Analysis of coastal dune dynamics, shoreline position, and large woody debris at Wickaninnish Bay, Pacific Rim National Park, British Columbia

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Abstract: Large woody debris (LWD) and colonizing vegetation alter the sediment budgets and stability of coastal dune systems. In British Columbia, LWD on beaches consists largely of historical escape logs from the coastal logging industry. In areas with strong wind regimes and high sand supply, LWD can trap appreciable amounts of windblown sand in the backshore, which can enhance foredune development and stabilization (roles typically played by vegetation) on stable or prograding shorelines. This additional store of sediment provides an important buffer that reduces erosion of established foredunes and backshore ecosystems. This study examines trends in LWD and vegetation coverage and associated geomorphic changes within the Long Beach unit of Pacific Rim National Park Reserve derived from aerial photography since the early 1970s. Over this time LWD has been reworked seasonally to interannually and, at Wickaninnish Bay, has declined in areal coverage by 61%. Despite this decline, LWD is found extensively within established foredunes and swales in the study area. In combination with vegetation colonization, this has promoted shoreline advance rates as rapid as 1.5 $m \cdot a^{-1}$. At Schooner Cove and Wickaninnish Beach, vegetation colonization is occurring rapidly and has reduced active sand surfaces of large, transgressive dunes landward of the foredune by ~28% over the 34 year observation period. This may reflect both park protection initiatives (i.e., reduced foot and vehicular traffic) and a warming and wetter climate regime on the British Columbia coast over the study period and suggests increasing future stabilization of dune systems in the area.

Résumé : D'importants débris de bois et une végétation colonisatrice altèrent les bilans sédimentaires et la stabilité des systèmes de dunes littorales. En Colombie-Britannique, ces importants débris de bois sont en général constitués de billots égarés provenant de l'industrie forestière de la côte. Là où les vents sont très forts et que beaucoup de sable est disponible, les débris peuvent piéger de grandes quantités de sable soufflé par le vent dans l'arrière-plage, ce qui peut encourager le développement et la stabilisation d'avant-dunes (des rôles habituellement réservés à la végétation) sur des littoraux stables ou d'accrétion. Cette réserve additionnelle de sédiments fournit un tampon important qui réduit l'érosion des avant-dunes et des écosystèmes d'arrière-plage établis. La présente étude examine les importants débris de bois et la couverture végétale ainsi que les changements géomorphologiques connexes à l'intérieur de l'unité Long Beach de la Réserve de parc national du Canada Pacifc Rim à partir de photographies aériennes depuis le début des années 1970. Durant cette période, les importants débris de bois ont été travaillés selon les saisons et les années et, à la baie Wickaninnish, leur superficie a été réduite de 61 %. Malgré cette diminution, les débris de bois se retrouvent un peu partout dans les avant-dunes et les bassières établies du secteur à l'étude. Jumelés à la colonisation par la végétation, ces débris ont aidé à obtenir des taux d'avancement du rivage atteignant 1,5 $m \cdot a^{-1}$. à l'anse Schooner et à la plage Wickaninnish, la colonisation par la végétation s'effectue rapidement et elle a diminué les surfaces actives des grandes dunes de sable transgressives du côté de la terre de 28 % au cours des 34 ans de la période d'observation. Ce fait pourrait être le reflet des initiatives de protection du parc (p. ex. réduction de la circulation des piétons et des véhicules) et d'un régime plus chaud et plus humide sur la côte de la Colombie-Britannique au cours de la période d'étude; cela suggère aussi une stabilisation accrue des systèmes de dunes du secteur dans le futur.

[Traduit par la Rédaction]

Introduction

The role of large woody debris (LWD) in beach–dune geomorphology is understudied compared to that within fluvial systems (e.g., Keller and Swanson 1979; Nakamura and Swanson 1993; Kail 2003; Wallerstein and Thorne 2004), particularly as it relates to coastal foredune initiation, stabilization, and shoreline progradation. In coastal British Columbia, LWD deposits consist largely of historical escape logs from the coastal logging industry with smaller, locally significant contributions from landslides, coastal erosion, and (or) river transport (Walker and Barrie 2006). Large woody debris provides distinct ecological habitat in coastal regions (Maser and Sedell 1994) and its role in coastal ecology and dune dynamics also have important implications for geoindicator monitoring (Welch 2002) and more recent species-at-risk restoration initiatives by Parks Canada.

