolic dunes, a flattening of the foredune crest, and creation of new landward transport corridors via blowout development.

Similarly, indicator 5, improved geomorphic diversity, has increased with the development of a new blowout along the foredune as well as others in the landward transgressive dunefield where, additionally, several new deflation basins and depositional lobes not active prior to restoration actions were created. Blowouts and parabolic dunes, as well as other depositional features, are strongly associated with patch dynamics in dune vegetation (Hesp and Martinez, 2007). The targeted species for the restoration project are gap specialists and sand accretion opportunists which should thrive under the current, more dynamic conditions.

Finally, indicator 6, enhanced geomorphic resilience is indicated by a change in foredune morphology towards a lower, more hummocky, foredune complex (Figure 16b) which, at least temporarily, likely better resembles the pre-invasion foredune (cf. Cooper 1958, Wiedemann and Pickart, 1996; Wiedemann, 1998). Sand transport pathways through the foredune have improved and a corresponding increase in aeolian erosion, transport and deposition has been observed in the backing transgressive dunefield. The more dynamic processes now operating should allow the system to absorb disturbances and adjust to changing environmental conditions within the bounds of its dynamic equilibrium. If sustained, populations of threatened species could thrive for the foreseeable future. However, *Ammophila* reinvasion continues to be a major threat to the dune habitat as it can easily shift the system back to a less dynamic, more stabilized state particularly in light of recent trends toward stabilization in the study area (Heathfield and Walker, 2011) and in coastal dunefields elsewhere in the region. Superimposed on current climatic and stabilization trends then, a fully stabilized dunefield may result unless constant vegetation removal treatments continue regularly.

3.7 Conclusions

Research on beaches and surf zones has long noted the importance of 3-D data collection and modelling for complete assessments of site morphodynamics (e.g., Sonu, 1973; Wright and Short, 1984; Roelvick and Broker, 1993; Davidson-Arnott and Law, 1996; Woolard and Colby 2002; Saye et al., 2005; Anthony et al., 2006). This clearly extends to research on beach-foredune systems and transgressive coastal dunefields, but DEM data at appropriate spatial and temporal scales is often lacking (Sherman and Bauer, 1993; Sherman, 1995; Bauer and Sherman, 1999; Delgado-Fernandez et al., 2009; Delgado-Fernandez and Davidson-Arnott, 2011; Darke et al., 2013). As such, the survey data collected here are somewhat novel, particularly as they are closely timed with an ecological restoration initiative and capture broader landscape dynamics of an active foredune-transgressive dunefield system. In addition, the fairly frequent survey intervals allow for production and interpretation of change surfaces that extend interpretations of dune morphodynamics and sediment budgets using a 4-D spatial-temporal framework (James et al., 2012). Meso-scale sediment budget monitoring as applied here demonstrates the importance of survey frequency, extent, and detail and it is suggested that future research of this nature implement and improve upon the foundational approach used here with careful, systematic land surveying initiated in early stages of planning.

Overall, mechanical removal of foredune vegetation at this study site as part of a dynamic restoration project initiated a variety of geomorphic responses within the associated dune landscape. The results presented here provide insights into both the restoration response and the effective use of sediment budgets in monitoring dynamic

restoration efforts and studying beach-dune interaction. The following conclusions can be made:

- 1) Traditional two dimensional cross-shore profiles are limited in their applicability for monitoring landscape restoration efforts in dynamic coastal landscapes and, as possible, broader three dimensional survey campaigns with a repeat survey protocol should be used to enable detection and interpretation of 4-D (spatial-temporal) landscape-scale morphodynamics.
- 2) Beach-dune sediment budgets recorded in the WICK3/4 control site demonstrated a distinct downwind pulse of sediment following mechanical removal of invasive vegetation. Moreover, the contrasting sediment budget responses demonstrate the importance of a study design which includes representative source and sink components, such as the WICK1 site, where a coupling in volumetric changes was observed.
- 3) A commitment to simple but detailed repeat land surveys provides an invaluable source of meso-scale landscape change data for use in sediment budget studies and represents an under-utilised source spatial-temporal data to improve studies of beach-dune interaction.
- 4) Several positive responses in identified geo-indicators of restoration effectiveness were observed. Namely, increases in aeolian activity, positive sediment budgets, enhanced morphodynamics, improved geomorphic diversity, and enhanced geomorphic resilience.

4.0 Dynamic geomorphic mapping and spatial-temporal analysis of a disturbed coastal dune landscape, Wickaninnish Dunes, British Columbia, Canada.

Ian B. Darke, Ian J. Walker, and Patrick A. Hesp

In Preparation

4.1 Abstract

Advances in land surveying technologies demonstrate that it is now possible to track the dynamics and evolution of coastal dune landscapes in greater detail. Dune ecosystem restoration efforts in Pacific Rim National Park Reserve, British Columbia, Canada has provided an opportunity to monitor changing dunefield dynamics. New mapping techniques using geomorphic change detection and other spatial-temporal sediment budget analyses are used to assess dunefield responses to a vegetation removal disturbance associated with an ecosystem restoration project. Rich datasets collected from airborne LIDAR and orthophotographs, combined with repeat land surveys and photography provide the basis for a dynamic geomorphic map that aids in landform identification and assessments of geomorphological change. Additionally, sediment budgets for contiguous beach, foredune, and transgressive dunefield landscape units, based on spatial-temporal change detection methods between 21 survey intervals from August 26, 2009 to September 17, 2012, provide novel insights into landscape scale sediment exchanges and morphodynamics following foredune devegetation. The foredune landscape unit shows a loss of $-0.04 \text{ m}^3 \text{ m}^{-2}$ immediately following vegetation removal and after a year recovery period positive volumetric growth resumes. An increase of $+0.11 \text{ m}^3 \text{ m}^{-2}$ in the landward dunefield unit corresponds mostly with the onset of aeolian activity in the spring season 8 months after devegetation. However, this increase is followed by a loss in volume and appears as a

single spike in the volumetric time series suggesting a disturbance related pulse of sediment through the dunefield and into a precipitation ridge (sediment sink) at the forest margins. Finally, vignettes of three landform types within the dunefield: a blowout, foredune, and transverse dune, are examined to determine their individual responses to foredune disturbance. The transverse dune that is most distal from the foredune is dominantly erosional ($-0.08 \text{ m}^3 \text{ m}^{-2}$) following the disturbance while the blowout and parabolic dunes were more depositional ($+0.29$ and $+0.45 \text{ m}^3 \text{ m}^{-2}$, respectively). The study demonstrates that geomorphic maps that incorporate spatial-temporal change detection can better highlight site morphodynamics and evolution of discrete landforms within coastal dunefields, especially following disturbance events.

KEYWORDS: coastal dunes, dynamic geomorphic mapping, aeolian, sand transport, dune restoration

4.2 Introduction

Recent developments in surveying technologies, have significantly improved our ability to generate high resolution digital elevation models (DEMs) at a range of spatial-temporal scales (Allen et al., 2012; Bishop et al., 2012). For coastal dune ecosystems, these data represent an important source of information to drive research and inform decisions on how to quantify and site morphodynamics into management options. For instance, rather than simply using these advanced surveying methods to improve the accuracy, presentation, and spatial extent of geomorphic maps, it is now possible to incorporate information that informs our understanding of the spatial-temporal patterns of landscape change processes so as to better characterize landscapes as dynamic vs. 'static' environments (Allen et al., 2012). The ability to integrate high-resolution digital mapping and geo-computational technologies is becoming integral to geomorphological

research and increases the ability to understand and model earth surface processes and broader ecosystem dynamics (Bishop, 2012). Repeat surveys of a landscape over time, combined with spatial-temporal change detection methods and digital mapping in GIS now make it possible for geomorphological maps to convey more 'dynamic' information extending into a 4-D spatial-temporal domain (e.g., Mitasova, et al., 2009, 2012; Bishop et al. 2012; Petras et al., 2015; Darke et al., 2016). DEM differencing using more informed spatial statistical methods is being used increasingly for sediment budget monitoring (e.g., Woolard and Colby, 2002; Wheaton et al., 2010a, 2010b; Merz et al., 2006; Anthony et al., 2006; Eamer and Walker, 2013; Walker et al. 2013), or to simply better highlight the complexity of topographic change and related morphodynamic processes (Wyrick and Pasternack, 2016; Wheaton et al., 2013).

This study explores the morphodynamic responses within a coastal foredune-transgressive dunefield complex in western Canada to a widespread foredune disturbance (invasive vegetation removal for ecosystem restoration) and interprets the impacts on broader dunefield dynamics using repeat DEMs of the study site and a geomorphological mapping method that incorporates spatial-temporal change detection methods.

Threats to coastal dune ecosystems are well known and documented (e.g., Martinez and Psuty, 2004; Nordstrom, 2008, Martinez et al., 2013; Malavasi, 2016) and current trends in dune restoration promote dune dynamism and enhanced morphodynamics (Nordstrom, 2008; Martinez et al., 2013; Arens, 2013; Walker et al., 2013; Konlechner and Hilton, 2014). These programs provide an opportunity to better understand foredune disturbance and associated impacts to dunefield behaviour. Existing research

highlights the complexity of disturbance processes in coastal dune environments (e.g. White, 1979; Ehrenfeld, 1990; Garcia-Mora et al., 1999; Stallins and Parker, 2003; Forey et al., 2008; Miller et al., 2010, Pardini et al., 2015, etc.) but comprehensive long-term (interannual) studies are lacking.

The effectiveness of dune ecosystem conservation and restoration efforts are limited without informative baseline maps and quantification of the patterns and processes of landscape change that influence the dynamics of landforms and plant communities therein (e.g., Berry et al., 2014). The purpose of this study is to present and interpret a spatial-temporal dataset collected over 3 years following a dune restoration initiative in the Wickaninnish Dunes within Pacific Rim National Park Reserve. This dataset is used to generate dynamic, 4-D (vs. temporally static) geomorphic maps, based on statistical geomorphic change detection methods, that illustrate seasonal to interannual dune morphodynamics and allow for a better understanding of landscape responses to foredune disturbance processes. The specific research objectives of the study are as follows:

- 1) To develop a refined mapping method for dynamic landscapes that incorporates spatial-temporal change detection
- 2) To map geomorphological and land unit changes over time in a coastal dune landscape, and, in particular, examine the evolution of three distinct dune types at an interannual scale.
- 3) To explore the impacts of a widespread foredune disturbance on the broader morphodynamics and sediment budgets within a temperate coastal dune field.

4.3 Study Area

The Wickaninnish Dunes complex exists within Pacific Rim National Park Reserve on the west coast of Vancouver Island near Ucluelet, British Columbia, Canada (Figures 22 and 23). Wickaninnish Beach is an intermediate bar and trough beach with a southwest aspect to the open Pacific Ocean. A nearly continuous foredune ridge exists along the shoreline of Wickaninnish Bay and is often fronted by an incipient dune system within sparse vegetation and/or large woody debris (Heathfield and Walker, 2011; 2015). Due to regional tectonic uplift along the Cascadia Subduction Zone located offshore of Vancouver Island, the study area is experiencing a drop in relative sea level of -0.9 mm a^{-1} (Wolynech, 2004; Mazzotti et al. 2008) that, combined with high onshore sand supply, assists in dune maintenance and fairly rapid rates of shoreline progradation at the site approaching $+1.1 \text{ m a}^{-1}$ (Beaugrand, 2010; Heathfield and Walker, 2011; 2015). The Wickaninnish barrier system comprises a transgressive dunefield which are typically defined as relatively large scale dunefields migrating (transgressing) over prior terrain, and may be fully mobile to fully vegetated depending on evolutionary stage (Hesp and Thom, 1990; Martinho et al., 2010; Hesp and Walker, 2013; Pickart and Hesp, 2019). The transgressive dunefield system at Wickaninnish comprises three distinct phases separated by surrounding forest. They range in size from small to extensive and are all experiencing an overall trend towards vegetative stabilisation at an estimated rate of stabilization of approximately 1% per year (Heathfield and Walker, 2011). The largest, and most-seaward transgressive dunefield phase is the focus of this study (Figures 23, 24). A variety of dune types are found within the dunefield including blowouts, parabolic and sub-parabolic dunes, transverse

dune ridges, nebkha, shadow dunes, as well as other aeolian features such as trailing arms, active slipfaces, depositional lobes, remnant knobs, and deflation basins.

