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Evolution of a foredune and backshore river complex on a high-energy, drift-aligned beach

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ABSTRACT

This paper examines the multi-decadal evolution of a foredune and backshore river complex on a wave-dominated, drift-aligned coast at Wickaninnish Bay on southwestern Vancouver Island, British Columbia, Canada. Local shoreline positions are generally prograding seaward as fast as $+1.46$ m a^{-1} in response to rapid regional tectonic uplift and positive onshore sediment budgets. The northern end of the foredune system has extended rapidly alongshore in response to net northward littoral drift. Despite these net accretional responses, the beach–dune system experiences relatively frequent (return interval ~1.53 years) erosive events when total water levels exceed a local erosional threshold elevation of 5.5 m above regional chart datum. Geomorphic recovery of the beach–dune system from erosive events is usually rapid (i.e., within a year) by way of high onshore sand transport and aeolian delivery to the upper beach. This response is complicated locally, however, by the influence of a backshore river that alters spatial–temporal patterns of both intertidal and supratidal erosion and deposition.

Historic landscape changes and rates of shoreline positional change are derived from several years of aerial photography (1973, 1996, 2007, 2009, 2012) using the USGS Digital Shoreline Analysis System (DSAS). Significant volumetric changes are also estimated from aerial LiDAR-derived DEMs in 2005, 2009 and 2012, and related morphodynamics are interpreted using a statistically constrained geomorphic change detection method. Results suggest that supratidal bar development, overwash deposition and aeolian deposition on a low-lying supratidal platform, combined with alongshore extension of the foredune complex, is forcing Sandhill Creek to migrate northward in the direction of beach drift. In response, the river actively erodes (-1.24 m a^{-1}) a bluff system landward of the channel, which generates substantial sediment volumes (-0.137 m^3 m^{-2} a^{-1}) that feed a large intertidal braided channel and delta system. These local responses provide context for a conceptual model of the evolution of a wave-dominated, drift-aligned beach–foredune system that interacts with a backshore river. This model may provide useful information to local park managers as erosion and sedimentation hazards threaten visitor safety and park infrastructure.

1. Introduction

The morphodynamics and longer-term evolution of wave-dominated coasts are shaped dominantly by erosion, deposition, and transport of sediment via high-energy wave processes and wave-generated currents (Davidson-Arnott, 2011). Coastal geomorphology in wave-dominated environments is often characterized by elongate shore-parallel sedimentary forms including longshore bars, beaches, beach ridges, and foredunes (e.g., Wright, 1977; Short and Hesp, 1982; Hesp, 2002). On such wave-dominated coasts, process-response morphodynamics typically depend on the magnitude and timing of wave energy with other forcing mechanisms such as tides, surge, and/or wind energy that control nearshore and onshore sediment transport and supply. Davies (1980) distinguishes drift-aligned coasts as those that are oriented obliquely to an incident wave approach that generates strong, alongshore sediment transport gradients. In contrast, swash-aligned coasts are oriented essentially parallel to the incident wave approach and have negligible net alongshore transport rates. On drift-aligned coasts, beach–dune morphology is the net result of alongshore alignment of beach and barrier deposits and elongate swash bars and levees that can weld to the beach and, in turn, provide an onshore sediment source for shore parallel foredune growth and establishment (Sherman and Bauer, 1993; Anthony and Blivi, 1999).

Foredune development is common on high-energy coasts with high onshore sediment supply and competent winds (Short and Hesp, 1982; Hesp, 2002). Foredune morphology can vary in complexity, height, and volume depending on a number of variables such as: i) sand supply; ii) vegetation type and density; iii) rates of aeolian deposition and/or erosion; iv) shoreline movement state (i.e. progradation or retrogradation); v) frequency and magnitude of other environmental forcing

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mechanisms (e.g., storm erosion, wave, or tidal forcing); and vi) anthropogenic impacts (Hesp, 2002). High energy, dissipative beaches typically host the largest foredunes as a result of high potential wave-induced sand transport and aeolian sand delivery to the upper beach (Short and Hesp, 1982). Compared to tidally-dominated or -modified beaches with moderate wave energy, wave-dominated beaches typically provide the largest volume of sediment necessary for dune formation. On beaches with oblique wave approach, a net alongshore drift can form nearshore and intertidal bars that can develop into an alongshore ridge that, in response to wave run-up, can grow to supratidal elevations and extend into vegetation and other debris (Carter et al., 1992). Aeolian transport and deposition on supratidal ridges or beach plains can, in turn, initiate development of incipient dunes in the backshore (Carter et al., 1992; Hesp, 2002; Anthony et al., 2006). With infrequent storm wave erosion and overwash, this incipient foredune zone can develop into an established foredune, which is distinguished by a greater height and volume of sediment and often the establishment of woody plant species (Hesp, 2002). On drift-aligned beaches, foredunes can extend alongshore and build upon former swash bars, overwash deposits, or supratidal beaches, partially in response to the preferential down-drift deposition of sediments (e.g., Wright, 1977).

River outflows on high-energy coasts and resulting sediment dispersal and accumulation in marine deltas are modified to varying degrees by wave, tide, and surge forcing (e.g., Wright, 1977; Carter et al., 1992; Cooper, 2001; Bhattacharya and Giosan, 2003; Psuty, 2004; Ashton and Giosan, 2011; Nardin et al., 2013; Anthony, 2015). More specifically, these marine processes alter fluvial outflow and associated sediment transport by: i) promoting rapid mixing and momentum exchange between river discharge and ambient waters, ii) adjusting base level and hydraulic gradient in the lower reach of the river, and iii) redistributing and reshaping river mouth morphology following initial deposition and formation of the channel. Combined littoral and aeolian activity can promote supratidal barrier development and result in a closure-breach process common to some estuarine or lagoon systems (e.g., Carter et al., 1992; Rich and Keller, 2013; Clarke et al., 2014). On high-energy coasts, however, this process may not always occur as wave energy and tidal incursions that rework the lower channel may prevent channel closure. A recent review by Anthony (2015) describes in detail the importance of wave energy in mobilizing and redistributing nearshore deposits alongshore and thereby influencing delta formation. Essentially, the spread and direction of incoming wave energy control fluvial sediment discharge patterns and, in turn, delta forms and related geomorphic processes such as shoreline progradation.

This paper examines the decadal-scale evolution of a foredune and backshore river complex on a wave-dominated, drift-aligned beach wherein process-response morphodynamics are controlled by the joint interactions between fluvial, littoral, and aeolian processes. The objectives of the paper are to: i) examine changes in historical shoreline positions from aerial photographic coverage, ii) quantify significant volumetric erosion and deposition changes within defined geomorphic units using aerial LiDAR, and iii) integrate these results with other similar studies to develop a conceptual model that describes the landscape evolution of a foredune and backshore river complex on a wave-dominated, drift-aligned coast. This model provides important information that may be of utility to coastal managers and stakeholders about potential erosion and landscape change impacts in similar geomorphic settings.