On coasts with strong wind regimes and high sand supply, LWD serves essentially three important geomorphic functions

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(Walker and Barrie 2006, Eamer and Walker 2010). First, LWD creates a zone of increased surface roughness and (or) airflow stagnation that can trap appreciable amounts of windblown sand in the backshore (Walker and Barrie 2006; Eamer and Walker 2010). As sand accumulates within the woody debris matrix, a greater volume of sediment is stored on the upper beach than would be without log debris. Eamer and Walker (2010) used airborne light detection and ranging (LiDAR) data to quantify sand storage capacity of large LWD deposits (85 to 110 m backshore depth) on northeast Graham Island in Haida Gwaii (formerly the Queen Charlotte Islands). They estimated that existing storage quantities above the high tide elevation ranged from 9.19×10^4 to 1.39×10^5 $kg \cdot m^{-1}$ beach width, which translates to normalized storage depths of approximately 1.14–1.60 m. The same LWD deposits had a further potential storage capacity of 1.04–1.70×10^4 $kg \cdot m^{-1}$ beach width or 0.21–0.28 m depth. The level of sediment deposition within the LWD also controlled the backshore geomorphology and rates of sediment transport to established foredunes deeper in the backshore. Eamer and Walker (2010) suggested that this additional sediment storage could provide an enhanced buffer against increasing storm surge flooding, wave attack, and gradual sea-level rise on beaches with appreciable onshore sand supply.

Second, LWD provides nuclei for incipient dune growth. If aeolian accretion within LWD continues without erosion by waves or high water levels, deposits fill and vegetation eventually colonizes. This process may take months to years depending on LWD extent, sand supply, high water event frequency, and vegetation type. Dune stabilization by vegetation has been well documented (e.g., Hesp 1989, 2002; Kuriyama et al. 2005; Levin et al. 2008), however, the role of LWD in promoting foredune growth and stabilization is largely unexplored. Unlike typical incipient foredunes (cf. Hesp 1989), sizable dunes can develop within LWD without vegetation colonization. In coastal British Columbia, foredunes and LWD deposits are colonized predominantly by native dunegrass (*Leymus mollis*) and invasive beach (marram) grasses (e.g., *Ammophila* spp.), which are very effective at trapping and storing large quantities of aeolian sand (Wiedemann and Pickart 1996; Hesp 1999). With continued vegetation colonization and sand trapping, an established foredune may eventually develop from an incipient LWD dune.

Third, sediment-laden LWD deposits can divert and (or) dam river channels in backshore environments to create and (or) preserve backshore lakes and wetlands. Backshore lakes or swales are common on LWD-laden beaches and aeolian accretion is often key to their development. Where onshore sand supply is very high, backshore lakes may eventually infill with sand (Walker and Barrie 2006; Eamer and Walker 2010). Rapid drainage and rupture of these lakes via channel incision or wave erosion of the foredune is also common.

Large woody debris deposits can be eroded and redeposited on a seasonal to interannual scale. In Haida Gwaii on the northern British Columbia coast, relict backshore scarps behind extensive LWD deposits suggest that erosive high water events may completely rework LWD on an interdecadal scale (Eamer and Walker 2010). Although significant amounts of drift logs are reworked in the littoral system to maintain extensive LWD deposits, there appears to be a general decline in the supply to beaches in British Columbia. Actual quantities and trends are difficult to estimate because log losses have not been tracked and recorded historically (BC Ministry of Sustainable Resource Management 2003). Though speculative, this decline in the supply of log debris may relate to more efficient methods of transporting and storing felled logs by the coastal logging industry.

The purpose of this article is to quantify and interpret trends in LWD, vegetation coverage and associated geomorphic changes on beach-dune systems in Wickaninnish Bay in Pacific Rim National Park Reserve, British Columbia. This is accomplished by mapping and quantifying changes in LWD, shoreline position, and active dune sand surface using aerial photography dating back to the 1970s, onsite photographs, local personal accounts, and field surveys. This research improves our understanding of the geomorphic significance of LWD in sandy beach-dune systems and, in partnership with Parks Canada Agency, contributes to ongoing assessment of coastal dune dynamics, erosion monitoring, and foredune restoration initiatives for endangered species listed under the federal Species at Risk Act (SARA).

Study region

Wickaninnish Bay is located between Ucluelet and Tofino on the west coast of Vancouver Island, British Columbia, Canada (Fig. 1). Within the bay are four embayed, sandy beaches bound by rock headlands including: Wickaninnish Beach, Combers Beach, Long Beach, and Schooner Cove (Fig. 2). Combined, this 10 km stretch of shoreline is known as the Long Beach Unit and it resides within the Pacific Rim National Park Reserve (PRNPR). These beaches are highly dissipative (wide surf zone) with gradual, shallow bathymetry, mesotidal range (2–4 m) and subject to a seasonally variable, energetic wave regime (e.g., average summer significant wave height, H_s, of 1.14 m and period, T, 10.89 s; average winter H_s of 2.47 and T of 12.07 s; maximum observed H_s of 11.44 m and T of 28.57 s). The wind regime is highly competent and seasonally bimodal (i.e., average windspeed of $2.82\ m \cdot s^{-1}$) and total annual aeolian sand transport potential is estimated at $9984.31\ m^3 \cdot m^{-1}$ (beach width)$\cdot a^{-1}$ with a resultant value of $3268.28\ m^3 \cdot m^{-1} \cdot a^{-1}$ toward the north (356°) (Fig. 3) (Beaugrand 2010). These conditions provide for very active foredunes and transgressive dune complexes in the region.