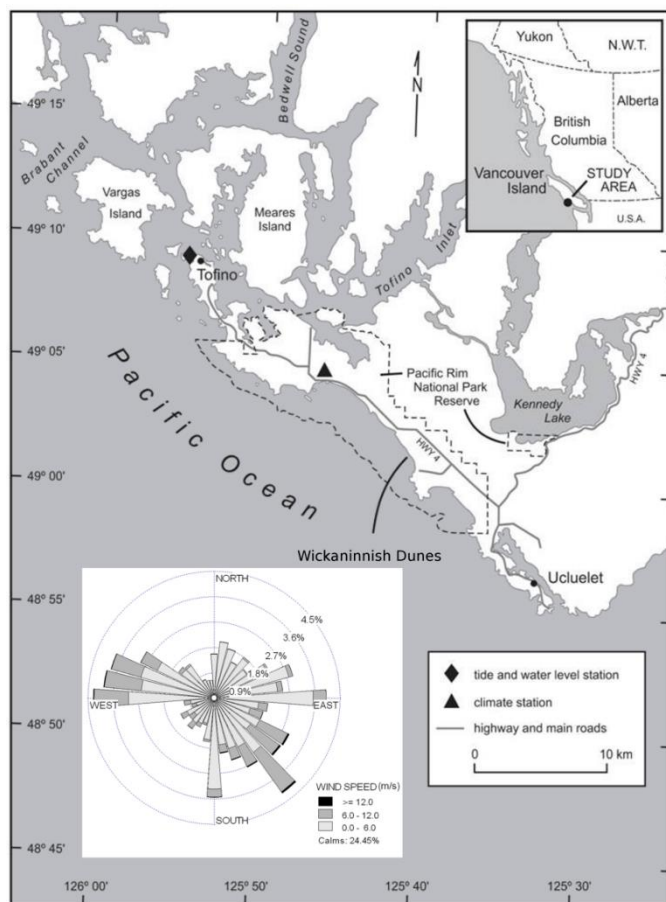


Figure 22. The study area with regional map and local wind rose inset.

The regional wind regime is highly competent and seasonally bimodal (see inset wind rose in Figure 22, Beaugrand, 2010), which permits active foredune building, recovery from erosive events, and ongoing mobility of landward transgressive dunes. The alignment and geomorphology of deflation basins, parabolic dune arms, blowouts and depositional lobes within the dune complex suggests a dominant transport vector from the WNW driven largely by summer wind events. Despite strong SE winds dominating the other mode in the wind regime, high precipitation during the winter months renders these winds largely ineffective in overall dunefield dynamics. The

beaches are subject to a seasonally variable, energetic wave regime (Beaugrand, 2010; Heathfield and Walker, 2015). Foredune erosion and scarping occurs frequently along Wickaninnish Beach with a recurrence interval of approximately 1.5 years, but is typically followed by rapid aeolian rebuilding via sand ramp development and incipient dune growth, often in the presence of large woody debris and seasonal vegetation (Heathfield and Walker, 2011; 2015).

In 2009, this dune system experienced vegetation removal associated with a restoration program designed to eradicate an invasive beach grass (*Ammophila arenaria* and to a lesser extent *Ammophila breviligulata*). While manual hand pulling efforts began on the foredune in summer 2009, there was very limited observed impacts in the landward transgressive dunefield until two subsequent and more extensive phases of mechanical clearing completely denuded the foredune (Figure, 23; see also Darke et al., 2013, 2016 for further details). In September 2010, the large area to the north and the smaller area at the southern extent of the foredune system was cleared followed by a smaller area between them in September 2011 (Figure 23).

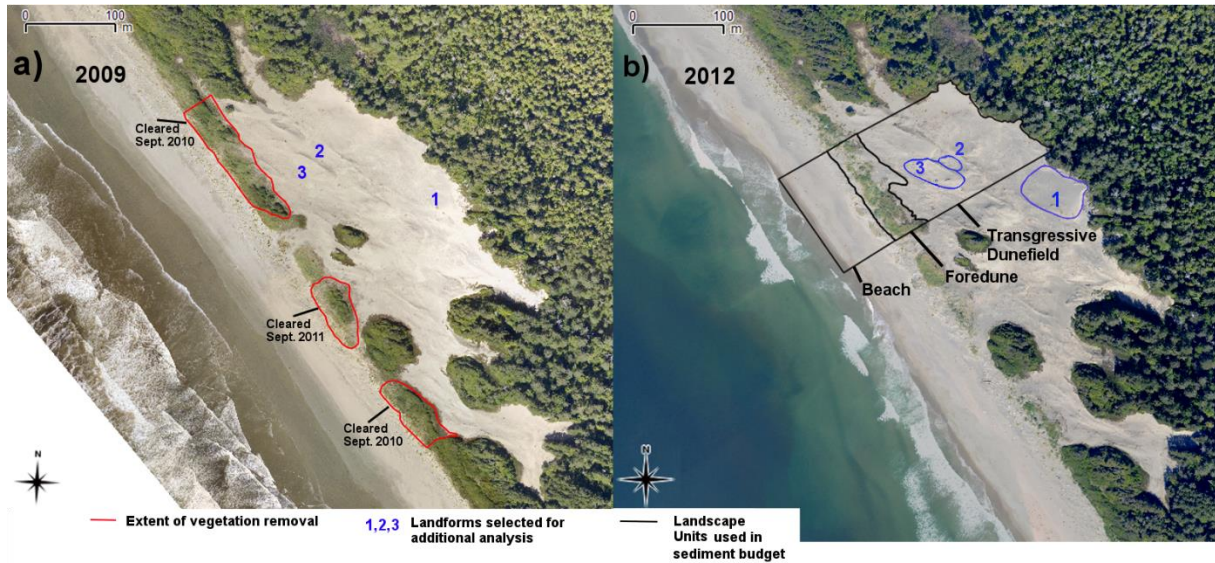


Figure 23. Before (August, 2009) and after (September, 2012) orthophotos of the study area. In part a) on the 2009 orthophoto, the extent of vegetation removal is indicated with red lines. In part b) on the 2012 orthophoto, the boundaries of the landscape units used for sediment budget calculations are indicated with black lines and the landforms selected for additional analysis (1. a transverse dune, 2. a blowout, and 3. a parabolic dune) are numbered and outlined in blue.



Figure 24. A panoramic view of the coastal dune landscape analysed and mapped in the study.

4.4 Methods and Data

4.4.1 Land surveys and DEM generation

An initial bare earth DEM base map of the entire Wickaninnish Dunes system was derived from airborne LIDAR flown on 27 August 2009. Following this, detailed manual topographic surveys (nineteen in total) were conducted approximately bi-monthly between August 2009 and February 2012. A final aerial LIDAR survey was flown on 17 September 2012, giving a total of 21 survey intervals. Digital orthophoto mosaics of the study site were captured simultaneously with each airborne LIDAR

survey and provide a high resolution aerial view of the dune system prior to, and following, the foredune devegetation and disturbance (Figure 23). The manual topographic survey data were collected using a Topcon GTS226 laser total station between August 2009 and August 2010 and an Ashtech ProFlex 800 base station and ProMark 800 Rover for Real Time Kinematic (RTK) GPS surveys between October 2010 and February 2012. Acquisition reports for LIDAR surveys indicate accuracies of 2 cm horizontally and 15 cm vertically. Instrument errors associated with the manual RTK and total station surveys are within manufacturer's specifications with horizontal accuracies of <1 cm and <2 cm vertically. For every survey, the survey base station was set up over top of an established survey benchmark and was referenced to the local UTM grid (Horizontal: NAD83 UTM Zone 10 N, Vertical: CGVD28). For total station surveys, this was completed by performing a free-station or resection utilizing a network of control monuments tied into the corresponding UTM grid. For RTK GPS surveys, the base station was set up over one of these control monuments with additional surveys shots taken on all other local monuments to confirm the coordinates were within 1 cm horizontally and 2 cm vertically at each location. Following each field survey, the data were reviewed and additional control shots were removed from the file. The points were then gridded using Surfer™ version 8 mapping software using linear kriging interpolation to create a digital elevation model (DEM) surface. Following this, the surface was cropped using Quantum GIS (QGIS) to match digitized polygons of smaller landscape units of beach, foredune and dunefield for use in sediment budget analysis (described in section 4.4.2), or for the entire dune system for use in geomorphic

mapping (described in section 4.4.3), and finally for three discrete dune landforms: one blowout, one parabolic and one transverse dune (described in section 4.4.4).

4.4.2 Sediment budget analysis

Sediment budget responses were assessed by quantifying volumetric changes over time in three contiguous landscape units: beach, foredune, and transgressive dunefield (defined in Figure 23b, rationale explained in Darke et al., 2013, 2016, i.e. Chapter 2 and 3). Changes in sediment volume were calculated within each landscape unit by differencing the 20 DEMs in sequential order against the initial August 2009 LIDAR DEM using the open source desktop version 1 of the Geomorphic Change Detection (GCD) software (copyright Wheaton, 2010, see Wheaton et al. 2010). GCD identifies statistically significant surface elevation changes between two DEMs and calculates associated volumetric changes. Surface differencing was conducted using a 95% confidence level threshold with a uniform vertical DEM error of +/- 15 cm for the LIDAR surveys (per stated maximum error in data acquisition reports) and +/- 5 cm vertical error for all manual surveys (stated maximum errors from the manufacturer for the total station and RTK instruments used were 0.5 cm and 2 cm respectively). The software also provides a difference surface as a geo-referenced raster layer of significant vertical changes that can be colour banded by customized ranges of vertical change and added as a layer in a GIS. By differencing each survey interval against the initial LIDAR survey, a 3-year time series (ending with the September 2012 repeat LIDAR survey) of bi-monthly volumetric changes in each of the landscape units was generated. This allowed for analysis of coupled responses across the linked beach, foredune, and dunefield landscape units with reference to the first phase of vegetation

removal. This most extensive phase of mechanical vegetation removal from the foredune occurred on 27 September 2010, approximately one year following the initial baseline LIDAR survey in August 2009 (see Darke et al., 2013). An additional 2 years of volumetric and morphodynamic monitoring results was collected following this with a final LIDAR survey interval in September 2012. Local wind and precipitation data were collected from the Tofino airport (approximately 10 km away) and hours in a month above a transport threshold velocity and total monthly precipitation values are summarised based on findings from (Darke et al., 2016). The threshold velocity for aeolian sediment transport was calculated using Bagnold's (1941) formula:

$$u^*_t = A \sqrt{\frac{(\rho_p - \rho_a)gd}{\rho_a}} \quad (1)$$

where A is an empirical coefficient (0.08 for impact threshold); ρ_p is the density of quartz sand particles ($2.65 \times 10^3 \text{ kg m}^{-3}$); ρ_a is air density (1.22 kg m^{-3}); g is gravitational acceleration (9.81 m s^{-2}); and d is mean sand grain diameter at the study site ($1.74 \times 10^{-4} \text{ m}$). The resulting threshold velocity was estimated to be 0.154 m s^{-1} and, to relate it to the elevation of the wind measurements ($Z = 10 \text{ m}$), the threshold normal velocity $V_{t(z)}$ was determined using the method of Hsu (1974):

$$V_{t(z)} = \frac{u^*_t}{k} \ln\left(\frac{Z}{Z_0}\right) \quad \text{if } Z > Z_0 \quad (2)$$

Where $V_{t(z)}$ is impact threshold normal velocity at height Z (10 m); U^*_t is impact threshold shear velocity from Eq. 1 (0.154 m s^{-1}); k is von Karman's constant (0.4); Z_0 is a roughness coefficient ($5.82 \times 10^{-6} \text{ m}$) equivalent to $d/30$. From this, the calculated threshold normal velocity in the study region was approximately 5.53 m s^{-1} .