2. Study site

Wickaninnish Bay is a 10 km-wide embayment located between Ucluelet and Tofino on the west coast of Vancouver Island, British Columbia, Canada (Fig. 1). The bay is open to the Pacific Ocean and hosts four embayed, sandy beaches bound to varying degrees by rock headlands including: Wickaninnish Beach, Combers Beach, Long Beach, and Schooner Cove. Wickaninnish and Combers beaches are barred and dissipative (wide surf zone) with gradual, shallow bathymetry, mesotidal range (higher high water mean tide, HHWMT, 3.36 m above navigational Chart Datum, or m aCD), and are subject to a seasonally variable, energetic wave regime. During summer, average significant wave height (H_s) is 1.14 m and wave period (T) is 10.89 s, while the average winter H_s is 2.47 m and T is 12.07 s. Overall, Wickaninnish Bay has a maximum observed H_s of 11.44 m and T of 28.57 s. The regional wind regime is seasonally bimodal (Fig. 1, inset) and frequently competent to transport local sands with an estimated aeolian sand transport potential of 9984 $m^3\ m^{-1}$ (beach width) a^{-1} (Beaugrand, 2010). The dominant mode in the wind regime results from strong SE storm winds in the winter months, however, these winds often occur with intensive precipitation, which limits aeolian transport. Winds associated with a more moderate summer mode from the WNW appear to be more geomorphically effective, as reflected in blowout and transgressive dune alignments at Wickaninnish Bay. Combined with a high onshore sand supply, this wind regime produces very dynamic beach, foredune, and landward transgressive dune systems in the region.

Periodic erosive water levels are an integral part of beach–dune morphodynamics in the study area. Frequent dune scarping indicates that high water events capable of exceeding the elevation of the beach–dune junction occur often. Using four cross-shore monitoring profiles, Beaugrand (2010) derived a local erosion threshold elevation of 5.5 m aCD and, based on observed water level records in the region, estimated a recurrence interval for erosive events of approximately 1.53 years. Despite frequent erosion, foredunes along Wickaninnish Bay are prograding seaward by as much as $+1.5\ m\ a^{-1}$ (Heathfield and Walker, 2011), partly in response to rapid regional tectonic emergence in the region (discussed below) but also in response to high nearshore sand supply and rapid dune rebuilding at the site.

Elevated total water levels (TWL) capable of beach–dune erosion are driven by three forcing mechanisms: storm surge, wave run-up, and regional manifestations of known climatic variability (CV) phenomena, such as the El Niño Southern Oscillation (ENSO) and the longer term Pacific Decadal Oscillation (PDO). At Wickaninnish Bay, 61.5% of historical erosive events were driven principally by high stage wave energy, followed by 21.8% resulting from enhanced storm surge events (Heathfield et al., 2013). Regionally, recent research has identified strong associations between the magnitude of environmental forcing mechanisms and known ocean–atmosphere CV phenomena, such ENSO and the PDO, as well as the intensity of the Aleutian Low Pressure System (e.g., Ruggiero et al., 2001; Allan and Komar, 2002, 2006; Barrie and Conway, 2002; Abeysirigunawardena and Walker, 2008; Heathfield et al., 2013). For example, the ENSO phenomenon, which ultimately results in warmer sea surface temperature (SST) in the equatorial eastern Pacific, can trigger varying regional and distal changes in weather phenomena (i.e., teleconnections) along the western coast of North America. This can result in regional-scale manifestations of CV events including enhanced storminess. Contrary to several articles (e.g., Crawford et al., 1999; Storlazzi et al., 2000; Subbotina et al., 2001; Allan and Komar, 2002) that identify El Niño as an important driver of erosion on the western coast of North America, Abeysirigunawardena et al. (2009) and Heathfield et al. (2013) found a stronger correlation between the cold La Niña phase and storm activity on western Vancouver Island. Essentially, this results from a shift in storm tracks toward the southern coast of British Columbia and the northern coast of Washington during La Niña events (Heathfield et al., 2013: Fig. 6).

Regional geology also exerts control on beach geomorphology as local outcrops can influence nearshore currents, wave dynamics, and littoral sediment transport pathways. Tectonic uplift along the Cascadia Subduction Zone, which lies immediately offshore of western Vancouver Island, is causing crustal emergence at rates of 2.9 to 2.6 $mm\ a^{-1}$, which exceeds rates of absolute (i.e., eustatic and steric) sea-level rise in the Tofino region (1.7 $mm\ a^{-1}$) and results in a net fall of relative sea level of $-0.9\ mm\ a^{-1}$ (Mazzotti et al., 2008). This geological setting,

Fig. 1. Location of study area showing the intersection of Wickaninnish Beach, Sandhill Creek, and Combers Beach in Wickaninnish Bay on western Vancouver Island, British Columbia, Canada. Inset, top right, is the annual wind rose derived from Environment Canada's Tofino Airport station (1038205). The local wind regime is bi-modal, with the highest magnitude winds, associated with winter storms, coming from the southeast and lower magnitude summer winds coming from the west.

combined with high onshore sand delivery, results a general trend of beach and dune accretion and seaward progradation in the study region.

Sandhill Creek flows behind approximately 1 km of the northern portion of the Wickaninnish Dunes complex and, over time, the river's course has migrated alongshore to the NW. Bank undercutting during this migration has contributed to erosion of former beach and relict foredune deposits along a stretch of active bluffs on the landward side of the river (Fig. 2). This site hosted a parking lot managed by Parks Canada Agency (PCA) and a former historic hotel site that have since been eroded. Due to the relatively small size and remote location of Sandhill Creek, there are no gauging stations or stage data available for the river system. Anecdotal evidence suggests that flow stage variability is low and the channel rarely floods from basin contributions, but is controlled predominantly by tidal, surge, and wave incursions. Northwest of the outlet of Sandhill Creek is Combers Beach, which is somewhat more sheltered than Wickaninnish Beach from wave action by a group of rocky islets, islands, and headlands.

3. Data and methods

3.1. Aerial photography and pre-processing

Historical aerial photographs spanning 39 years (1973 to 2012) were selected to create digital orthophotographic mosaics of the study region. Only photo coverage that was of relatively small scale (i.e., <1:15,000) and that provided complete coverage of the study site was selected. Additional photo coverage dating back to 1938 was available, but it was unsuitable for analysis due to low image quality and/or large-scale coverage limitations. Contact prints of vertical aerial photographs from 1973 and 1996 were acquired from the Province of British Columbia (GeoBC) and were scanned as uncompressed TIFF files at a resolution of 1200 dpi, providing a pixel resolution of 0.31 m and 0.30 m (or a scale of ~1:15,000), respectively, following the method described by Nelson et al. (2001). More recent digital orthophotographic coverage of the study site was flown at a pixel resolution of 0.30 m in 2007 and at 0.15 m in 2009 and 2012 (Table 1).

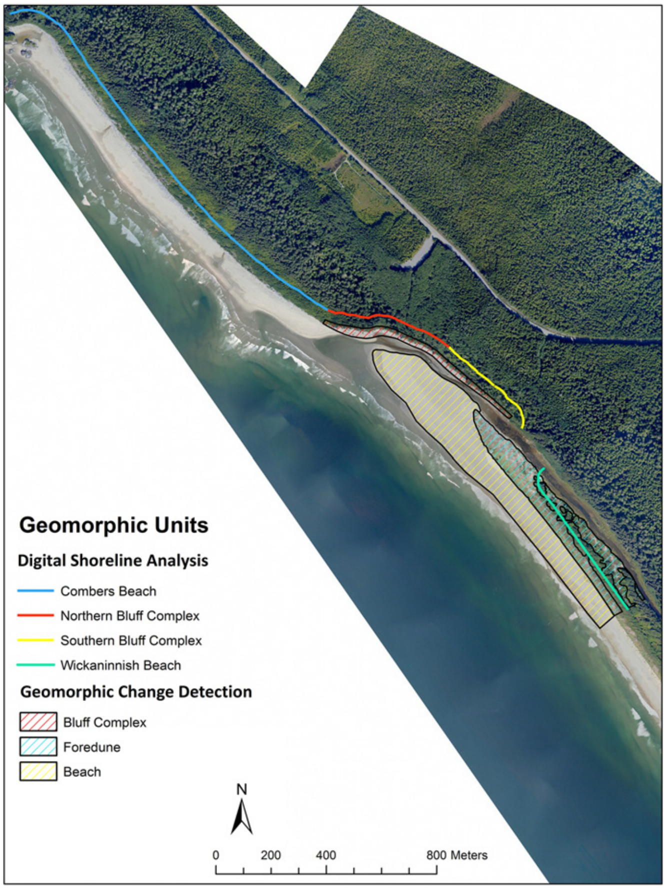

Fig. 2. Study site map showing the areas of analysis superimposed on a 2012 orthophoto mosaic. Four shoreline units were delineated and used for the DSAS analysis, and three geomorphic units were delineated and used for the GCD analysis.