Study sites

Four study sites were selected within the Long Beach Unit (Wickaninnish Beach, Combers Beach, Long Beach, Schooner Cove) (Figs. 1 and 2). All sites have active incipient and established foredunes, and Wickaninnish Beach and Schooner Cove host large transgressive dunes and blowouts landward of the foredune. Foredunes in the region are colonized predominantly by dune grass (*Leymus mollis*) and invasive American and European beach (marram) grasses (*Ammophila breviligulata* and *Ammophila arenaria*, respectively). Invasive beach grasses are of concern to park managers owing to their aggressive expansion on foredunes and their ability to outcompete many native plant species (Wiedemann and Pickart 1996), some of which are endangered and listed under the federal SARA (e.g., Pink sand verbena, *Abronia umbellata var breviflora*). Landward of the foredune,

Fig. 1. Study region map showing the Long Beach Unit and study site locations within Pacific Rim National Park Reserve on western Vancouver Island, British Columbia, Canada.

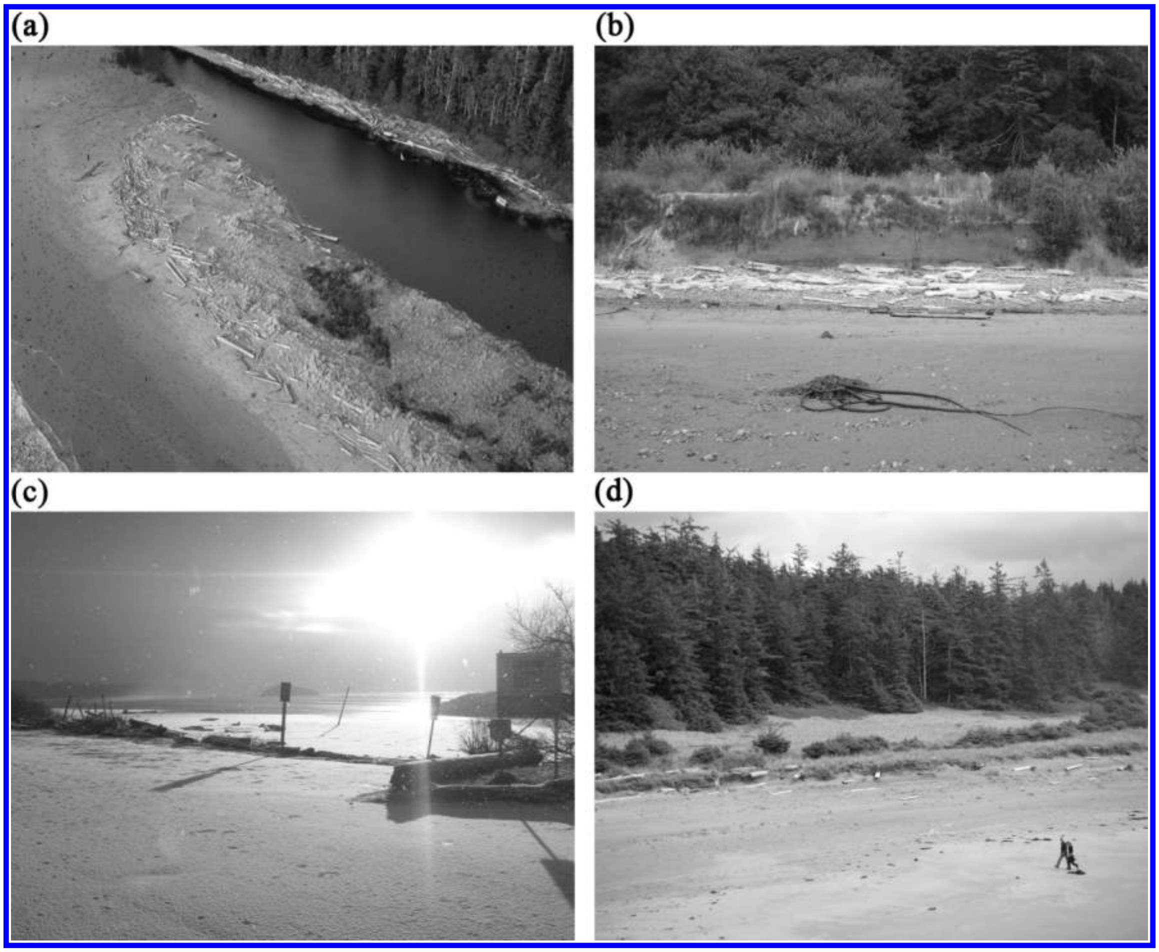
Sitka spruce (*Picea sitchensis*) and the low shrub, Kinnikinnick (*Arctostaphylos uva-ursi*), are the predominant species that colonize the transgressive dune surfaces.