4.4.3 Geomorphic Mapping and Change Detection

Identification and nomenclature of initial landform units was carried out following geomorphological mapping techniques and nomenclature of Hesp and Thom (1990) and Hesp et al. (2011). Next, site morphodynamics (i.e., spatial and temporal patterns of geomorphic change and sediment volume changes) were incorporated to develop a more 'dynamic' geomorphic map. The first step involved identifying and digitizing broad geomorphic units within the overall dune system (beach, foredune, transgressive dunefield plain, transgressive dunefield slopes (>25 degrees), and precipitation ridge) by overlaying transparent coloured polygons onto the 2012 orthophotograph. Second, a DEM of Difference (DOD) surface generated using the GCD software was added as an overlay in QGIS to highlight surface elevation changes between the August 2009 and September 2012 LIDAR surveys. As such, the resulting DOD layer could then be used, in conjunction with the orthophoto itself, to define the boundaries of specific landforms within the landscape. In other words, the extent of vertical changes in the DOD layer informed the delineation of each landform and its dynamic components by clearly indicating volumetric exchanges, such as those between deflation basins and depositional lobes. Once delineated, each landform was given an alphanumeric abbreviation and a legend was created to identify landform units.

4.4.4 Spatial-temporal analysis of select dune landforms

Selected dune landforms were chosen from the dynamic geomorphic map for additional spatial-temporal analysis (see Figure 23b). Using the same GCD change detection parameters from the broader landscape analysis, several additional change detection simulations were processed at the landform scale using smaller polygons of

individual features as delineated in the geomorphic map. From this, a subset of three landforms were identified for further analysis: a transverse dune, a parabolic dune, and a blowout. Given the comparatively small size and low volumes of change detected in the blowout, a less conservative 10 cm uniform DEM vertical detection threshold and 90% confidence level was used for change detection on this landform. While not consistent with the other landforms examined, this allowed for a specific, albeit relative, means of change detection on a feature with observed evidence of erosion, deposition, and morphological change (see inset photo in Figure 32a) that was not detected at the more conservative thresholds used for the broader study site. The output raster DOD files for each landform were then overlain on the respective sections of the September 2012 orthophoto with all other surfaces changes removed to prepare individual vignettes of landform evolution for each dune type. Additional descriptive statistics regarding the distribution of volumetric changes for each landform we completed but given the conservative thresholds used for change detection no in depth assessment of the statistics is completed in this study.

4.5 Results

4.5.1 Sediment budget responses to foredune disturbance

Figure 25 presents the results of the 3-year record of bi-monthly volumetric changes within the three contiguous landscape units (beach, foredune, and transgressive dune). As expected, the scales of volumes and variability within the beach unit is much greater than those observed in the landward dune units. Overall, the beach gains $+0.5 \text{ m}^3 \text{ m}^{-2}$ by the end of the observation period and volumetric variability was roughly 4-5 times greater than that of the other two geomorphic units and varied to

a maximum of nearly $0.6 \text{ m}^3 \text{ m}^{-2}$ between the latter observation intervals. The foredune landscape unit experienced its largest loss in volume of $-0.1 \text{ m}^3 \text{ m}^{-2}$ in April 2010 associated with a foredune scarping event that relocated sediment to the upper beach, which demonstrated a corresponding gain of $+0.44 \text{ m}^3 \text{ m}^{-2}$. The second notable erosive event in the foredune unit ($-0.04 \text{ m}^3 \text{ m}^{-2}$) corresponded with the mechanical vegetation removal disturbance event, which involved notable sediment reworking and dune crest flattening. A third erosive event occurs in July 2011 during the active aeolian season and may be associated with wind erosion from the sparsely vegetated foredune as it recovers from the devegetation disturbance in October 2010. The transgressive dunefield had the least variability in volumetric change and small gain in volume ($+0.035 \text{ m}^3 \text{ m}^{-2}$). The only notable fluctuation in the transgressive dune unit was a volumetric gain of $+0.11 \text{ m}^3 \text{ m}^{-2}$ in May 2011 that corresponded with increased aeolian activity and erosion of the foredune which followed the de-vegetation disturbance event in the preceding October. This is discussed in more detail below.

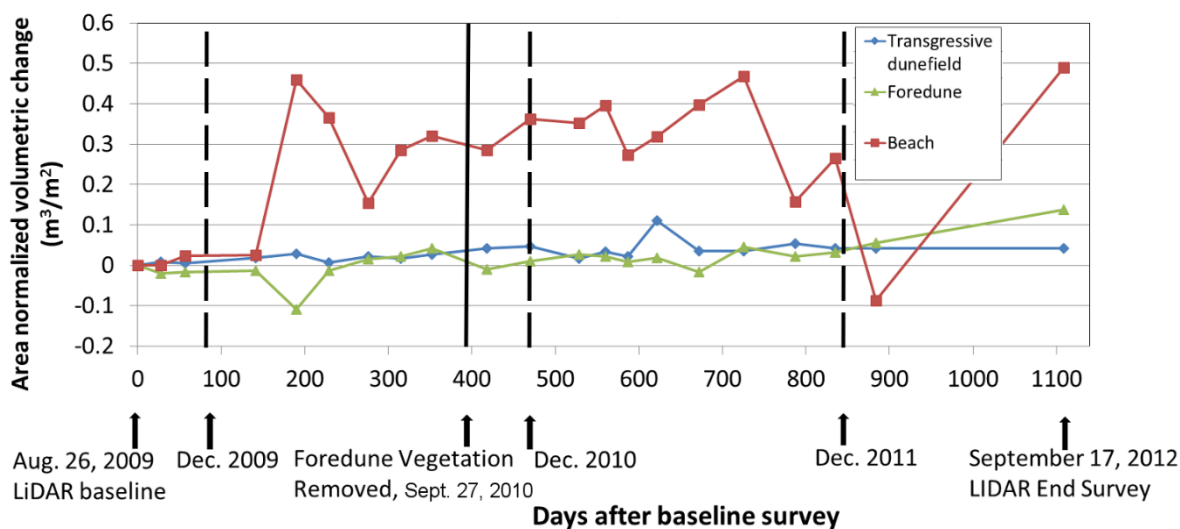


Figure 25. Bi-monthly sediment budget indicating volumetric change within each of the three defined landscape units: Beach, Foredune, and Transgressive Dunefield over the three year record of land surveys. To aid in the interpretation the volumes have been area normalized, so coupled patterns among the three landscape units, which vary in size, could be better assessed.

Table 5 provides a summary of erosional, depositional, and net volumetric changes in each landscape unit at the end of the three-year period as both total and area-normalized volumetric changes. The total area of each landscape unit and the areas of erosional or depositional change are also summarized. Descriptive statistics for these volumetric change data are summarized in Table 6. Overall, deposition constitutes a vast majority of the observed surface change between the initial August 2009 and final September 2012 LIDAR surveys, both volumetrically and based on land area. Figure 26 presents the distribution of volumetric change based on elevation ranges for the three landscape units. In all cases, it is evident that vertical gains (deposition) are much more dominant than vertical losses (erosion). Also, on the erosional (red) side of the histograms, it is clear that as the magnitude of vertical loss increases, the corresponding volume of change decreases, as such, volumetric losses result from small but widespread vertical changes. Whereas on the depositional (blue)

side of the histogram there is a more varied pattern with large volumetric gains occurring both from small vertical changes as well as large vertical changes.

Table 5. Summary of erosional, depositional and net volumetric changes in each landscape unit with surface area of erosion, deposition, and total area experiencing change also indicated.

Landscape Unit (Area indicated in m ²)		Total volume (m ³)	Area normalized volume (m ³ m ⁻²)	Total area of change (m ²)
Beach (7684 m ²)	Erosion	-76.1	-0.011	136
	Deposition	+3480.2	+0.501	4592
	Net change	+3404.1	+0.49	4728
Foredune (4682 m ²)	Erosion	-96.3	-0.021	131
	Deposition	+741.4	+0.159	1057
	Net change	+645.1	+0.138	1188
Transgressive Dunefield (16489m ²)	Erosion	-312.3	-0.019	410
	Deposition	+1003.5	+0.061	870
	Net change	+691.2	+0.042	1280
Total (28855 m ²)	Erosion	-484.7	-0.017	677
	Deposition	+5225.1	+0.186	6519
	Net change	+4740.4	+0.169	7196

Table 6. Descriptive statistics for the volumetric changes within the landscape units, listed in Table 5, with summaries for net change, erosional change, and depositional change.

Landscape Unit	Mean (m³)	Standard Deviation	Standard Error	Variance	Skewness	Kurtosis	Shapiro-Wilk p-value
Beach	+97.54	125.34	18.68	15709.6	1.24	0.04	0.00089
Beach Erosion	-19.73	14.91	3.73	222.27	0.18	-1.75	0.256
Beach Deposition	+145.38	138.51	26.18	19183.68	0.51	-1.33	0.292
Foredune	+29.17	33.25	4.48	1105.23	1.05	-0.49	0.0286
Foredune Erosion	-7.95	6.09	1.13	37.12	0.48	-0.55	0.5733
Foredune Deposition	+54.77	34.52	6.9	1191.48	-0.29	-1.42	0.7479
Transgressive Dunefield	+44.98	78.77	8.44	6204.22	3.63	13.19	0.0048
Transgressive Dunefield Erosion	-23.19	16.32	2.93	266.37	0.49	-0.7	0.23
Transgressive Dunefield Deposition	+57.47	96.43	13	9298.84	2.81	7.18	0.0826