Geometric distortions introduced to aerial photography by aircraft attitude (roll, pitch, and yaw) and/or altitude changes were corrected for using ground control points and the OrthoEngine® photogrammetry module of PCI Geomatica®. Image–image transformations for the 1973, 1996, and 2007 coverage and subsequent georeferencing of the imagery was conducted using a thin plate spline (TPS) model. An orthorectification was run using NAD83 Canadian Spatial Reference System (CSRS) Datum and the Canadian Geodetic Vertical Datum of 1928 (CGVD28).

3.2. Airborne LiDAR and pre-processing

Airborne LiDAR was flown in late summer to early fall months of 2005, 2009, and 2012 at varying point densities (Table 1). LiDAR point clouds were classified to extract ground points that were then used to generate bare-earth DEM surfaces using ordinary kriging at a density of 1 m. This spacing was chosen as representative to capture morphological and volumetric changes within coastal sedimentary systems on an annual timescale (as per Woolard and Colby, 2002). The bare earth DEMs were then used to detect significant geomorphic changes and corresponding sediment volume estimates using the methods described in the following sections.

3.3. Shoreline change analysis

Rates of change were calculated in ESRI ArcGIS software using the Digital Shoreline Analysis System (DSAS, vers. 4.3) plugin provided by the United States Geologic Survey (USGS) (Thieler et al., 2008). Shore-normal transects were created at 5 m intervals from a manually generated shore-parallel baseline located deeper in the backshore. Deviations in shoreline positions from this baseline were then used to calculate shoreline change statistics from each profile, including net shoreline movement (NSM — a measure of the distance in meters between oldest and youngest shorelines) and end point rate (EPR — an annualized rate of the time elapsed between the oldest and youngest shoreline positions in m a^{-1}). Shoreline position was defined as the seaward extent of vegetation along the foredune (Heathfield and Walker, 2011).

For the purposes of this study, DSAS transects were compartmentalized into four shoreline units: 1) Combers Beach; 2) Northern Bluff Complex; 3) Southern Bluff Complex; and 4) Wickaninnish Beach (Fig. 2). These units were distinguished by geomorphic setting and dominant sedimentary processes and, as such, served to reduce bias in estimates of average shoreline changes. For example, the Combers Beach unit is geomorphically distinct from the adjacent northern and southern bluff units as it has prograded historically in response to aeolian accretion and foredune progradation (Heathfield and Walker, 2011). In contrast, the bluff complexes have remained erosional and were kept distinct from the beach units so as not to skew shoreline change estimates negatively.

Shoreline change estimates derived from two-dimensional aerial orthophotography contain a certain amount of error that results from a combination of positional and measurement uncertainty (e.g., Stojic et al., 1998; Moore, 2000; Fletcher et al., 2003). Positional uncertainty is incurred from data limitations (e.g., digital pixel size) that reduce the precision in determining a spatial position. Measurement uncertainty results from user-based error in the operation of vector generation during onscreen delineation. Based on an arbitrary uncertainty threshold of three pixels, positional uncertainty for 1973, 1996, and 2007 orthophoto mosaics was assigned a value of 0.9 m, while for 2009 and 2012 coverages, a value of 0.45 m was assigned. A measurement uncertainty value of 2.5 m, based on repeat trials of onscreen shoreline delineation, was also assigned to all orthophoto years. Combined, a total uncertainty value of ± 3.4 m was derived for NSM and processed in DSAS to calculate annualized EPR confidence interval value of ± 0.09 m a^{-1} (Table 2).

Table 1
Data used in this research, including aerial photography and LiDAR. Nominal scales are expressed for aerial photos that were scanned and orthorectified, NA applies to previously orthorectified imagery. Imagery sources include the Government of British Columbia (BC Gov.), Integrated Mapping Technologies Inc. (IMTI), and Terra Remote Sensing Inc. (TRSI).

	Year	Source	Nominal scale	Month	Scan resolution (dpi)	Ground resolution (m)
Aerial photos	1973	BC Gov.	1:15000	Unknown	1200	0.31
	1996	BC Gov.	1:15000	July	1200	0.30
	2007	IMTI	1:30000	May	NA	0.30
	2009	TRSI	NA	August	NA	0.15
	2012	TRSI	NA	September	NA	0.15

	Year	Source	Point density (m^{-2})	Month	Vertical error (m)
LiDAR	2005	TRSI	0.83	July	0.15
	2009	TRSI	0.86	August	0.15
	2012	TRSI	1.02	September	0.15

Table 2
Summary of shoreline change values derived from DSAS for each time period at each shoreline unit. Net shoreline movement (NSM) distance values and annualized end point rate (EPR) values are provided for each unit over the 39-year study period, with an associated uncertainty of ±3.4 m and ±0.09 m, respectively.

Time period	Shoreline change rate (EPR in m a^{-1} ± 0.09)			
Beach unit	Combers Beach	Northern Bluff Complex	Southern Bluff Complex	Wickaninnish Beach
1973–1996	0.78	−1.26	0.14	1.75
1996–2007	0.76	−1.26	0.09	0.95
2007–2009	0.30	−0.40	0.49	2.36
2009–2012		−1.63	0.23	0.49
NSM (m ± 3.4)	27.89	−48.50	5.89	56.97
EPR (m a^{-1} ± 0.09)	0.715	−1.244	0.151	1.461

3.4. Geomorphic change detection and volumetric change estimation

Within the central study area, three geomorphic units (beach, foredune, and bluff complex) were delineated (Fig. 2) using a combination of orthophoto interpretation and field surveys. Similar to the shoreline units described above, these units were identified based on distinct formative processes so as to more accurately detect and analyze landform specific changes in morphodynamics and sediment volumes. The spatial extent of each unit was held fixed over the interval of LiDAR coverage (2005 to 2012) so as to provide spatially and temporally normalized significant volumetric change estimates.

Clipped DEMs for each geomorphic unit were imported to the Geomorphic Change Detection (GCD) package (Wheaton et al., 2010), which was used to identify statistically significant volumetric changes within geomorphic units. Each LiDAR dataset contained inherent vertical uncertainty (±0.15 m) as stated in LiDAR data acquisition reports that were also included in the calculation. Output from the GCD method included statistically significant volumetric change estimates based on the student's *t* distribution and a test statistic, as described in Wheaton et al. (2010).

Volumetric change uncertainty was accounted for by the t-test and allows for a confidence interval to be calculated based on assumed lidar vertical uncertainty (±0.15 m) plus interpolation error as determined by cross-validation. Only statistically significant values were reported at a p-value of 0.05. Resulting maps illustrate spatial patterns of significant volumetric change (both erosional and depositional) throughout each geomorphic unit. Change detection maps were imported into ESRI software and superimposed onto the 2012 orthophoto mosaic for visual interpretation.

4. Results

Shoreline change results (Table 2) and volumetric change estimates (Table 3) are also conveyed visually in Figs. 6 and 7 to demonstrate both spatial variability and temporal trends. Sequential aerial photographs showing digitized shorelines (Fig. 5) qualitatively complement these results within the Sandhill Creek region where all geomorphic units intersect.