The geomorphology of each study site differs slightly. Wickaninnish and Long beaches are wide (4.2 and 5.6 km, respectively) and have relatively open and uninterrupted southwest fetch aspects to incoming winds and waves. Combers Beach and Schooner Cove are narrower (1.8 and 2.5 km, respectively), embayed beaches that are more sheltered from wave action via rocky islets, islands, and headlands. Nearshore transport of sediments and LWD within coastal circulation cells is altered by outcrop and headland wave refraction, which protects these regions of Wickaninnish Bay and distributes the majority of flotsam to more open beaches. At Combers Beach, Sandhill Creek emerges from behind a prograding foredune system. Over time, the dunes have diverted the river's course to the northwest, resulting in erosion of a former, elevated coastal plain deposit and formation of a backshore bluff on the landward side of the river. This site hosted a parking lot managed by Parks Canada and a former historic hotel site that have been eroded since by coastal and fluvial processes.

Geological and tectonic setting

Regional bedrock geology controls modern embayment and beach geomorphology as it influences nearshore cur-

Fig. 2. Site photos showing local features within the Long Beach Unit of Pacific Rim National Park. (*a*) The outflow of Sandhill Creek fortified by LWD and migrating northward from the foredune complex at Wickaninnish Beach; (*b*) shows LWD fronting a bluff feature eroded by Sandhill Creet at Combers Beach; (*c*) a low-lying parking lot very near the upper beach at Long Beach; (*d*) depicts the prograding foredune complex at Schooner's Cove. Photo Credits: (*a*) Nick Page; (*b*) Hawley Beaugrand; (*c*) Jordan Eamer; (*d*) Ian Walker.



rents, wave dynamics, and littoral sediment transport pathways. Bedrock backing beaches and forming headlands within Wickaninnish Bay is of the Pacific Rim Complex, which is a mélange of Cretaceous submarine landslide material consisting of severely deformed sandstone and mudstone turbidites, limestone, volcanic rocks, and chert (Yorath 2005).

Tectonic uplift occurs along the Cascadia Subduction Zone, which lies immediately offshore of western Vancouver Island. As the Juan de Fuca plate subsides under the North American plate, crustal uplift occurs at rates of 2.9 to 2.6 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 regression in relative sea level of –0.9 mm·a^{-1} (Wolynec 2004; Mazzotti et al. 2008).

Climate and climatic variability

The long term (30 year) Canadian Climate Normals from Environment Canada's Tofino Airport meteorological station show moderate daily average temperatures ranging from 4.5 °C in January to 14.8 °C in August and 3306 mm·a^{-1} of precipitation per year, 98% of which falls as rain. Most precipitation falls from October to March (340 to 471 mm·month^{-1}), while the summer months (June to August) experience significantly less (77 to 247 mm·month^{-1}). The local wind regime is seasonally bimodal with a dominant southeast winter storm wind component and a strong west–northwest component resulting from summer winds. Maximum gusts often exceed 100 km·h^{-1} through the winter months.

Sandy beach systems on the western coasts of North America are exposed to distinct wind, wave, and water level variations that are correlated with known climatic variability events. For instance, recent major El Niños (e.g., 1982–83, 1997–98) produced elevated wind and wave regimes throughout the northeastern Pacific Ocean causing mean ocean levels from California to Alaska to rise by as much as 1 m above average levels (Subbotina et al. 2001) and by 10–40 cm above long-term seasonal mean heights in coastal British Columbia (Crawford et al. 1999; Barrie and Conway 2002), producing extensive coastal erosion (e.g., Storlazzi et al. 2000; Allan and Komar 2002; Barrie and Conway 2002). An increase in extreme events (e.g., windstorms, storm surges) is also evident in wind and water level data sets along the northeast Pacific coast (e.g., Graham and Diaz 2001; Ruggiero et al. 2001; Subbotina et al. 2001; Allan and Komar 2006; Abeysirigunawardena and Walker 2008; Abeysirigunawardena et al. 2009) and their frequency and magnitude are