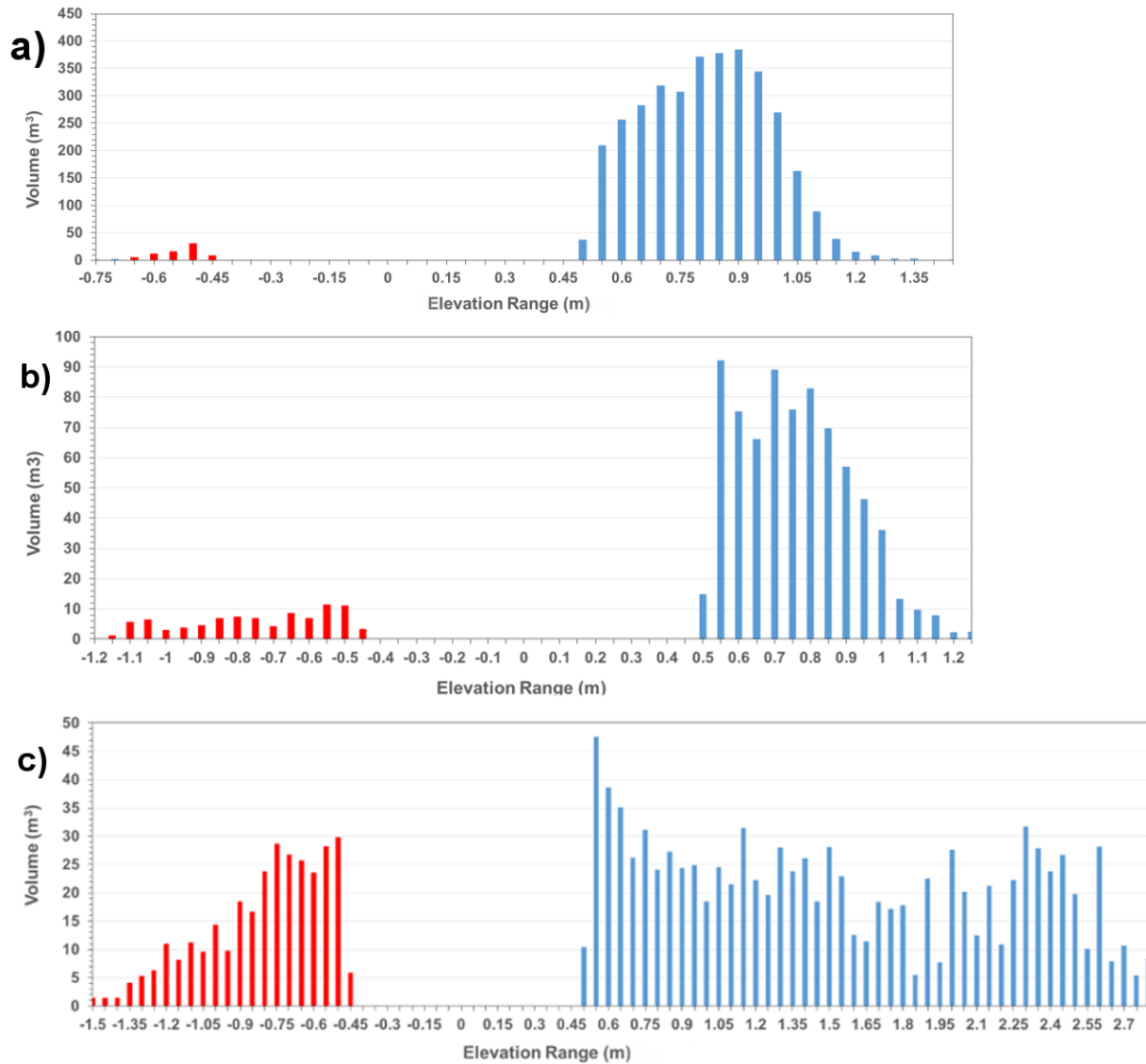


Figure 26. Distribution of volume by elevation range for the a) foredune, b) beach, and c) transgressive dunefield landscape units based on August 2009 to September 2012 GCD change detection runs.

Figure 27a displays a time series of area-normalized volumetric changes from the transgressive dunefield unit, which is presumed to be the landward sink for sediments moving inland via aeolian activity. Area-normalized volumetric changes over the three-year observation period indicate a distinct pulse of sediment deposition in May 2011, which is at the beginning of the active aeolian season. This pulse follows vegetation removal in late September 2010, which marks the onset of regional wet

winter conditions that limit aeolian transport through early spring. A maximum gain of $+0.11 \text{ m}^3 \text{ m}^{-2}$ is observed following vegetation removal in contrast to a gain of only $+0.04 \text{ m}^3 \text{ m}^{-2}$ the year before the vegetation disturbance.

Data from the Tofino airport weather station were used to assess the monthly variability in potential aeolian activity. Figure 27b shows the total monthly rain (mm) and hours per month with windspeeds above the aeolian transport threshold velocity, $V_t(z)$ of 5.53 m s^{-1} . These data provide an (albeit limited) proxy for transport- and supply-limiting conditions during the study period and demonstrate expected seasonal variability in precipitation and sand transporting winds. No anomalous records exist to suggest that the sediment budget and geomorphic responses in the foredune and dunefield were not primarily associated with the vegetation disturbance.

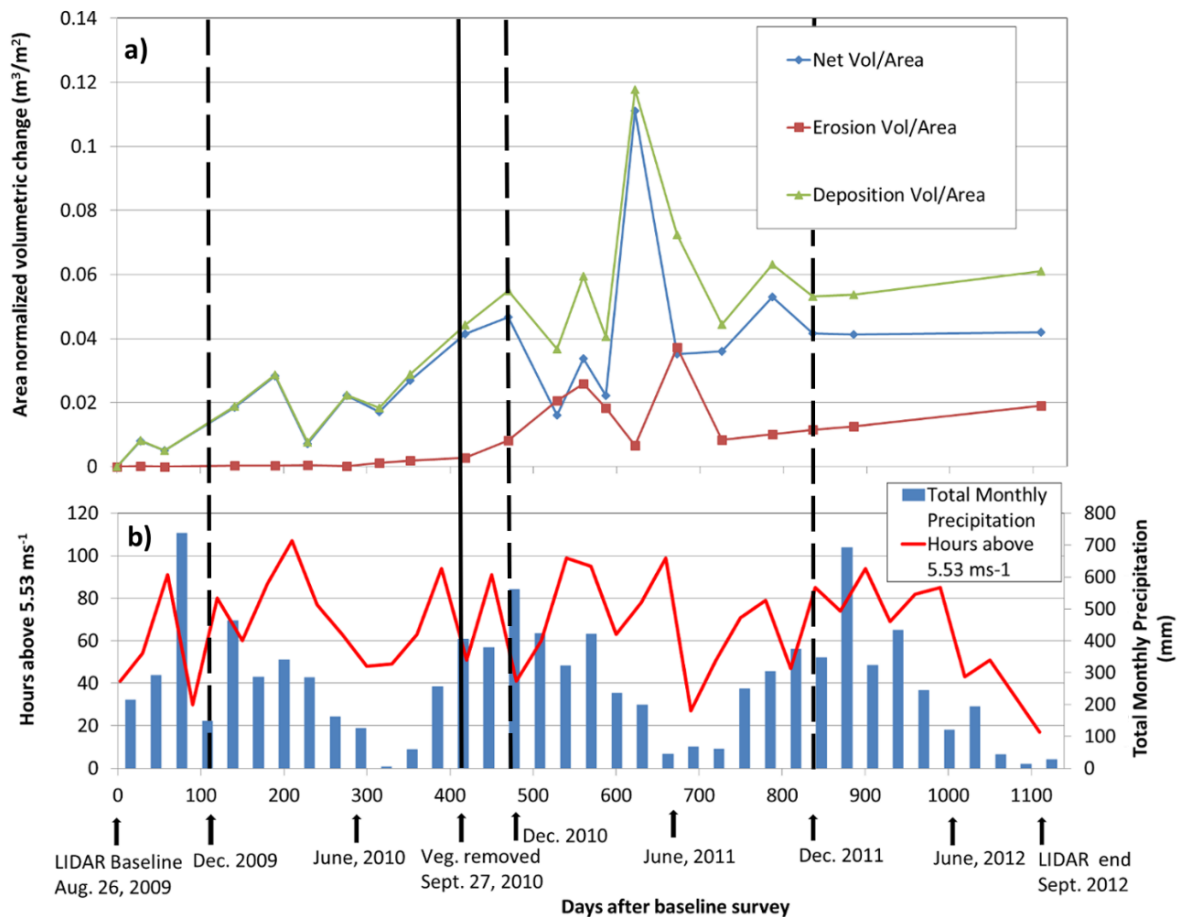


Figure 27. a) Summary of the area normalized volumetric changes observed solely within the transgressive dunefield landscape unit from the preceding sediment budget. Note the pulse of sediment observed following vegetation removal and b) the precipitation and wind records that do not indicate any anomalous meteorological conditions.

4.5.2 Dynamic geomorphic mapping

A detailed geomorphic map of the study site, based on the GCD dynamic mapping method described above, is provided in Figure 28. Broad geomorphic units were identified and digitized within the landscape (beach, foredune, transgressive dunefield plain, transgressive dunefield slopes (>25 degrees), and precipitation ridge) within which discrete landforms and sediment budget responses were identified and analysed. The beach unit (red transparent polygon) shows a fairly contiguous berm feature (blue depositional zone), but was analysed as a single morphological unit

wherein volumetric changes are assumed to be the result of largely littoral processes and reflect changes in sand supply to the landward dune systems. The foredune unit (green transparent polygon) includes both an incipient foredune region on the backshore and the established foredune itself. The foredune was fairly uniform in morphology, with the exception of sporadic blowouts and related depositional lobes that extended landward into the transgressive dune plain (beige transparent polygon). The majority of digitized, discrete landforms exist on this relatively flat transgressive dune surface backing the foredune, while further landward the surface becomes steeper (facing seaward, yellow transparent polygon) and has fewer distinct landforms. The last major landscape unit (purple transparent polygon) is a depositional precipitation ridge on the landward (SE) margins of the transgressive dunefield. Precipitation ridges are aeolian dune forms that typically form as distinct ridges with dominant slip-faces or long-walled deposits on the downwind margins of transgressive dunefields where sediment is being deposited (or precipitating) into forested or otherwise stabilized terrain (Cooper, 1967; Hesp and Walker, 2013).

Importantly, the map also includes the DOD generated from the GCD change detection simulation calculated from the August 2009 to September 2012 LIDAR DEMs across the full landscape. Erosional (red) areas and depositional (blue) areas and their respective magnitudes are clearly distinguishable and were used to identify and delineate various dune features on the geomorphic map. The nomenclature for these landforms is indicated in the legend of Figure 28. With reference to the vertical elevation changes, generally, the greater magnitudes of vertical change (darker colours of red or blue) are used to infer greater amounts of aeolian activity (deflation or

accretion) and, thus, areas of greater sediment mass exchanges and morphodynamics. Identification of the landform boundaries and the interconnectedness of landform and landscape components, such as deflation basins and depositional lobes, was aided by the GCD DOD overlays as it provides more detail regarding the magnitude and extent of areas experiencing change than is visible from interpretation of orthomosaic imagery alone.

The landscape contains many readily identified dune types, including blowouts, parabolics, transverse dunes, remnant knobs, nebkha, precipitation ridges, and shadow dunes. The southern extent of the dunefield, however, is more complicated due to the presence of large tree islands (in the sense of Cooper, 1958), which are classified here as nebkha and remnant knobs. In actuality, it is difficult to distinguish the genesis of these in the dunefield as the photographic record is not long enough, and we have identified the two (nebkha vs remnant knob) purely on their present morphologies. Deflation basins and depositional lobes are often interconnected amongst semi-vegetated and static dune ridges as well as trailing arms of actively migrating parabolic dunes. These semi-vegetated ridges are interspersed amongst other clearly identifiable dune landforms and become more convoluted with complex deflation basin networks and overlapping depositional lobes migrating into the forest margin downwind. The result is a complex network of interacting and possibly temporally superimposed features that are not easily identified. As such, these areas are simply identified as dune complexes 1 and 2. Several smaller landforms are delineated on the map but, given the conservative thresholds for change detection and low change volumes, they remain

unclassified due to uncertainty in accurate classification using the change detection method.

At the landscape scale, the beach accumulates a very large amount of sediment compared to the other geomorphic units given the ample supply of sediment offshore, a high-energy, dissipative littoral system, and ongoing relative sea-level drop. Combined, this leads to long-term coastal progradation at rates of up to 1.1 m a^{-1} , although localized erosion is frequent. Erosion is evident in the DOD map (red pixels) toward the north of the study area where a beach cusp established by the time of the September 2012 LIDAR survey. Given the ample sediment supply on the beach and competent wind regime, the coupled incipient and established foredune zone accumulates large amounts of sediment on the seaward (stoss) slope of the foredune with up to $+1.5 \text{ m}$ of vertical growth along the seaward edge of the landscape unit. Vertical gains on the foredune crest itself are more modest ($+0.25$ to $+0.5 \text{ m}$) and are not continuous due to the presence of interspersed blowouts with corresponding vertical losses (deflation troughs or basins) and connected depositional lobes (vertical gains).