4.1. Changes in shoreline positions

The shoreline change analyses show a general trend of progradation at Wickaninnish and Combers beaches while the north bluff complex at Sandhill Creek is rapidly retreating. Since 1973, Combers Beach experienced a net shoreline movement (NSM) of +27.9 m with an average shoreline change rate (EPR) of +0.72 m a^{-1}, with the highest maximum rate of progradation (+0.78 m a^{-1}) occurring between 1973 and 2007 (Table 2). Spatially, the highest rates of progradation (>+1.0 m a^{-1}) occurred on the northern end of Combers Beach furthest away from Sandhill Creek (Fig. 3a). There are no change values for Combers Beach between 2007 and 2009 due to the limited spatial extent of 2009 orthophoto coverage.

Wickaninnish Beach prograded seaward by +56.97 m at a mean EPR of +1.46 m a^{-1}, however, this average response did not completely represent the rapid rates of lateral extension (alongshore advance) at the northern end of the beach near Sandhill Creek (Fig. 3b), which skew the mean trend rate. By analyzing Wickaninnish Beach in two zones (the prograding beach and the laterally extending dune tip), much faster rates of lateral extension were found at the northern tip of the Wickaninnish foredune complex (+3.48 m a^{-1}) while the remaining established foredune was advancing seaward at a more modest rate (+1.05 m a^{-1}). Between the two rapidly prograding beach systems, the bluff complex at Sandhill Creek eroded with an average NSM of −48.5 m over the observed period and an EPR of −1.24 m a^{-1}. The highest rates of erosion within the northern bluff complex exceeded −1.5 m a^{-1} and were concentrated along the last (seaward-most) 200 m of Sandhill Creek where a substantial deposit of large woody debris existed between the bluff base and the channel. Temporally, erosion rates were fastest (−1.63 m a^{-1}) within the last three years (2009 to 2012) of the study period, which corresponded with a period of historically high water events and a recent La Niña phase of ENSO (Heathfield et al., 2013).

4.2. Significant volumetric changes and geomorphic responses

Statistically significant volumetric changes derived from the LiDAR bare earth DEMs (Table 3) show generally that the bluff complex at Sandhill Creek showed the highest net (negative) volumetric changes (−18,658 m^3 or −0.131 m^3 m^{-2} a^{-1}) over the period of study. The amount of sediment lost from the bluffs also increased over time with erosion rates increasing from −0.086 to −0.190 m^3 m^{-2} a^{-1} between 2005–2009 and 2009–2012 intervals, respectively. Fig. 4 illustrates the spatial distribution of erosion within the bluff complex for both intervals and shows that the highest rates of sediment loss were

Table 3
Statistically significant volumetric change estimates from the region where Sandhill Creek intersects Wickaninnish and Combers beaches (see Fig. 4). Total erosion and deposition values for each period and geomorphic units are presented in addition to net change normalized by area (m^3 m^{-2}) and over time (m^3 m^{-2} a^{-1}). All results were derived from LiDAR flown in the late summer to early fall months (see Table 1).

Geomorphic unit (area, m^2)	Time period	Total volume of erosion, m^3	Total volume of deposition, m^3	Net volumetric change, m^3 (m^3 m^{-2})	Net volumetric change rate, m^3 m^{-2} a^{-1}
Bluff (20,417)	2005–2009	−8072.1	1033.9	−7038.2 (−0.345)	−0.086
	2009–2012	−12,517.8	897.5	−11,620.3 (−0.569)	−0.190
	Total	−20,589.9	1931.4	−18,658.5 (0.914)	−0.131
Beach (145,152)	2005–2009	−6586.4	1127.8	−5458.6 (−0.038)	−0.009
	2009–2012	−3891.5	32,338.5	28,446.9 (0.196)	0.065
	Total	−10,477.9	33,466.3	22,988.3 (0.158)	0.023
Foredune (66,587)	2005–2009	−1635.7	3400.4	1764.7 (0.027)	0.007
	2009–2012	−2845.6	1352.7	−1492.9 (−0.022)	−0.007
	Total	−4481.3	4753.1	271.8 (0.004)	0.001

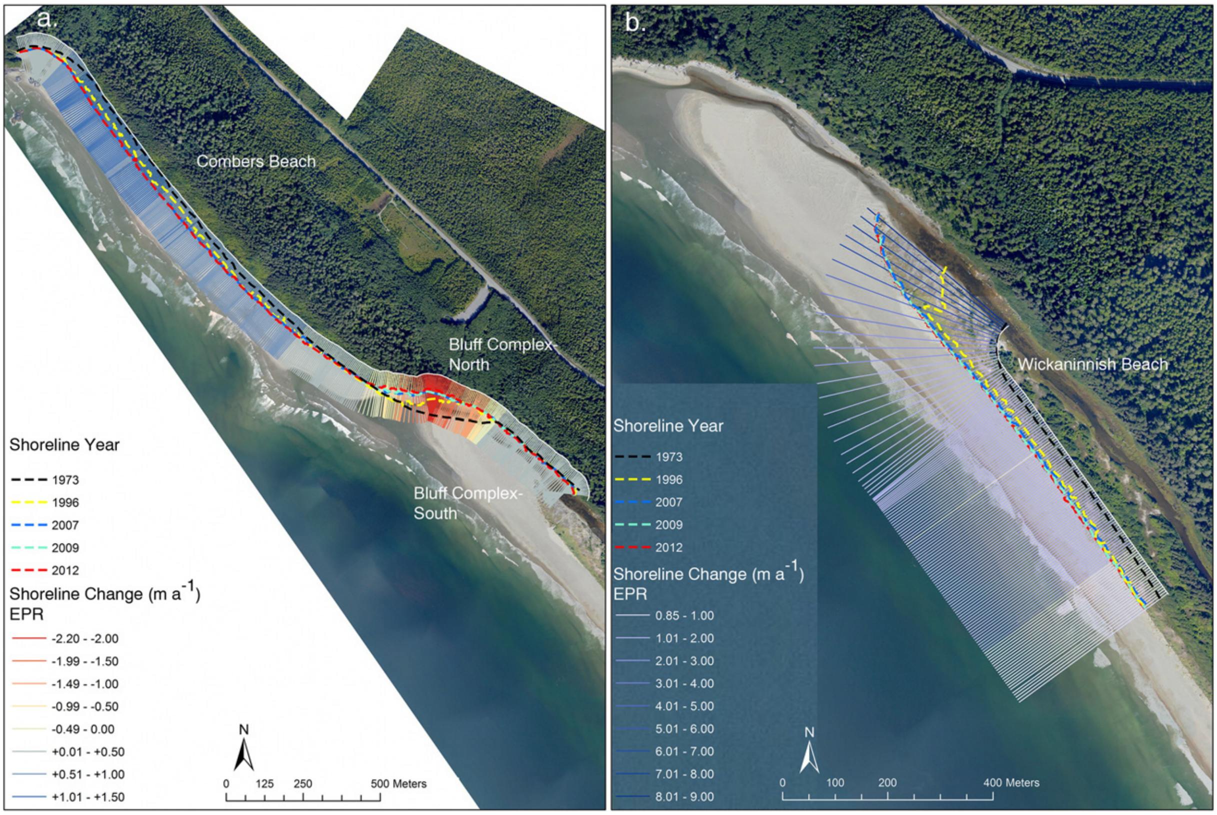

Fig. 3. DSAS maps showing shoreline change transects and related change rates (EPR). Fig. 3a shows Combers Beach where the highest rates of progradation occurred at the northern end. The most rapid rates of erosion occurred at the intersection of Combers and Wickaninnish Beaches near Sandhill Creek (-1.24 m a^{-1}). Fig. 3b shows the northern end of Wickaninnish Beach where lateral (northward) extension of the foredune complex result in rapid average rates of progradation (3.48 m a^{-1}). For comparison, the rate of seaward progradation of the southern portion of Wickaninnish Beach is comparatively slower (1.05 m a^{-1}).

concentrated along the final reach of Sandhill Creek where the channel meanders to enter the beach and delta system.