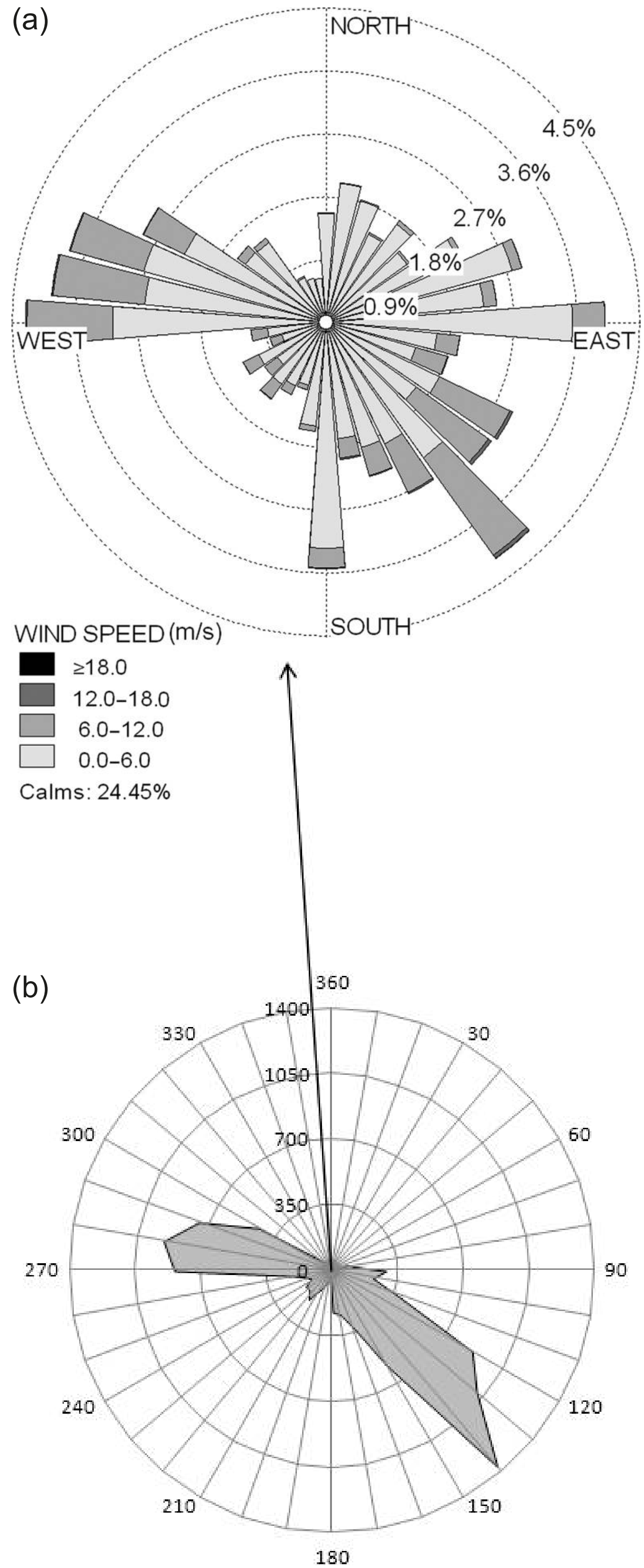


Fig. 3. The annual wind rose (*a*) and annual aeolian sediment transport potential (TP) rose (*b*) derived from data recorded at Environment Canada's Tofino Airport station (1038205) for 1971 to 1977 (last period during which 24 hour continuous data were recorded). (*a*) A mode of frequent strong winds from the southeast and a secondary mode of lower magnitude winds from the west. Winds above 6 $m \cdot s^{-1}$ are generally competent to move sand-sized grains. (*b*) Average annual aeolian sand transport potential of 9984.31 $m^3 \cdot m^{-1} \cdot a^{-1}$ with a resultant value of 3268.28 $m^3 \cdot m^{-1} \cdot a^{-1}$ toward the north (356°). The grey region indicates sand (TP) quantities from respective wind directions and the arrow shows the resultant transport potential (RTP) vector. Modified from Beaugrand (2010).

also linked to longer term climatic variability cycles, such as the Pacific Interdecadal Oscillation (PDO) (Abeysirigunawardena and Walker 2008). Although it is uncertain how climatic variability and change signals are impacting beach–dune dynamics in the study region, Beaugrand (2010) found that: (*i*) El Niño events were significantly correlated with maximum wave period and maximum water levels, (*ii*) the PDO had a significant shared variance with peak wave periods, and (*iii*) the Aleutian Low Pressure Index (ALPI) showed a significant shared variance with total water levels and significant wave heights. These oceanographic variables, combined, can produce erosive total water levels and, while a causal relationship cannot be drawn, these findings suggest that climate variability events (El Niños in particular) may increase the frequency of erosive events at Wickaninnish Beach.

Methods

Mapping changes in coastal beach–dune systems is challenging owing to complex interactions between topography, vegetation, and aeolian processes that either limit or enhance sand transport throughout the system (Andrews et al. 2002) as well as various logistical constraints that may obscure or inhibit change detection including irregular land survey or aerial photograph intervals, different image resolutions, and varying interpretations of active sand surface. Analysis of sequential aerial photography using geographic information system (GIS) mapping tools is a common means to measure and describe spatial and temporal landscape changes. Digital aerial photographs are particularly useful because of the relative ease of manipulation and image enhancement (e.g., atmospheric and geometric corrections) and multiple viewing options (Nelson et al. 2001). In this study, photos from 2007, 1996, and 1973 were selected for their availability, coverage of study sites and key features (e.g., LWD, vegetation cover, dune sand surface), and relatively large-scale resolution (i.e., >1 : 15 000). Additional historical aerial photographs dating back to 1938 were available, however, their poor image quality and small scale hindered interpretation of important site features including LWD and herbaceous vegetation cover. Aerial photograph interpretations were enhanced with field visits in summer and fall of 2008 with Parks Canada Agency staff to identify vegetative species and ground-truth geomorphic features. Selected photo imagery was digitized, georeferenced, orthorectified, and mosaicked as needed and then analyzed in GIS software (PCI Geomatica®, Richmond Hill, Ontario, Canada) to measure spatial and temporal geomorphic changes at Wickaninnish Bay.