The transgressive dune plain units have large areas of negligible change at this detection threshold, but a network of dynamic landforms is visible by way of active deflation and deposition patterns, large resulting volumetric changes, and rapid downwind migration patterns (Table 8). For instance, a lone transverse dune (Trv1) migrated along the upward sloping transgressive dune surface near the precipitation ridge at an average rate of 2.77 m a^{-1} with vertical losses up to -2.0 m on the upwind deflation basin and vertical growth exceeding $+3.5 \text{ m}$ downwind on the slipface. This transverse dune, along with several other depositional lobes in the dune complexes

vantage photographs that show; a) the evolution of a foredune blowout migrating into a landward swale, and b) the evolution of parabolic dune migrating inland; both following the foredune vegetation removal disturbance. In Figure 29a, the sequence shows the foredune two years prior to disturbance, five months after (with nebkha (tree island) and swale devegetated), one year after (with some grass vegetation re-establishing), and nearly 6 years following the initial disturbance. Considerable reworking of sediment from the foredune is evident with infilling of the swale in the lee of the cleared foredune. In the final image from May 2017, the development of a new blowout is evidenced by a distinct depositional lobe extending from the lee of the foredune crest (see Figure 28, Blowout 6). In Figure 29b, Parabolic dune 1 (see Figure 28) is shown one month prior to the disturbance of the seaward foredune in September 2010, seven months after, two years after, and nearly seven years after in May 2017. The rapid extension of the depositional lobe and trailing arms of the parabolic dune is shown and indicates an increase in landward transfer of sediment through the foredune into the transgressive dune field. As of May 2017, the depositional lobe had engulfed several smaller landforms such as Blowout 4 and may do the same to the smaller Parabolic dune 2 as it continues to migrate and encroach upon the trailing arm and deflation basin of the downwind landform. Interpretation of these photo sequences confirms what is seen in the sediment budget data, which indicate large volumes of sediment accumulating downwind of the beach and foredune during the spring and summer months following removal of foredune vegetation the preceding fall.



Figure 29. Photo sequences taken between August 2010 and May 2017 demonstrating: a) foredune vegetation removal, recovery and evolution; and b), the evolution of a landward parabolic dune following widespread foredune disturbance, note the migration of the depositional lobe relative to a consistent vegetation patch indicated by the black arrow.

To provide a more in-depth assessment of morphodynamic changes in the landscape, several individual landforms in the transgressive dunefield were analyzed using the raster based GCD method within discrete boundaries of the features themselves. Three different dune types were selected from the geomorphic map (Transverse dune 1, Blowout 4, and Parabolic Dune 2, see locations in Figure 28) and vector polygons delineating their boundaries were digitized to crop data from the 2009 and 2012 LIDAR DEMs. This approach allowed for the assessment of 4D changes in morphology and sediment volume for assessing responses of different dune types within the transgressive dune system to disturbance on the foredune. Vignettes of landform change and active morphodynamics for each of three landforms are presented in Figures 30, 31, and 32. For each, the active surfaces of the landform (blue = depositional, red = erosional) defined by the raster DoD overlay from the GCD analysis are indicated within the overview orthophoto and an inset photograph with vantage cone shows a ground perspective view. The distribution of statistically significant volumetric changes for each landform at the end of the three-year study period is also shown as a

histogram. Related values of net, erosional and depositional changes, as well as migration distances and rates are shown in Table 7 and various descriptive statistics are provided in Table 8.

Table 7. Summary of volumetric and areal changes and migration rates for the three distinct landforms: Transverse dune 1 (Trv1), Blowout 4 (Bo4) and Parabolic 2 (Pb2).

Dune Feature	Volumetric Change (m ³) / Area normalized (m ³ /m ²)			Areal change (m ²)		Migration Distance (m)	Migration rate (m yr ⁻¹)
	Erosion	Deposition	Net change	Area of erosion	Area of deposition		
Transverse Dune 1 (Trv1)	-478.6 / -0.92	+413.3 / +1.51	-65.3 / -0.08	521.3	273.1	8.3	2.77
Blowout 4 (Bo4)	-4.87 / -0.19	+42.8 / +0.41	+37.94 / +0.29	25.41	103.28	3.8	1.27
Parabolic 2 (Pb2)	-103.6 / -0.77	+285.4 / +1.07	+181.9 / +0.45	135.3	267.5	8.8	2.93

Table 8. Descriptive statistics for the volumetric changes in the individual landforms, listed in Table 3, and broken down accordingly with summaries for net change, erosional change, and depositional change.

Landform	Mean (m ³)	Standard Deviation	Standard Error	Variance	Skewness	Kurtosis	Shapiro-Wilk p-value
Transverse Dune 1 (Trv1)	+21.43	16.27	2.15	264.65	1.49	1.62	0.0000013
Transverse Erosion	-33.86	21.36	4.78	456.23	0.12	-1.15	0.386
Transverse Deposition	+14.85	6.24	1.04	38.99	0.49	0.29	0.3507
Blowout 4 (Bo4)	+1.59	1.08	0.2	1.16	0.48	-0.36	0.04915
Blowout Erosion	-0.47	0.28	0.09	0.08	-0.25	-0.79	0.6933
Blowout Deposition	+1.95	0.99	0.21	0.98	0.21	0.21	0.9479
Parabolic 2 (Pb2)	+7.91	5.24	0.58	27.47	0.71	-0.22	0.00144
Parabolic Erosion	-7.16	4.37	0.86	19.12	-0.13	-1.01	0.1565
Parabolic Deposition	+8.38	5.6	0.76	31.31	0.8	-0.46	0.000426

4.5.3.1 Transverse Dune 1 (Trv1)

The only transverse dune observed at the study site was migrating along the precipitation ridge at the landward edge of the dunefield (Figure 30). As such, this dune was selected to represent landform responses that are considerably removed from the disturbed foredune. Transverse Dune 1 migrated laterally along the precipitation ridge approximately 8.3 m to the southeast with some encroachment onto the forest margin. This translates to a rate of 2.7 m a^{-1} between August 2009 and September 2012. Volumetric changes for the landform as a whole over this time show a slight net loss of sand volume of -65.3 m^3 ($-0.08 \text{ m}^3 \text{ m}^{-2}$). However, examination of erosional and depositional components show that the upwind deflation surface experienced widespread erosion of -521.3 m^2 ($-0.92 \text{ m}^3 \text{ m}^{-2}$) to change what was previously a flat and consistently sloped surface on the precipitation ridge into a pronounced deflation basin on the northern upwind extent. Concurrently, the leading depositional slip face shows a smaller area of change 273.1 m^2 ($+1.51 \text{ m}^3 \text{ m}^{-2}$) but advanced along the upper ridge and began depositing large amounts of sediment in a concentrated area just over the edge of a pre-existing slope break resulting in the higher value of area normalized change. This resulted in volumetric gains across a wider range of elevation changes (up to $+3.6 \text{ m}$ of vertical change shown Figure 30b). The majority of erosion is associated with vertical losses of between -0.5 m and -1.2 m with a steady decline to slight volumetric losses with vertical changes up to -2.0 m . The depositional volumes, in contrast, are much more consistently spread out across the 3-meter range of vertical gains.

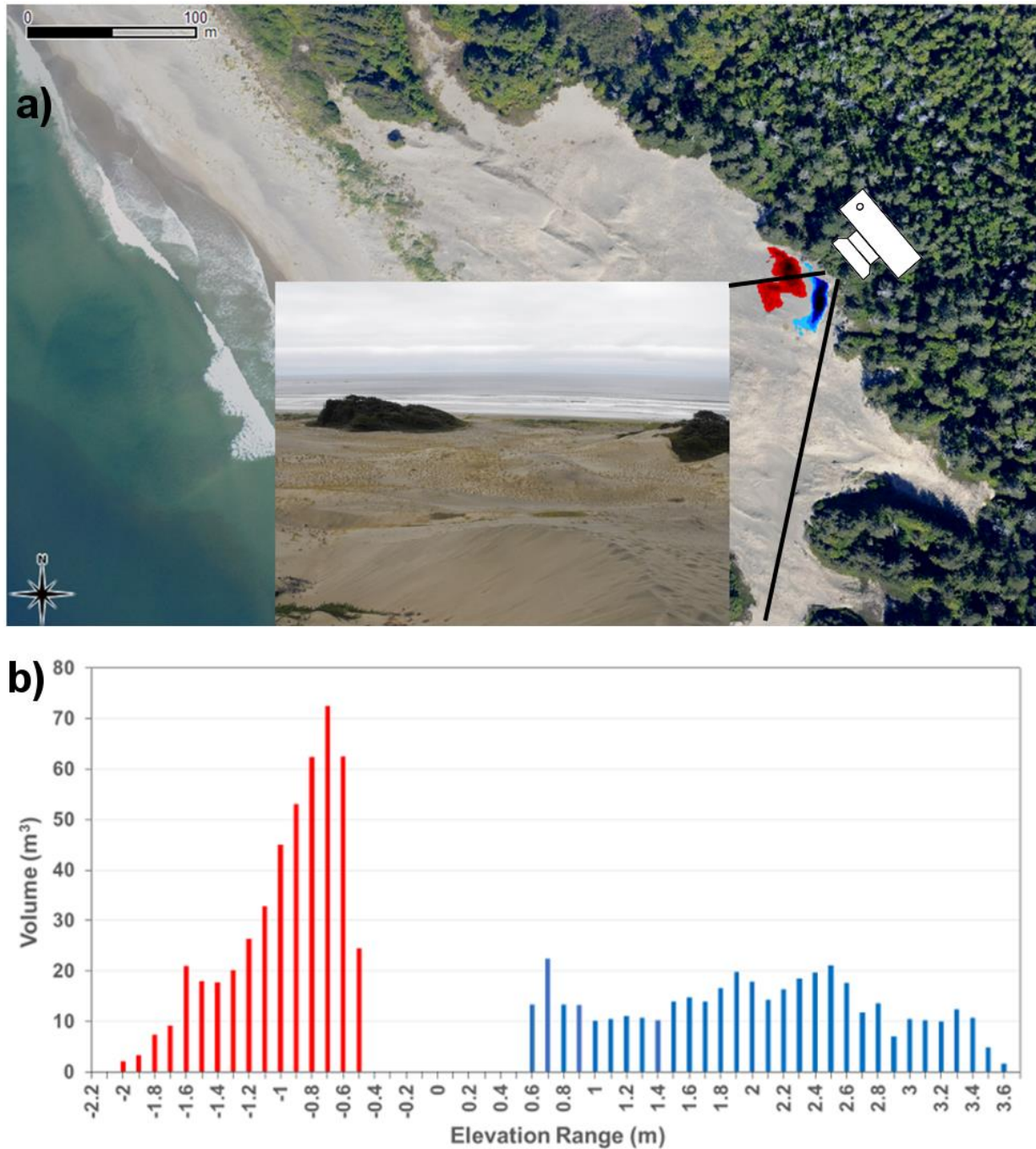


Figure 30. Vignette of geomorphic change for the only transverse dune (Trv1) in the landscape, including: a) location within the landscape and change patterns, using the difference surface overlay from the GCD between the 2009 and 2012 lidar DEMs, and b), corresponding histogram showing the distribution of volume by elevation range. An inset photograph is also included in part a) with a vantage cone indicated by black lines and the camera icon.