The beach unit experienced the highest total positive volumetric change ($+22{,}988.3$ m^3 or $+0.023$ m^3 m^{-2} a^{-1}) over the same period. Responses were variable with slight erosion between 2005 and 2009 (-0.038 m^3 m^{-2}) followed by an appreciable gain of sediment during 2009–2012 ($+0.196$ m^3 m^{-2}). Fig. 4 shows notable erosion of the upper beach toward the south end of the beach unit, erosion on the supratidal platform near Sandhill Creek, and distinct deposition at the toe of the foredune between 2005 and 2009. Between 2009 and 2012, significant deposition occurred by intertidal bar welding along the beach and overwash deposition on the landward edge of the supratidal platform near the channel. Erosion was more pronounced along the foredune toe and on the seaward side of the supratidal platform.

The foredune unit experienced comparatively small to negligible net volumetric change (271.8 m^3 or -0.003 m^3 m^{-2} a^{-1}) over the period of analysis, with net accretion in 2005–2009, net erosion in 2009–2012, and the lowest area-normalized volumes of all units. This suggests that the sediment budget of the foredune remained relatively stable during the study period. Analysis of the GCD map (Fig. 4) shows distinct and fairly continuous accumulation along the seaward toe of the foredune during the 2005–2009 interval and sporadic locations of erosion (small blowouts and scarps) during the 2009–1012 period.

5. Discussion

5.1. Shoreline dynamics

Between 1973 and 2012, shoreline positions throughout the study area exhibited variable rates of change, signaling a dynamic regime of geomorphic processes operating over a relatively small area. Combers and Wickaninnish Beaches are prograding rapidly in response to high on-shore sediment delivery, a regressing relative sea level, a frequently competent wind regime, and the presence of large woody debris (LWD) accumulations that serve to stabilize aeolian sands on the supratidal beach (Heathfield and Walker, 2011). If these accumulations remain undisturbed by erosive water levels and, in particular, if they become stabilized by vegetation, LWD can promote foredune growth and shoreline progradation (Walker and Barrie, 2006; Eamer and Walker, 2010; Heathfield and Walker, 2011). This process is most evident on Combers Beach where LWD is abundant amongst incipient, established, and stabilized foredunes extending 50–70 m into the backshore forest.

In addition to local geomorphic processes, tectonic uplift contributes to promoting shoreline advance. Mazzotti et al. (2008) found that crustal uplift occurring along the Cascadia Subduction Zone, which lies immediately offshore of western Vancouver Island, at rates of $+2.6$ to 2.9 mm a^{-1}, which is offsetting absolute (i.e., eustatic and steric) sea-level rise in the Tofino region of $+1.7$ mm a^{-1} to produce a fall in relative sea level of -0.9 mm a^{-1} (Mazzotti et al., 2008). Other research (e.g. Ruz and Allard, 1994; Hesp, 2002) has shown that under conditions of moderate to high onshore sediment supply, a regressing sea level can promote and possibly enhance vegetation colonization and foredune development, ultimately driving shoreline advance.

Despite net shoreline progradation rates, frequent erosion occurs at the toe of foredunes along both Combers and Wickaninnish Beaches and more extensive bluff erosion occurs along the landward shore of Sandhill Creek. Long-term shoreline changes are evident throughout the 39-year study period (1973–2012) (Fig. 5). Bluff erosion along Sandhill Creek is most likely in response to the combined influences of longer-term fluvial, littoral, and internal slope failure processes. Qualitative observations (vantage photos in Figs. 6, 7, anecdotal accounts from PCA staff, field surveys) combined with variability in EPR estimates

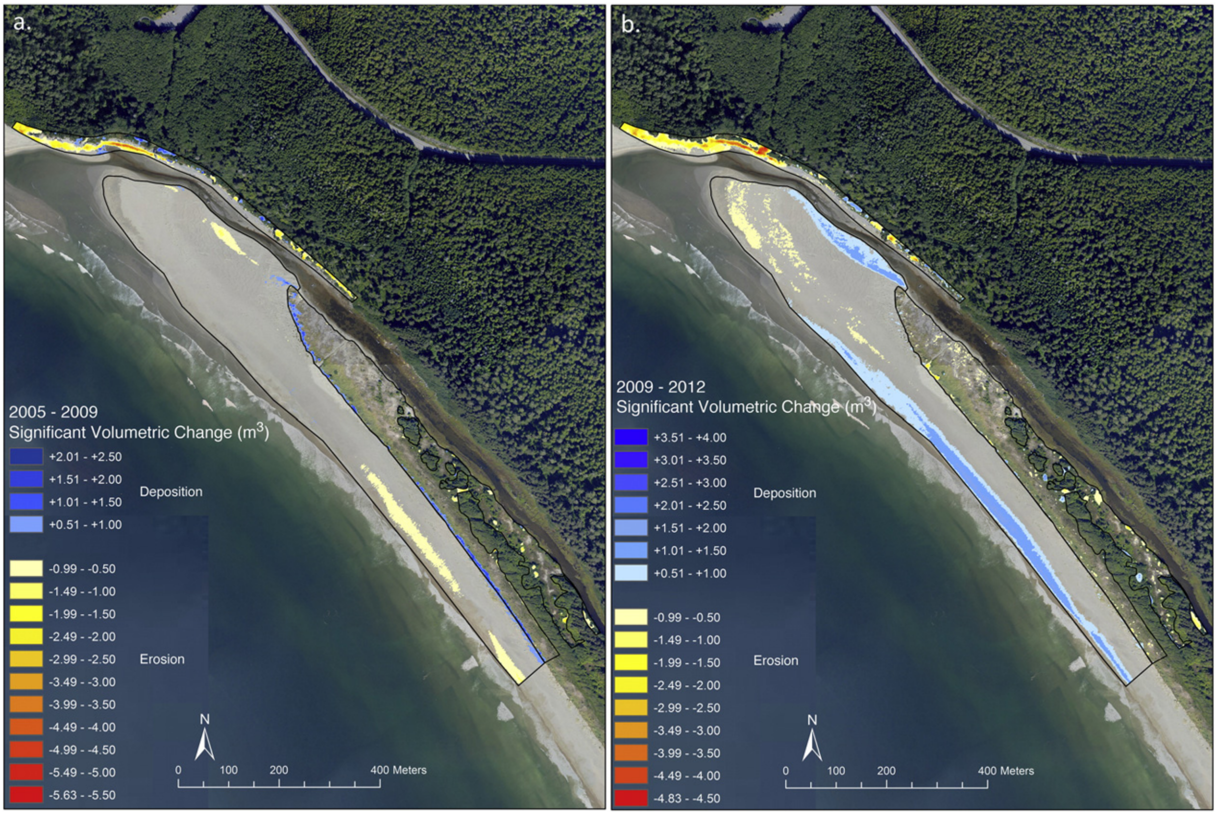

Fig. 4. Geomorphic change detection maps showing statistically significant patterns in surface erosion or deposition (red or blue, respectively) shown for 2005–2009 (a) and for 2009–2012 (b).

suggest that local erosion along the bluffs is associated with episodic erosive events driven by extreme storms (see also Heathfield et al., 2013). The braided channel outflow of Sandhill Creek (Fig. 6b) modifies the intertidal to subaerial beach each tidal cycle creating a wide floodplain of incised channels and general deflation. During high water events, wave set-up and run-up submerge the supratidal beach and water progressively floods the deflated river channel during tidal encroachment. If surge and/or high wave conditions persist, water levels may not retreat in phase with the tides, as is the case on adjacent dissipative beaches backed by foredunes. High storm surges combined with modulated storm wave action in the lower reaches of Sandhill Creek combine to destabilize and erode the bluff by three combined processes: i) direct wave erosion and undercutting, ii) saturation of basal bluff sediments and internal failure from pore water pressure effects, and iii) mobilization and direct mechanical action of LWD against the bluff (Figs. 6a, 7). These effects are more pronounced during high stage flow events that are common during intense fall and winter storms in the region.