Aerial photograph digitization and orthorectification

The 2007 aerial photo series was digital and was georeferenced and orthorectified to a spatial resolution of 0.30 m (Integrated Mapping Technologies Inc.). The 1973 and 1996 aerial photographs were analog and were scanned and digitized to the same resolution by altering the scanning aperture (i.e., size of the pixel used to sample an image) based on the scale of the aerial photograph using the method described by Nelson et al. (2001). Both 1973 and 1996 photo series were taken at a scale of 1 : 15 000 and, thus, were scanned at an aperture of 1200 dpi (dots per inch) to maintain a spatial resolution of ~0.30 m. All images were scanned as uncompressed TIFF files, so as to avoid reduced pixel accuracy due to data compression.

Geometric distortions may be introduced to air photos by aircraft attitude (roll, pitch, and yaw) and (or) altitude changes during data collection. These can be corrected for using ground control points and an appropriate mathematical model (Jensen 2005). The OrthoEngine® photogrammetry module of PCI Geomatica® was used to conduct an image–image orthorectification that also georeferenced resulting images. A minimum of ten ground control points (GCPs) were collected for each image to geographically coordinate the orthorectification. Where possible, roads and buildings were used, however, as the study region is relatively undeveloped and forested, rocky outcrops and headlands were also used. Following the collection of GCPs, an orthorectification was run using the NAD83 Canadian datum and WGS84 reference ellipsoid. The nearest neighbour interpolation resampling method was applied during image processing because it is efficient and relatively accurate as it does not alter pixel values.

Geographic information system (GIS) analyses

Line distance and polygon area tools in PCI Geomatica® were used to measure the spatial extent and changes in three key features at all sites: (*i*) LWD extent in square metres, (*ii*) relative shoreline position in metres, and (*iii*) dune sand surface in square metres. LWD extent was quantified by digitizing visible polygons of driftwood in the backshore within a stretch of beach that remained consistent across the photo series. Initially, a supervised classification was attempted to separate log versus sand surfaces, however, the spectral signatures were fairly similar in most imagery and, thus, the method was deemed less accurate than manual digitization of coverage polygons.

Relative shoreline position was defined by the seaward extent of vegetation along the foredune. This is considered a suitable shoreline proxy (Stockdon et al. 2002; Morton 1991) that indicates the landward extent of high water events. This was digitized for all photo series at each site and then positional changes were measured from consistent points at increments of 200 m to estimate average and maximum shoreline change distances. Values were expressed as a rate ($m \cdot a^{-1}$) by dividing the distance of change by the number of years between photo series. Shoreline vectors from each photo record were also overlain on the 2007 orthophotos for each site to allow for interpretation of spatial differences and related morphological responses over time (e.g., shoreline retreat vs. progradation at different locations on the beach).

Change in active dune sand surface area was quantified by digitizing the extent of active or bare sand surface within the backshore transgressive dune complexes at Wickaninnish Beach and Schooner Cove. Vegetation islands within the dune complexes were also digitized and subtracted from surrounding sand polygon areas as they may have expanded over time. The seaward extent of the dune complex was delineated by the seaward limit of grassy vegetation at the foredune toe. Values were expressed as percentage change from the previous time period and as a rate ($m^2 \cdot a^{-1}$) by dividing the change in surface area by the number of years between photo series.

The positional accuracy of all measurements was assigned as 0.90 m for distance and 0.81 m^2 for area using an arbitrary error range of three pixels of 0.30 m resolution. These results are also constrained by their temporal resolution and, as such, interpretations of trends in coverage or distances measured do not account for any seasonal to interannual variability that occurred between photo periods.

Results

Measured LWD coverages, shoreline position changes, and dune sand surface change values for all study sites are presented in Table 1. Aerial photographs showing the modern landscape and measured quantities for select sites are provided in Figs. 4–7.

Large woody debris coverage

Measurements of LWD coverage (Table 1) reveal decreasing trends at all four study sites over the time intervals analyzed. Although these trends may have been punctuated by higher or lower LWD coverages not captured in the photo series, this confirms local accounts that LWD has generally declined on beaches in Wickaninnish Bay (Barry Campbell, Personal Communication, 2009). Combers Beach had the largest LWD areas (ranging from 65 869 m^2 in 1973 to 23 840 m^2 in 2007) and greatest total reduction in areal extent (–1236.1 $m^2 \cdot a^{-1}$) of the four sites (Fig. 4), despite being the smallest site analyzed, while Wickaninnish Beach (second largest site) showed the lowest LWD coverages. The greatest total percentage reduction in LWD over the entire 34 year observation period was at Long Beach (–77.3% or 700.4 $m^2 \cdot a^{-1}$) and the least reduction occurred at Wickaninnish Beach (–56.8% or 213.4 $m^2 \cdot a^{-1}$). Figure 4 also shows that some of the LWD at Combers Beach became stabilized in the backshore by sand deposition and (or) colonizing vegetation. Therefore, some of the decline in LWD coverage at this site is attributed to foredune stabilization and progradation as opposed to direct removal by littoral processes. Field surveys revealed that this occurs to varying extents at all sites, but quantification of stabilized LWD in the photo coverage was difficult at most sites owing to an inability to discern buried or vegetated logs.