4.5.3.2 Parabolic Dune 2 (Pb2)

Parabolic dune 2 (Figure 31) was selected for additional analysis as it was a distinct feature identifiable in the August 2009 orthophoto prior to vegetation removal on the foredune, as opposed to new sub-parabolic or parabolic dunes that may have emerged following disturbance. Moreover, it was located just to the southeast of a wide area of foredune that was mechanically cleared of vegetation, with only a 15 m wide swale separating it from the disturbed area. The depositional lobe of Pb2 migrated 8.8 m downwind to the SE at a migration rate of 2.93 m a^{-1} over the observation period. Overall, this landform experiences -103.6 m^3 ($-0.77 \text{ m}^3 \text{ m}^{-2}$) of erosion and $+285.4 \text{ m}^3$ ($+1.07 \text{ m}^3 \text{ m}^{-2}$) of deposition for a net volumetric gain of $+181.9 \text{ m}^3$ ($+0.45 \text{ m}^3 \text{ m}^{-2}$). This volumetric gain corresponds with the large area of deposition (267.5 m^2) and rapid growth and migration of the depositional lobe, versus the smaller area of erosional change (-135.3 m^2) contained within the deflation basin.

Figure 31 b) demonstrates the distribution of volumetric change with respect to associated elevation changes. From the histogram you can see there is a steady decline in volume of erosion (red) as the magnitude of vertical elevation loss increases. With respect to vertical gains and deposition (blue), there is again a decrease in volume with increasing magnitude of vertical elevation change, but there is a larger range of vertical changes (up to $+2.65 \text{ m}$) leading to the overall positive sediment balance of the landform. Most of this sediment is contained within the leading edge of the depositional lobe that is migrating down a large slope which, in part, drives the high elevation changes and corresponding high volumes of deposited sediment. As this parabolic dune is located within the transgressive dunefield landscape unit used for sediment budget

analysis (section 4.5.1), the timing of its growth likely mirrors the volumetric record of the broader landscape unit (Figure 27a).

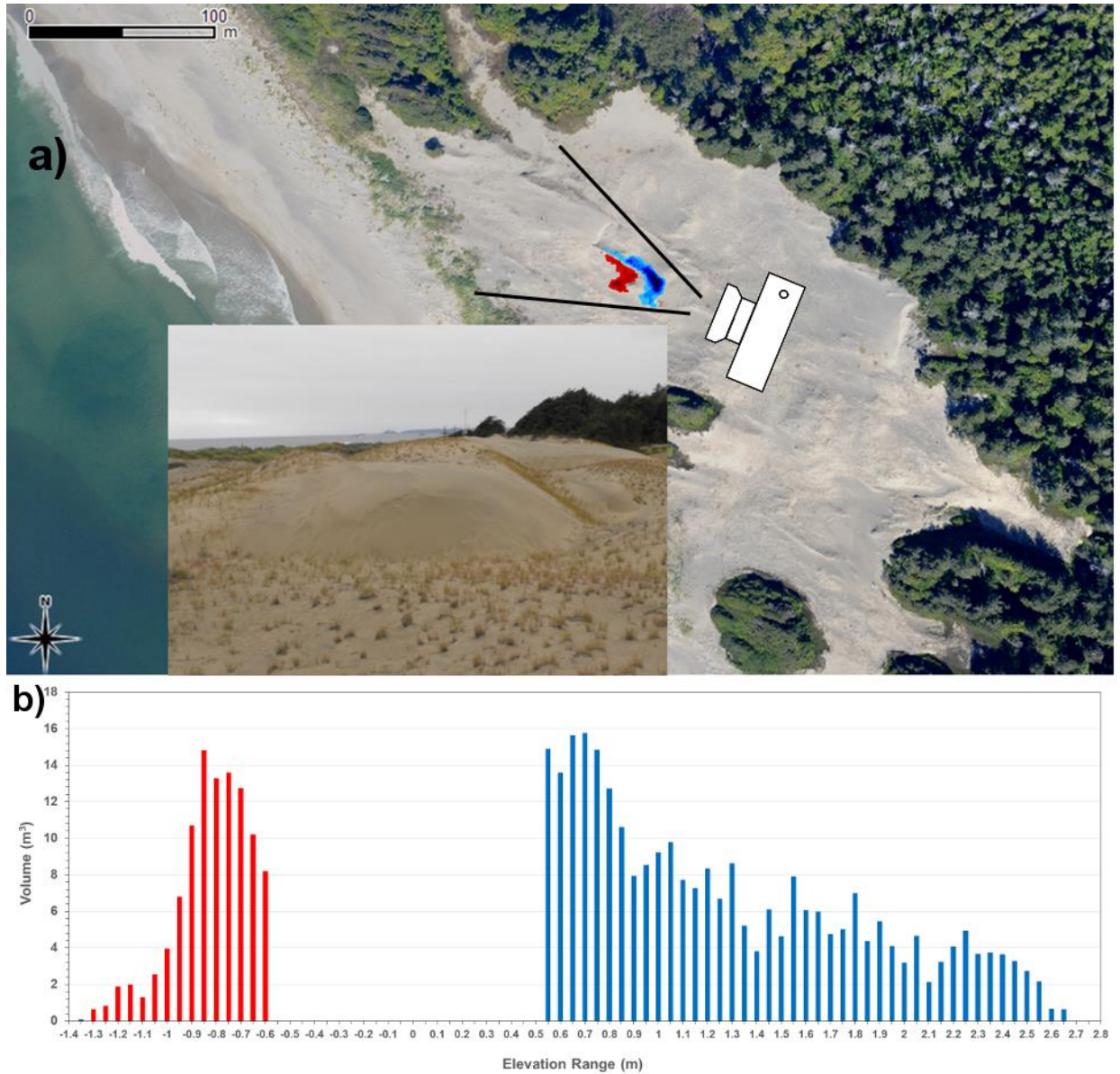


Figure 31. Vignette of geomorphic change for a prominent parabolic dune (Pb2) in the landscape, including: a) location within the landscape and change patterns, using the difference surface overlay from the GCD between the 2009 and 2012 lidar DEMs, and b), corresponding histogram showing the distribution of volume by elevation range. An inset photograph is also included in part a) with a vantage cone indicated by black lines and the camera icon.

4.5.3.3 Blowout 4 (Bo4)

Blowout 4 (Figure 32) is located between Parabolic Dune 1 and Parabolic Dune 2 on the leeward side of their tall depositional lobes (location shown in Figure 28 and Figure 32). This landform did not exist prior to foredune disturbance and was not observed until the spring months following the foredune vegetation removal. By the time the inset photograph was taken in May, 2017 (Figure 32a), the blowout had a clearly defined deflation basin and depositional lobe. Despite blowouts being perceived as predominantly 'erosional' features, this new landform is net depositional and saw a net volumetric change of $+37.94 \text{ m}^3$ ($+0.29 \text{ m}^3 \text{ m}^{-2}$) with -4.87 m^3 ($-0.19 \text{ m}^3 \text{ m}^{-2}$) of erosion and $+42.8 \text{ m}^3$ ($+0.41 \text{ m}^3 \text{ m}^{-2}$) of deposition. The leading edge of the depositional lobe migrated 3.8 m (1.27 m a^{-1}). In terms of areal change, the blowout was considerably smaller than the other landforms examined (25.41 m^2 of erosion, 103.28 m^2 of deposition). The pattern from the histograms further demonstrates the dominance of depositional processes. Erosive (red) changes and volumes come from a discrete range of vertical losses -0.25 m to -0.5 m . Whereas the depositional (blue) side of the histogram indicates that vertical gains ranging from $+0.25 \text{ m}$ to 1.1 m all contribute to the higher volume of deposited sediment. Moreover, the large 1.1 m vertical gains also confirm that the leading depositional lobe is migrating down a slope. Generally, the timing of the blowout development aligns with the pulse of sediment observed in the transgressive dunefield unit (Figure 27a), demonstrating the link between landscape and landform scale behavior.

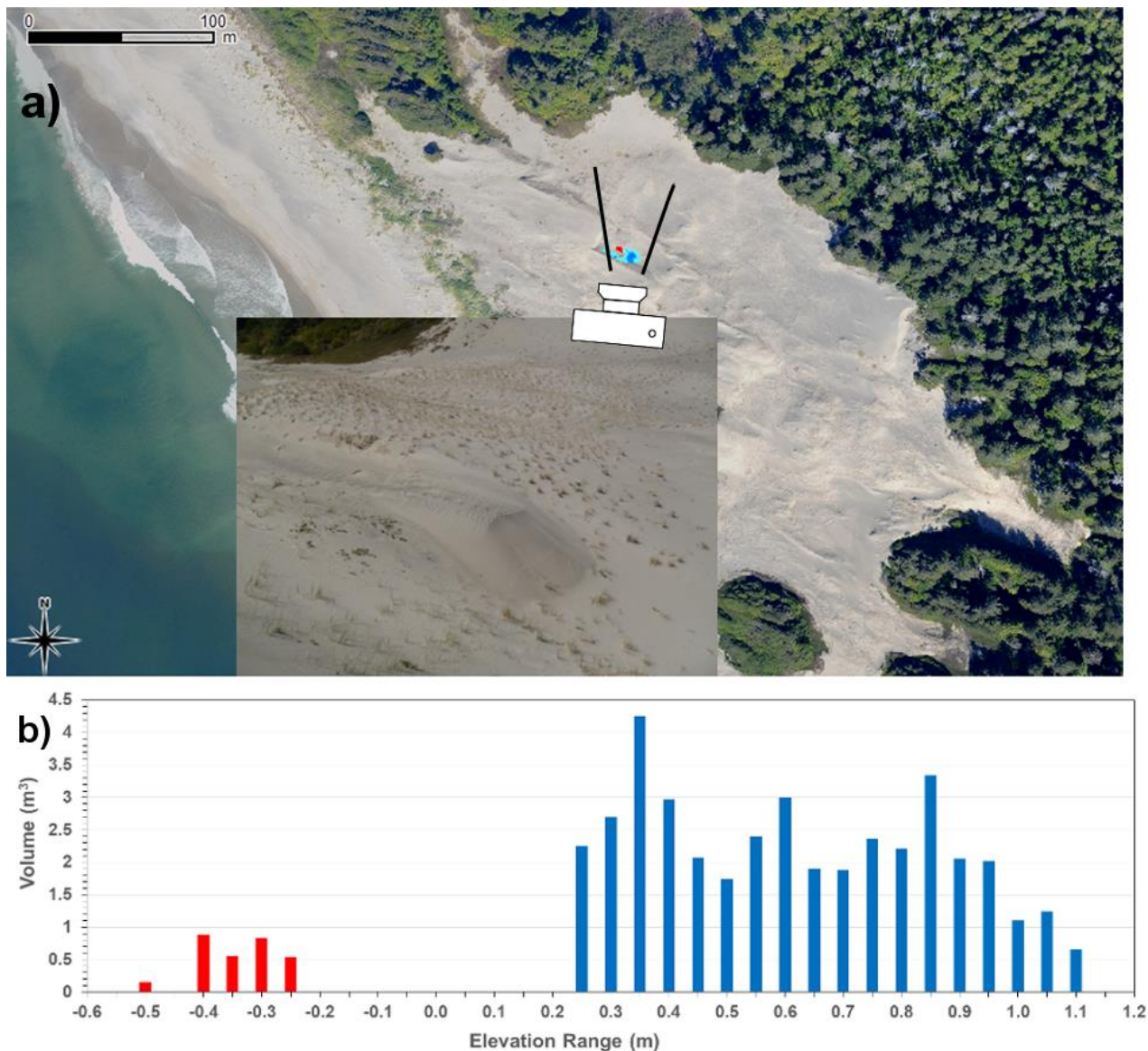


Figure 32. Vignette of geomorphic change for a small blowout (Bo4) in the transgressive dunefield, including: a) location within the landscape and change patterns, using the difference surface overlay from the GCD between the 2009 and 2012 lidar DEMs, and b), corresponding histogram showing the distribution of volume by elevation range. An inset photograph is also included in part a) with a vantage cone indicated by black lines and the camera icon.