At the decadal scale, broader landscape-scale processes such as channel migration and foredune development also contribute to the morphodynamics of the study site (Figs. 3, 5). Lateral extension of the Wickaninnish foredune complex has occurred continually in response to northward littoral drift and high onshore sediment delivery back to the foredune complex from competent WNW winds. Aeolian activity and vegetation colonization promote incipient dune development at the seaward edge of the Wickaninnish foredune and, more extensively, on the supratidal platform that extends northwest from the foredunes to Sandhill Creek. Over time these incipient dunes become established, which results in further lateral extension of the foredune complex (Fig. 5). These depositional processes act to restrict the course of Sandhill Creek and promote a northward migration of the channel that, in turn, results in bluff erosion of pre-existing coastal deposits that back the southern extent of Combers Beach. Over time with continued alongshore extension, the Wickaninnish foredune complex provides an effective buffer for the more southern portions of the bluff system against erosive high water events and storm wave attack.

5.2. Geomorphic responses

Maps of significant surface changes within the three geomorphic units (Fig. 4) reflect the highly dynamic and interrelated nature of sediment exchange between different components of this coastal landscape. Although the temporal extent of the LiDAR coverage is limited (i.e., only three time periods over seven years) and, as such it is difficult to discern seasonal or episodic responses, the analyses presented here characterize inter-annual scale variability of erosion and deposition patterns and associated changes within geomorphic units and their sediment budgets. The bluff unit experienced a substantial net loss of sediment over the period of observation while the adjacent beach unit gained proportionately less sediment and the foredune unit remained essentially stable in terms of volumetric change. Focussed patterns of local erosion on the bluff complex (Fig. 4) suggest that the interaction of fluvial and nearshore littoral processes at Sandhill Creek modify intertidal beach and delta morphology that can, in turn, amplify oceanographic forcing during storm events. High volumetric losses and spatial concentration of erosion at the southern end of the bluff complex suggests a combination of fluvial erosion and oceanographic forcing from high wave and/or storm surge events. Furthermore, increased rates of volumetric change at the bluff system (-0.086 to -0.190 m^3 m^{-2} a^{-1} between 2005 and 2012) are consistent with the findings of Heathfield et al. (2013) that show recent increases in the frequency and magnitude of regional storms and associated oceanographic forcing mechanisms (e.g., significant wave heights, surge magnitudes).

Despite shoreline change and sediment volumetric analyses showing rapid lateral extension and notable seaward progradation (Figs. 3b, 5) over the study period, the established foredune exhibited

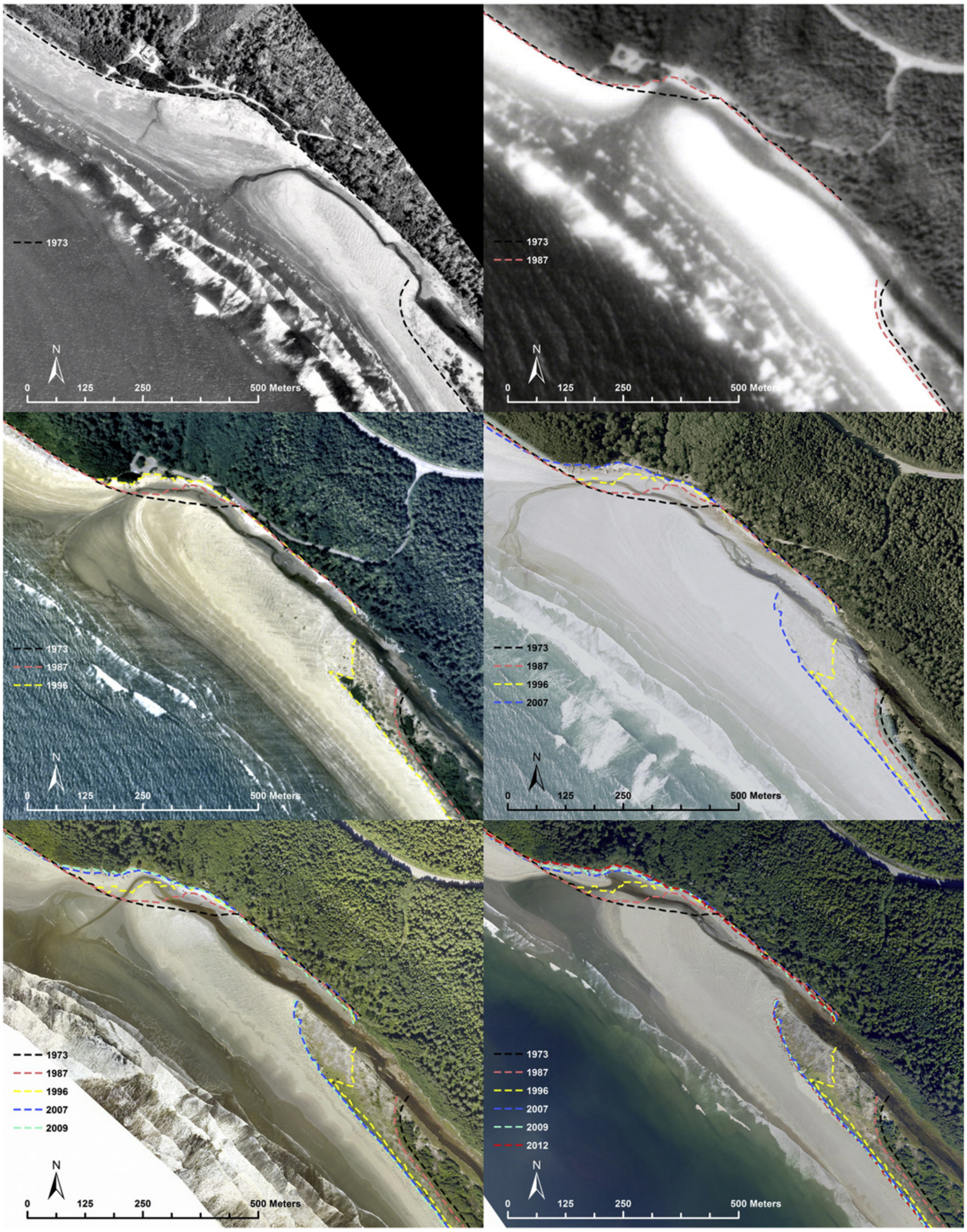

Fig. 5. Orthorectified photo mosaics of the study area between Wickaninnish and Combers Beaches showing historical evolution in shoreline position over a 39-year period (1973, 1987, 1996, 2007, 2009 and 2012).

relatively small volumetric changes. This reflects the observation that most of the deposition within the foredune over this time period occurred on the lower seaward slope, at the dune toe, and upper backshore within the incipient dune zone (Fig. 4). Volumetric growth in the foredune was the result of vegetation trapping and sub-aerial storage of aeolian sands in the backshore, building the foredune upward and seaward. Very little sediment accumulation was observed landward of the foredune slope, which may also relate to the influence of dense, invasive vegetation (*Ammophila breviligulata*) that restricts landward sand transport over the foredune compared to that expected over dunes with less dense native plant cover and more open sand transport pathways (cf. Wiedemann and Pickart, 1996). This modulating effect of invasive vegetation (and its removal) on the beach–dune sediment budget is beyond the scope of this study and is the focus of related research ongoing at this site (Darke et al., 2013; Eamer and Walker, 2013; Walker et al., 2013).