Shoreline position changes

Shoreline position change values show a general positive trend at all sites (Table 1), indicating seaward progradation. Combers Beach had the largest mean shoreline advance of +35.7 m over the 34 year observation period ranging from no change to a maximum of approximately +50.0 m toward the north end (Fig. 4). The rate of shoreline advance at this site was fastest and has remained essentially constant at ~+1.1 $m \cdot a^{-1}$.

Table 1. Summary of measured large woody debris (LWD) coverage, shoreline change rates, and dune sand surface changes for each study site in the Long Beach Unit, Pacific Rim National Park Reserve.

	Study site			
Attribute / Year	Wickaninnish	Combers Beach	Long Beach	Schooner Cove
Beach width (km)	4.2	1.8	5.6	2.5
Analyzed width (km)	3.5	1.6	5.0	2.2
LWD coverage $m^2 \pm 0.81$ (% change)				
1973	14 255 (N/A)	65 869 (N/A)	30 811 (N/A)	14 920 (N/A)
1996	8 140 (–42.8)	30 367 (–53.9)	no data	9 020 (–39.5)
2007	6 999 (–14.0)	23 840 (–21.5)	6 999 (–77.3)	6 816 (–24.4)
Total change (%)	**–56.8**	**–75.4**	**–77.3**	**–63.9**
Shoreline position m±0.9 (rate, $m \cdot a^{-1}$)				
1973–1996	2.2 (0.1)	24.9 (1.1)	14.0 (0.6)	10.1 (0.4)
1996–2007	5.0 (0.5)	10.8 (1.0)	–1.5 (–0.1)	3.4 (0.3)
Total change	**7.2 (0.2)**	**35.7 (1.1)**	**12.5 (0.4)**	**13.5 (0.4)**
Dune sand surface $m^2 \pm 0.81$ (% change)				
1973	126 931 (N/A)	—	—	31 398 (N/A)
1996	91 013 (–28.3)	—	—	24 313 (–22.6)
2007	91 642 (0.7)	—	—	22 548 (–7.3)
Total change (%)	**–27.8**	—	—	**–29.9**

Wickaninnish Beach had the least average shoreline change over the observation period (+7.2 m) ranging from –5.5 m (erosion) in the central portion to +20.0 m advance at the south end. Field surveys showed that Wickaninnish Beach has experienced notable foredune erosion and scarping in the central portion (near northern parking lot access trails) and at the north end (toward Combers Beach) (Fig. 5). The average rate of shoreline advance at Wickaninnish Beach has increased appreciably from +0.1 to +0.5 $m \cdot a^{-1}$ for 1973–1996 and 1996–2007 periods, respectively, and most of this advance has occurred at the south end.

At Long Beach, average shoreline position advanced by +12.5 m from 1973 to 2007, although a notable retreat of –1.5 m occurred recently between 1996 and 2007. Thus, the average rate of shoreline advance changed from +0.6 to –0.1 $m \cdot a^{-1}$ for 1973–1996 and 1996–2007 periods, respectively, with an average rate of +0.4 $m \cdot a^{-1}$. Shoreline progradation rates at Schooner Cove have remained fairly steady at +0.3 to +0.4 $m \cdot a^{-1}$ and average shoreline position advanced by +13.5 m over the 34 year observation period.

Dune sand surface extent

Transgressive backshore dune complexes at Schooner Cove (Fig. 6) and Wickaninnish Beach (Fig. 7) have both experienced a notable decrease in active sand surface area resulting from vegetation colonization over the 34 year observation period (Table 1). Between 1973 and 2007, vegetation cover expanded rapidly and reduced active sand surface by 27.8% and 29.9% at the Wickaninnish and Schooner Cove dune sites, respectively. This translates to stabilization rates of –1561.7 $m^2 \cdot a^{-1}$ (or –0.83% a^{-1}) in the Wickaninnish Dunes and –308.0 $m^2 \cdot a^{-1}$ (or –0.66% a^{-1}) at the Schooner Cove dunes. Contrary to this trend, the Wickaninnish Beach dunes experienced a slight increase of 57.2 $m^2 \cdot a^{-1}$ in sand surface area from 1996 to 2007. For clarity of interpretation, only 1973 and 2007 polygons are shown in Fig. 7, however, data from 1996 is included in Table 1. Although colonization of Sitka spruce and Kinnikinnick continues, airphoto evidence and local accounts suggest this is in response to the expansion of several small trough blowouts in the transgressive dune plain. The established foredune has been rapidly colonized by pioneer plant species, mainly grasses, including invasive *Ammophila* spp.