4.6 Discussion

4.6.1 A new approach to ‘dynamic’ geomorphic mapping of aeolian systems

This study used repeat, detailed topographic surveys, originally acquired for dune restoration monitoring (Darke et al., 2016, 2013; Walker et al., 2013, Eamer et al., 2013) and established geomorphic mapping and volumetric change detection techniques to

develop a new dynamic mapping method that provides improved characterization and quantification of the morphodynamics and sediment budget responses of a beach-foredune-transgressive dune complex to a disturbance event (removal of invasive vegetation). The resulting dynamic mapping method incorporates statistically significant change detection outputs in a raster format and uses related data on volumetric changes to identify and interpret the spatial-temporal behaviour of dune features and their related aeolian activity.

Generation of geomorphic maps has traditionally relied on static images of landscapes that, individually, provide limited information regarding active morphodynamics and changes related to sedimentation patterns. For instance, parabolic dunes are defined not only by their morphology, but also by the linkages and sediment exchanges between their eroding deflation basins, trailing arms, and depositional lobes. More broadly, the method can reveal the interconnectedness of various landforms and landscape components using the change detection surface, which indicates not only the magnitude and rates of change, but also the spatial patterns of change that better define how erosional and depositional components are connected and, by inference, the aeolian processes at work. Such information is not typically incorporated in traditional 'static' maps and, thus, this dynamic mapping method provides insights into the 4-D spatial-temporal behaviour of dune systems (Mitasova, et al., 2009, 2012; Allen et al., 2012; Bishop et al. 2012; Petras et al., 2015; Darke et al., 2016). Integration of high-resolution geo-computational technologies and digital mapping methods can now be utilised easily to better model and understand geomorphic processes in dynamic environments (Bishop, 2012) such as beach-dune

systems. In the current study, this approach was used to provide a more informative mapping product that captures the dynamic nature of the dunefield by way of spatial-temporal erosion-deposition patterns following a foredune disturbance event.

As applied to the Wickaninnish Dunes system in this study, this method greatly aided the interpretation of system response to widespread foredune disturbance as part of an ongoing dune restoration program. Wave erosion and overwash events are some of the most common disturbance processes that impact foredunes (Hesp and Martinez, 2007), while widespread mechanical removal of foredune vegetation also can generate appreciable disruption in foredune morphodynamics and sediment budgets (Hesp and Hilton, 2013; Darke et al., 2013, 2016; Eamer et al., 2013; Walker et al., 2013). The dynamic mapping method used in this study, like other recent developments in geomorphological mapping, moves beyond the simple delineation of boundaries of dune features and allows for a fuller understanding of dunefield responses to disturbance (cf. Evans, 2012), and as discussed in detail in the following section.

4.6.2 Landscape sediment budget and morphodynamic responses to foredune disturbance

At the landscape scale, there are observed linkages between the morphodynamic and sediment budget responses of the beach, foredune, transgressive dunefield and the sub-features (parabolic, blowout, and transverse dunes) therein. Partly, this relates to the disturbance of the foredune for vegetation removal, which was part of a Parks Canada Agency (PCA) dynamic restoration program. As discussed in detail in Darke et al. (2016), the study area experienced a pronounced spike in area normalized volumetric change in the spring and summer months following foredune

vegetation removal in the previous fall of 2011. Meteorological records show no anomalous conditions to suggest that the observed responses were driven primarily by, for example, above average occurrence of transporting winds and/or below average precipitation. Site-wide assessment of sediment volume changes within connected landscape units suggests that the observed spatial patterns of sediment erosion and deposition might be linked more so to the foredune restoration disturbance. This disturbance event liberated significant amounts of sediment into the transgressive dunefield and allowed for increased aeolian inputs into and beyond the foredune directly from the beach, the majority of which might have been otherwise trapped in the prominent, densely vegetated foredune ridge. This increased sand bypassing is evident in photographs from May 2017, nearly six years following the initial disturbance event, which show depositional lobes associated with new foredune blowouts actively accumulating in the lee of the foredune, which was cleared of vegetation in September 2011 (Figure 29a). The combined effects of flattening the foredune crest during mechanical removal of vegetation and blowout development resulted in improved aeolian transport corridors into the landward dunefield. The more recent observations and vantage photographs (Figure 33) of the study site elsewhere in 2017 also demonstrate extensive revegetation and recovery of a relatively tall and continuous foredune that had been replanted densely by PCA staff with native *Elymus mollis* (dune grass). This response is particularly evident at the northern extent of the study area, which was impacted by the largest extent of vegetation removal (Fig. 23a). When compared with the September 2012 orthophotograph (Figure 23b), this suggests that re-vegetation of the disturbed foredune is occurring rapidly, which will reduce the

transport corridors created by the vegetation removal, thus progressively limiting sediment inputs to the transgressive dunefield. As such, without continued vegetation maintenance to ensure some landward transport, as is typical for native foredunes in this region that host *E. mollis* (vs. *Ammophila* spp) communities, it is possible that the system could eventually return to pre-disturbance conditions and a trend towards vegetation stabilization. Landforms landward of the disturbed foredune clearly exhibit active morphodynamics that are associated with landward transfers of sediment from the beach and foredune, yet many areas of the dunefield remain static and support sparse populations of *Poa marcanthra*, Kinikinick (*Arctostaphylos uva-ursi*), and other stabilizing plant species. Indeed, prior research (Heathfield and Walker, 2011) indicates that the longer-term trajectory of the system has been toward stabilization at an estimated rate of approximately 0.83 % loss of active sand surface area per year between 1973 and 2007. Encroachment of depositional lobes onto the downwind (southern) margins of the site appears to have accelerated in recent years, perhaps associated with the increased pulse of aeolian sediment within the system. This may cause some localized expansion of active sand surface in coming years, but the effects of this will slow as system-wide recovery from the disturbance continues in the absence of a vegetation maintenance program to limit re-establishment of invasive *Ammophila* spp. on the foredune. Thus, the system will most likely return to its natural trajectory towards stabilisation (Darke et al., 2016). As such, this study indicates that large scale foredune disturbances can trigger active morphodynamics and sediment exchanges within a much broader, linked transgressive dune ecosystem for periods of a few years. This enhanced dynamism will not necessarily be sustained by a single disturbance

event, however. Rather, continued phases of disturbance, either anthropogenic (e.g., restoration activities) or associated with increased frequency of natural disturbance events (e.g., climatic change, foredune erosion) would be required to sustain and/or increase the activity and dynamism of this transgressive dune complex as also indicated elsewhere (see Arens et al., 2013).



Figure 33. Current photo of the largest foredune area impacted by mechanical vegetation removal. The photo was taken in May, 2017 nearly seven years after being completely de-vegetated in September, 2010.

Additional focus on specific landforms within the transgressive dunefield (parabolic dune, blowout, transverse dune) allows for a more in-depth assessment of system dynamics following widespread disturbance to the foredune. Each dune type

demonstrates a unique distribution of volumetric change (see Figures 30-32) and sediment budget response, with the transverse dune exhibiting dominantly erosional behaviour, the parabolic being more depositional, while the blowout was more neutral (only slightly depositional). However, each demonstrate a period of active morphodynamics in the months following the disturbance when aeolian processes are active that mirrors the response of the broader dunefield. With repeat surveys, sediment budgets can be measured to match any desired temporal scale, which can provide incredibly detailed and valuable records of site morphodynamics through time.

4.6.3 Restoring coastal dune disturbance regimes and resilience

The threats to beach-dune systems and sandy coastal ecosystems more generally from climate change impacts, sea-level rise, increasing flooding and/or coastal erosion, and increasing pressures on coastal lands from tourism and development are well documented in the region and elsewhere (e.g., Martinez and Psuty, 2004; Nordstrom, 2008, Page et al., 2011; Martinez et al., 2013; Malavasi, 2016). Other threats, such as invasive species and over-stabilisation of dune landscapes, are more recently being addressed (Page et al., 2011; Martinez et al., 2013; Arens, 2013; Konlechner and Hilton 2014; Pickart and Hesp, 2019). Not surprisingly, trends in dune restoration are shifting to promote dune dynamism and enhanced morphodynamics (e.g., Nordstrom, 2008; Pickart, 2013; Walker et al., 2013). Typically, this has been achieved through widespread removal of stabilising vegetation, particularly on the foredune, and frequently, in the case of the west coast of North America, targeting invasive and non-native species such as marram grass species *Ammophila arenaria* (European beachgrass) and *Ammophila breviligulata* (American beachgrass).

Approaches to dynamic ecosystem restoration differ, but usually involve some type of disturbance to the foredune (where present) and removal of targeted vegetation.

Beyond the intended restoration goals and related research at this site (Darke et al., 2013), these types of restoration projects generally provide opportunities to better understand the resilience of coastal dune systems to, and responses to, large scale-disturbances, such as wave erosion or overwash events.

Disturbance types and processes in coastal dunes have been discussed in great detail in the literature (see e.g. summary by Hesp and Martinez, 2007) and dune research has consistently highlighted the complexity of disturbance processes in coastal dune environments (e.g. White, 1979; Ehrenfeld, 1990; Garcia-Mora et al., 1999; Stallins and Parker, 2003; Forey et al., 2008; Miller et al., 2010, Pardini et al., 2015). However, only a relatively small number of studies have examined the geomorphological impacts of large scale foredune disturbance (natural or induced) on landward dunefields (e.g., Arens, 2013; Van Boxel, 1999; Hesp and Hilton, 2013; Konlechner et al., 2014, 2015; Eamer et al. 2013; Walker et al., 2013; Darke et al., 2013; 2016; Pickart and Hesp, 2018) while research on dune vegetation changes following disturbance is better represented (e.g., Hayden, 1995; Miller et al., 2010, 2015; Malavasi et al., 2013, 2014; Garcia-Mora; Gonzalez-moreno 2013; Pardini et al., 2015; Vechio et al., 2015; Cheplick, 2017). Generally, however, comprehensive long-term (interannual) studies are lacking. Widespread destruction of vegetation may occur naturally following large storm scarping or overwash events, but it is rare that appropriate monitoring protocols are in place beforehand to assess the impacts of these disturbances on landward dunefields through time. An increasing number of dynamic

restoration programs have been implemented, however, that seek to restore the disturbance regime of the landscape and promote dune dynamism using a variety of intentional disturbances such as vegetation removal (frequently involving invasive species, e.g., Pickart, 2013), foredune notching (to promote blowout development, e.g., van Boxel, 1999), or the creation of larger scale blowouts and mini-transgressive dunes (e.g., Arens, 2013). These efforts provide an opportunity to study how natural or anthropogenic disturbance processes and responses in natural environments might be used to improve the longer-term effectiveness of restoration programs as well as dune ecosystem resilience in the face of changing climatic regimes and anthropogenic pressures.