Despite episodic erosive events, the incipient foredune can become established and prograde seaward and extend laterally, as was evident in shoreline change results (Table 2, Fig. 3b). Between 2005 and 2009, approximately 3400 m^3 of sediment contributed to accretion and extension of the Wickaninnish foredune complex and this declined slightly (1353 m^3) in the following interval (2009–2012). Erosion along the seaward margin of the foredune, particularly toward the tip of the complex (Fig. 4b), was consistent with field observations and a documented increase in regional erosive events (Heathfield et al., 2013).

As expected due to competing sedimentary processes (e.g., tides, waves, littoral drift, aeolian transport), Wickaninnish Beach has a highly variable sediment budget. As above, the temporally limited volumetric

Fig. 6. Composite of site photos displaying geomorphically distinct areas. Photo a. displays the rapidly eroding bluff complex and LWD accumulation backing Sandhill creek. Photo b. shows the eroding bluff complex from a different perspective, including a destroyed bridge. Photo c. shows the Wickaninnish foredune complex with Sandhill creek in the backshore. Overwash deposits are seen in the top left corner protruding into the channel. LWD at the leading seaward edge acts to trap aeolian sands and stabilize the foredune, effectively promoting lateral alongshore extension.
(Photos A&B, D. Heathfield; Photo C, PR-NPR).

change estimates presented here are also only indicative of interannual changes. Following only slight change between 2005 and 2009 (1128 m^3), the beach experienced appreciable deposition between

Fig. 7. Photo of bluff erosion at Combers beach following a winter storm in February 2011. Undercutting via storm-associated wave and surge action removed sediment and contributed to bluff erosion and the destruction of large vegetation.
Photo: D. Heathfield.

2009 and 2012 (32,338 m^3), most of which was concentrated on the upper foreshore as is expected during lower energy summer wave conditions when net sediment delivery is onshore from offshore bars to the beach face.

Similar to nearshore processes at Wickaninnish Bay, Hine (1979) discussed how an oblique wave approach served to set up a longshore transport system. Waves refract closer to the leading tip of a spit, altering breaking wave angle and slowing longshore transport to the point that deposition is accelerated. Next, an intertidal to supratidal terrace develops, upon which swash bars are deposited and weld to the beach, leading to supratidal berm-ridge development. Figs. 4 and 6c provide evidence of this process, where the tip of the Wickaninnish foredune complex hosts a supratidal platform with intertidal swash bar welding, berm development and overwash deposition into Sandhill Creek (cf. Carter et al., 1992). Despite higher SE storm winds in the winter and net northward littoral drift, most local aeolian delivery occurs onshore in the opposite direction from WNW winds in spring and summer months, as indicated by dune alignments in the larger transgressive Wickaninnish Dunes complex further south (see Darke et al., 2013).

5.3. A proposed model for foredune–fluvial interactions on drift-aligned beaches

Empirical results presented here combined with findings from previous research provide the basis for describing foredune–fluvial interactions on a drift-aligned beach. Previous research has documented extensively the interactions between coastal processes and fluvial dynamics. For instance, Wright (1977) described the formation of coastal deltas and sub-aqueous levees as they relate to incident wave energy. The model specifically discusses how incident wave energy and direction influences river-mouth morphologies and depositional patterns. Waves breaking at a river mouth oppose fluvial outflow, promoting mixing and exchange between marine and fluvial sediments. Oblique wave approach and associated littoral drift laterally deflect deposition and the resultant delta morphology. While instructive for identifying process interactions on a drift-aligned beach, Wright's (1977) model does not consider beach–dune morphodynamics and interactions with the fluvial channel, nor does it ascribe intertidal responses to subaerial incipient dune or established foredune morphodynamics. A more integrated model by Carter et al. (1992) described the sequence of coastal dune development following fluvial channel closure following overwash and sediment infilling. Their model describes how river outlet deltas and intertidal bars can be translated onshore during overwash events to form a flat, low-lying supratidal platform that effectively barricades and infills the lower reaches of the river. Carter et al. (1992) suggest that subsequent accretion and growth of dunes on this barrier platform may evolve into a foredune ridge and that a steeper, more reflective beach may develop and eventually erode and/or be breached by subsequent overwash events. This conceptual model is useful for understanding the role of high magnitude overwash events in altering the geomorphic trajectory of river outflows in areas of high onshore supply and aeolian activity, however, it does not describe conditions where channel function is maintained while being influenced by more recurrent processes that maintain beach–dune morphodynamics including littoral drift, wave action and/or storm surges, and onshore aeolian sediment.

Finally, a coastal foredune continuum model proposed by Psuty (2004) briefly addressed the long-term evolution of foredune development and associated sediment transport at a river mouth. The model posits that beach accretion and foredune development is more rapid closer to the river mouth, and the rate of accretion slows with distance away from this point. While conceptually this model makes sense, the assumptions that the dominant point source for sediment input is the river and that alongshore transport moves away from the extending spit does not apply to our study. In contrast, Combers and Wickaninnish beaches have an appreciable onshore sediment supply, which is subsequently reworked by littoral and aeolian processes. Although there are no gaging stations on Sandhill Creek, the river provides a relatively low sediment load as evidenced by a coarse cobble lag deposit and persistent organic staining of these sediments in the river that is evident behind the established foredune and further upstream. Furthermore, the scope of Psuty's (2004) model is limited to foredune development and ignores interactions between wave energy and nearshore sediment transport pathways that also control beach–dune form and morphodynamics.

Fig. 8 presents an empirical model that conceptualizes nearly 40 years of historic shoreline movements, recent significant sediment volume changes and related geomorphic responses on a high-energy, drift-aligned beach. The model incorporates interactions between littoral, fluvial, and aeolian processes on an accreting coast that control the morphodynamics and decadal-scale evolution of a laterally extending foredune complex backed by an active river system.

Foredune development and maintenance requires appreciable onshore aeolian sediment delivery from the foreshore to the backshore. On drift-aligned beaches, sediment is preferentially transported and deposited in a net alongshore littoral drift direction that results from oblique dominant wave approach. This often promotes lateral migration of swash bars and sub-aqueous levees and drift-oriented extension of