Recent trends in dune restoration programs addressing stabilisation of dune landscapes by invasive species (e.g., *Ammophila* spp. in Pacific North America), aim to promote dune dynamism and historic disturbance regimes (Nordstrom, 2008; Zarnetske 2009, 2012, Pardini et al., 2015, Darke et al., 2016). The research by Pardini et al., (2015) suggests that the restoration of these historic disturbance regimes is critical to the persistence of endangered plants in early and late successional microhabitats. Their study utilises vegetation data collected within traditional 1 m² quadrats to assess demography and abundance within early and late successional dune microhabitats as common for investigations into dune vegetation changes. In the current study at Wickaninnish Dunes, multi-scale geomorphic responses were monitored for the purposes of assessing restoration effectiveness in a geomorphic context. From the data and recent evidence in vantage photography, it appears the disturbance responses are, to some extent, sustained and the dune habitat now possesses more dynamic

conditions favourable for the persistence of threatened dune species. Accordingly, monitoring of vegetation dynamics (as in Pardini, et al., 2015; Pickart, 2013; Murphy et al., 2018) within the intermixed early and late successional microhabitats common to coastal dune systems, needs to be incorporated with robust geomorphic and morphodynamic information to more completely understand coastal dune disturbance regimes.

The results of the current study provide examples of a first step towards providing these types of data required to fill a void in understanding disturbance responses and overall dune dynamics. Multi-scalar geomorphic investigations of beach dunes systems are required to achieve a holistic understanding of those systems (Walker et al, 2017). The criteria for assessing restoration responses at the Wickaninnish Dunes site can be used, at least in part, to parameterise disturbance responses within a geomorphic context. According to Walker et al. (2013) restoration effectiveness is marked by: (1) increased aeolian activity (sand transport, erosion, deposition); (2) enlarged active sand surface areas; (3) a positive sediment budget; (4) increased dune mobility and morphodynamics; (5) improved geomorphic diversity; (6) enhanced geomorphic resilience. These indicators provide relatively straightforward metrics for assessing disturbance responses and their magnitudes in coastal dunefields.

4.7 Conclusions

This study has examined 4-D spatial-temporal changes in a beach-dune system starting at the landform scale and then scaled that up with coupled analyses at the sub-landscape and landscape scale. The mapping and sediment budget analysis used to monitor a beach dune system following a large scale foredune disturbance has

demonstrated that such data can be used to better characterize system dynamics, track disturbance impacts through time, and inform researchers and managers during dynamic restorations.

The effectiveness of dune ecosystem conservation and restoration efforts can now be better assessed using informative dynamic geomorphic maps and the improved techniques for the quantification of patterns and processes of landscape change. This study presented and interpreted a spatial-temporal dataset collected over 3 years following a dune restoration initiative and allowed for a dynamic, 4-D (vs. temporally static) assessment of the dune response and interannual dune morphodynamics to provide a better understanding of landscape responses to foredune disturbance processes. The following conclusions can be made:

1. Dynamic geomorphic maps conveying 4-D spatial-temporal data are under-utilised and can easily be generated using simple geomorphic change detection outputs as available from repeat topographic surveying.
2. The impacts of a large scale foredune disturbance on a landward transgressive dunefield, as studied through 3 year spatial-temporal records, reveals how sensitive a coastal dune landscape can be to a disturbed and/or altered foredune system. An increase of $+0.11 \text{ m}^3 \text{ m}^{-2}$ in the landward dunefield unit is recorded and reveals a disturbance related pulse of sediment through the transgressive dunefield in the active aeolian months following the disturbance. This sediment is ultimately deposited on the precipitation ridge at the forest margins and to some extent the depositional components of landforms within the dunefield. Select landforms, a transverse, parabolic and blowout dune in the transgressive

dunefield backing the disturbed foredune demonstrate a period of active morphodynamics following the disturbance that mirrors the response of the broader dunefield. However, there volumetric responses vary with the transverse dune that is most distal from the foredune being dominantly erosional ($-0.08 \text{ m}^3 \text{ m}^{-2}$) while the blowout and parabolic dunes were more depositional ($+0.29 \text{ m}^3 \text{ m}^{-2}$) and ($+0.45 \text{ m}^3 \text{ m}^{-2}$) respectively.

3. The observed impacts to the landscape and landforms, in similarity to findings of some of the Dutch studies (see Arens et al., 2013), suggest that strategic alterations to the foredune can be used to alter system dynamism but often ongoing interventions will be required to maintain active morphodynamics.
4. Finally, based on these findings it can be suggested that the methods used in this study can be utilised, more broadly, to better understand disturbance impacts in coastal dunefields from a variety of natural and human induced disturbance events.

Overall this research has presented several exciting new avenues for improved data collection strategies that can evolve concurrently with rapidly advancing survey technologies and when integrated with ongoing interdisciplinary and multi-scalar research will improve the understanding of coastal dune dynamics and in particular their evolutionary paths following natural or human-driven disturbance.

5.0 Conclusions

It is hoped that this dissertation has in some small way furthered the study of beach-dune systems, the restoration of the habitats they support, and our general ability to monitor and understand them. Removal of foredune vegetation at the Wickaninnish Dunes in Pacific Rim National Park Reserve near Uclulet, British Columbia, Canada was completed as part of a dune ecosystem restoration program. This project aimed to remove invasive marram grass (*Ammophia spp.*) in order to improve habitat for a variety of threatened or endangered dune species by stimulating aeolian sand transport, active morphodynamics, and a return to the pre-*Ammophila* invasion disturbance regime. The case study at the Wickaninnish sand dunes provided a valuable research opportunity to explore modern “dynamic” approaches to dune restoration, refine monitoring techniques to keep pace with the changing objectives of these dynamic restorations, and develop restoration success criteria that incorporate data from multiple sources and apply them to the Wickaninnish Dunes case study. An attempt was made to incorporate data at multiple spatial-temporal scales in order to provide the types of data, often lacking in monitoring programs, that allow for a more complete assessment of changes to system morphodynamics. As such, the techniques utilised may have implications more broadly to better understand dune processes and the response of dune ecosystems to disturbance.

The second chapter of this dissertation aimed to situate the dune restoration case study within current scientific literature on dune morphodynamics and “dynamic” restoration. Through an extensive literature review, it was clear that historically there was less emphasis placed on geomorphic processes in dynamic restoration projects as

they have typically been evaluated by measuring changes in species diversity, vegetation structure, or ecological processes such as nutrient cycling. As such, the literature review and the preliminary data were used to develop specific geomorphic success criteria for assessing restoration effectiveness that were applied in the third chapter to a more robust data set with streamlined methods of volumetric assessment.

The analyses in the third chapter confirmed what was suggested by the preliminary data in Chapter 2; that the WICK3/4 transgressive dunefield landscape unit was suitable as a control site with bi-monthly volumetric monitoring data covering a full year period prior to vegetation removal on the seaward slope of the foredune and two additional years after, directly capturing the response over a considerable time period. Most notably, the data demonstrated that a pulse of sediment moved through the transgressive dunefield in direct response to the foredune disturbance and that a more dynamic state could be sustained through ongoing invasive vegetation control. Additionally, responses of several geo-indicators suggested other measures of success or effectiveness of the restoration program, namely, increases in aeolian activity, positive sediment budgets, enhanced morphodynamics, improved geomorphic diversity, and enhanced geomorphic resilience. The findings of Chapters 2 and 3 have a specific focus on the dynamic restoration and were published prior to defense of the dissertation in the peer-reviewed journal *Earth Surface Processes and Landforms* (see Darke et al., 2013, 2016).

The more complicated question of the ability to maintain a more dynamic ecosystem state in the dunefield in any long-term or self-sustaining way, especially in light of natural and climatic trends towards stabilisation, remains unanswered.

Nevertheless, the approach used here was suggested as a first step towards more robust 4-D spatial-temporal change detection necessary for proper identification and interpretation of dune morphodynamics and long term evolutionary trends. Chapters 2 and 3 highlighted the fact that traditional 2-D cross-shore profiles are limited in their applicability for monitoring landscape restoration efforts in dynamic coastal landscapes with oblique onshore sand transport pathways. As possible, broader 3-D survey campaigns with a repeat survey protocol should be used to enable detection and interpretation of 4-D (spatial-temporal) landscape-scale morphodynamics and sediment budget responses. Thus, the goal of the fourth chapter was to extend the utility of the rich data sets acquired from the restoration monitoring and develop new techniques for mapping and monitoring 4-D beach-dune processes. By employing readily accessible survey technologies and data processing packages, detailed topographic datasets can be acquired to characterize and interpret the geomorphic and land-cover responses of large (landscape scale) dune ecosystems and their morphodynamics. The overall findings of the research can be summarised as follows:

1. An increased understanding of the dynamic and non-linear nature of dune processes in active coastal dunefields and the associated vegetation communities adapted to them has naturally led researchers to recognise the importance of aeolian processes and active morphodynamics in dune restoration projects. Overstabilisation of dune landscapes has occurred on temperate coastal dunefields around the globe, frequently due to spread of introduced or invasive species. If efforts are to be made to restore dune systems to pre-invasion conditions, dynamic restoration programs need to be

- informed by current biogeomorphic understanding and re-establishment of key geomorphic processes.
2. The Wickaninnish Dunes restoration program in Pacific Rim National Park Reserve was successful in reducing the cover of invasive *Ammophila* spp., increasing aeolian activity, stimulating positive sediment budgets, enhanced morphodynamics, improved geomorphic diversity, and enhanced geomorphic resilience. However, maintaining this new dynamic state is complicated by the pervasiveness of the invasive grass and current climatic trends that favour dune stabilisation.
 3. Finally, the findings and methodologies used in this study can be utilised to better characterize and understand disturbance impacts in coastal dunefields from a variety of natural and human induced disturbance events. This study demonstrated that readily employable survey technologies and data processing packages can be harnessed more effectively to evolve mapping and assessment strategies in dynamic natural dune environments.

5.1 Future Research

Dynamic coastal landscapes are the result of complex interactions between littoral and terrestrial process that, individually and combined, display non-linear and dynamic behavior that spans a variety of spatial and temporal scales (Walker et al., 2017). On the Pacific coast of British Columbia, Canada, the natural trajectory of most coastal dune systems is moving towards vegetative stabilisation. However, the impact of invasive *Ammophila* spp. on the dynamics of coastal dune systems, and the rate at which they are moving towards stabilisation, cannot be overlooked. Restoration

programs that seek to reactivate stabilised coastal landscapes and restore active aeolian transport and dune morphodynamics will undoubtedly continue in the coming years. For these to be successful, the objectives and criteria for these programs needs to be continually refined and to incorporate foundational geomorphic processes. Moreover, it will be important to determine the level to which dynamic system states can be maintained independently of human interventions and the costly invasive species management usually involved.

Additionally, it should be noted that future research on beach-dune systems and their restoration must address the open nature of these systems. As such, research needs to focus on the sedimentary linkages between the marine and terrestrial components of the system. Again, readily available technologies exist for monitoring nearshore bathymetry and currents and inputs from fluvial systems. The generation of dynamic geomorphic maps, as presented in Chapter 4, at the embayment or littoral cell scale, can be generated at a variety of spatial-temporal scales to more effectively characterize coastal sedimentary processes in order to improve understanding of coastal systems and better model their evolution. Ideally, this will be completed in conjunction with sediment budget records that track volumetric changes in linked landscape units. As demonstrated in this dissertation, special consideration needs to be given to defining unit boundaries that effectively represent the linked nature of the landscape units as source and sink components. Furthermore, linkages in processes at all scales should continue to better relate event based research, both marine (e.g. wave erosion events) and terrestrial (e.g. aeolian transport events) with meso- and macro-scale coastal evolution.

It is through this type of data integration that future research can aid in developing our understanding of coastal dune systems in general. Indeed, field-based investigations need to inform modelling studies that attempt to simulate nonlinear dynamics of geomorphic systems, not only to improve overall understanding, but also to inform ecosystem restoration efforts.

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