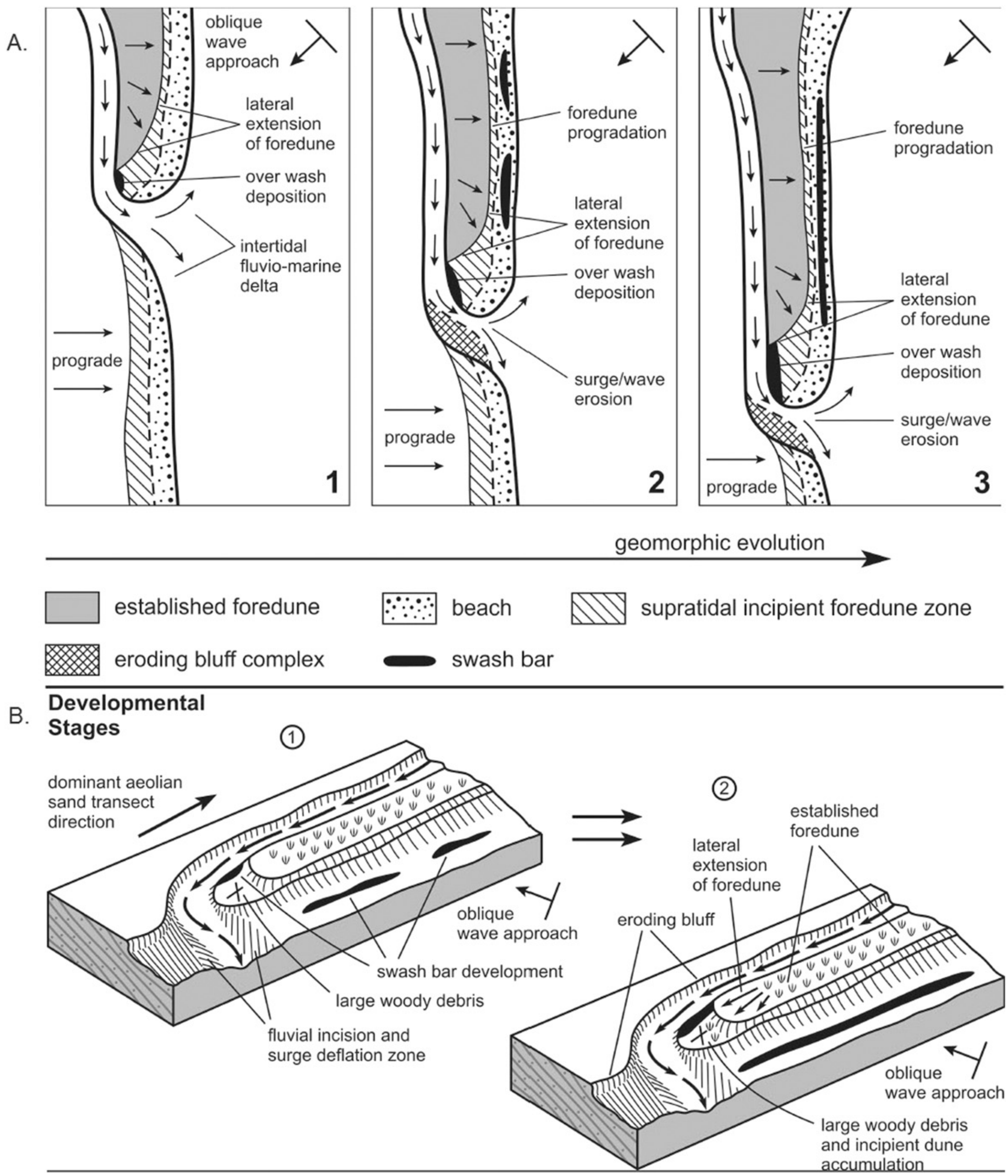

Fig. 8. Conceptual model describing the geomorphic evolution of a wave dominated beach–dune complex and backshore river system. Fig. 8A describes in plan-view the landscape features and processes found in this type of setting. Overwash deposits and bar welding on the supratidal zone feed sediment to LWD and incipient vegetation, promoting seaward advance and lateral extension of the established foredune complex. This process is promoted by oblique wave approach and resultant net-littoral drift, which provides sediment downdrift and subsequent shoreline progradation. Fluvial processes modify the river mouth such that a zone of deflation develops, allowing for erosive water levels to penetrate into the backshore and erode the bluff-complex. Fig. 8B describes the same process-response dynamic in 3D.

deltas and spits in the proximity of river outflows (e.g., Wright, 1977; Hine, 1979). In this study, adjacent to the established foredune complex and adjoining the river is a relatively flat, supratidal platform that is formed by extension of the beach in the net drift direction. Overwash deposition, bar welding, and berm development are ephemeral in this zone and vegetation is only able to colonize seasonally and usually very close to the established foredune. Vegetation and incipient dunes may persist on this platform during years with infrequent high water events, which can promote further accretion of aeolian sands and growth or extension of established foredunes (e.g., Carter et al., 1992; Hesp, 2002). Continued onshore sediment delivery and bedform development on the supratidal platform can eventually alter the course of the river channel. For instance, overwash bar deposition into the channel can partially block river discharge and/or cause channel migration into pre-existing deposits. Further aeolian deposition and growth or extension of established foredunes atop the supratidal platform provides an additional store of sediment that inhibits channel migration and forces the channel course further along the beach.

Fluvial incision into the beach occurs at the river mouth from entry in the supratidal backshore to lower elevations at the sub-tidal delta. During periods of elevated surge and/or storm waves, total water levels can enter the backshore via the channel, raise river stage heights, and erode beach and bluff deposits adjacent to the channel. In areas where LWD accumulates, this process is potentially amplified, as mobilized LWD can substantially increase erosion by way of battering and undercutting backshore deposits.

On sedimentary coastlines exposed to high-energy, oblique wave conditions, high rates of onshore sediment delivery combined with fluvial channel migration can have substantial geomorphic implications for adjacent beach-dune systems and other stabilized features or deposits. Swash bar deposition and incipient dune development promoting foredune progradation and alongshore extension of the down drift foredune complex can continually narrow and focus fluvial outflow. The result is that fluviomarine processes are concentrated in a relatively small area, creating a zone of lower beach elevation that lacks the buffering capacity of adjacent foredunes against storm waves and, hence, may cause of amplified coastal erosion in this zone. Although the proposed model is site specific, it is based on decades of observation and incorporates the interaction of a wide range of processes and forms (i.e., foredune development via nearshore and aeolian processes). By building on existing knowledge and incorporating a broader suite of active processes in this type of setting, the proposed model may provide an effective conceptual framework that could be adapted to understand other morphologically similar sites.

6. Conclusions

This study examines and interprets the historical landscape evolution of a wave-dominated drift-aligned beach-dune complex at the outflow of a backshore river on the southwestern coast of Vancouver Island, British Columbia, Canada. Shoreline position and significant volumetric change analyses reveal a highly dynamic environment with persistent long-term trends of both erosion and deposition across distinct geomorphic components that are maintained by the interplay of littoral, fluvial and aeolian processes. Results are synthesized into a conceptual model that may be applied to other drift-aligned coasts to better understand beach-dune-fluvial dynamics. Key results are as follows:

1. Shorelines in the study region exhibit a general trend of progradation over the study period (1973–2012) as a result of a high on-shore sediment delivery, a competent wind regime, and regional crustal uplift. Combers and Wickaninnish Beaches are advancing seaward at appreciable rates of $+0.715$ and $+1.461$ m a^{-1}, respectively. Located at the intersection of these two beaches is a bluff system backing Sandhill Creek, which is rapidly eroding at -1.244 m a^{-1} due to the alongshore migration of the river in combination with high wave run-up and surge events that enter the channel. Swash bar and overwash deposits on a low-lying supratidal platform that extends northward from the foredune complex, combined with aeolian deposition that feeds foredune progradation and alongshore extension, appear to force the outflow of Sandhill Creek northward resulting in progressive erosion of the bluff complex and pre-existing deposits. The variability of shoreline change rates in the study area reflects these complex geomorphic interactions.
2. Three selected geomorphic units examined over a shorter observed period (2005–2012) using aerial LiDAR, exhibited significant volumetric change rates that also reflect the complex interactions of fluvial, littoral, and aeolian processes. The bluff complex backing Sandhill Creek lost 18,658.5 m^3 at a rate of -0.131 m^3 m^{-2} a^{-1}, substantiated by shoreline retreat rates and field observations of bluff undercutting and slumping. Volumetric analysis of both the foredune and beach units reveal a long-term trend of dune growth and alongshore extension due to appreciable sediment deposition at the leading edge of the dune and bar attachment to the beach within the supratidal incipient dune zone.
3. These empirical observations form the basis for a conceptual model that describes the morphology, process-response dynamics, and longer-term evolution of a drift-aligned, wave-dominated, beach–foredune–riverine complex. Observed trends in shoreline positions and sediment volumes suggest that Sandhill Creek will continue to migrate to the northwest and contribute to bluff erosion. The model provides a comparative framework that may be used or modified to assess other similar drift-aligned systems.

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