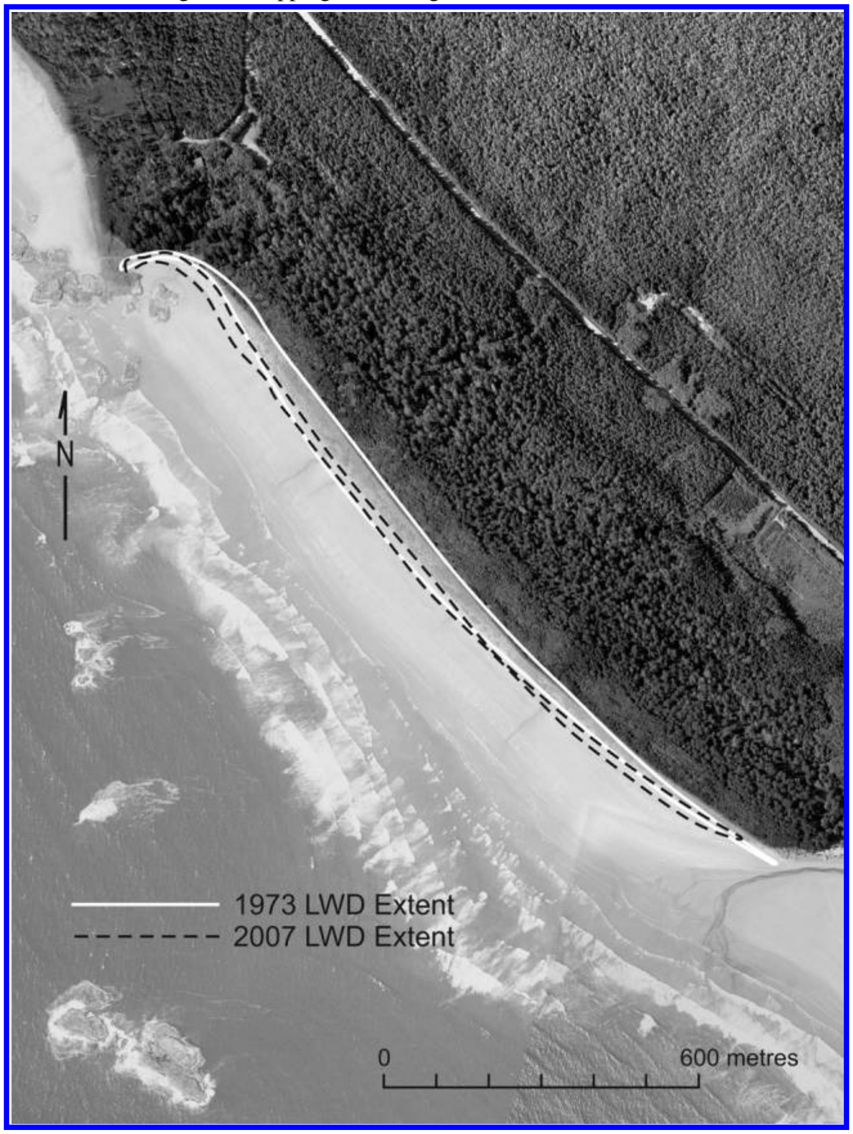
Discussion

The results presented in this paper demonstrate the dynamic nature of the beach-dune systems at Wickaninnish Bay. Each site shows a general decrease in LWD extent, a prograding shoreline, and decreasing dune sand surface extent. Some of these changes are geomorphic responses to ubiquitous controls such as climate changes and regional high-water events, while others may indicate influence of features unique to each site, such as bedrock outcrops, river outflows, or headlands and islets that, combined, alter patterns of nearshore and onshore sand delivery at each site. What remains unclear is to what extent land use changes (e.g., park designation and protection, elimination of vehicular traffic) have influenced these responses.

Declining coverage of large woody debris (LWD)

The extent of LWD generally decreased at each of the four study sites from 1973–2007 (Table 1). The trends vary between sites owing, in part, to differing site geomorphology (e.g., bedrock outcrops, nearshore bathymetry, headlands, and (or) islets) and resulting differences in nearshore currents, wave fields, and wave runup that, in turn, affect log transport, deposition, and (or) removal in the backshore. This said, the general decrease in LWD across sites can also be attributed, in part, to four general factors. First, it is likely that the supply of log debris has declined regionally owing to a less active coastal logging industry and more efficient methods of transporting and storing felled logs, as confirmed by local accounts and anecdotal information. The quantity of

Fig. 4. Aerial photograph of Combers Beach showing the 2007 (black dash) and 1973 (white line) large woody debris (LWD) coverage polygons. For clarity of interpretation, the 1996 polygon is omitted, however, data from 1996 is included in Table 1. Historical drift log debris is evident landward of the foredune in the vegetated backshore and has been stabilized by aeolian sand deposition, vegetation stabilization, and (or) foredune progradation. Photo credit: Integrated Mapping Technologies Inc. (2008).

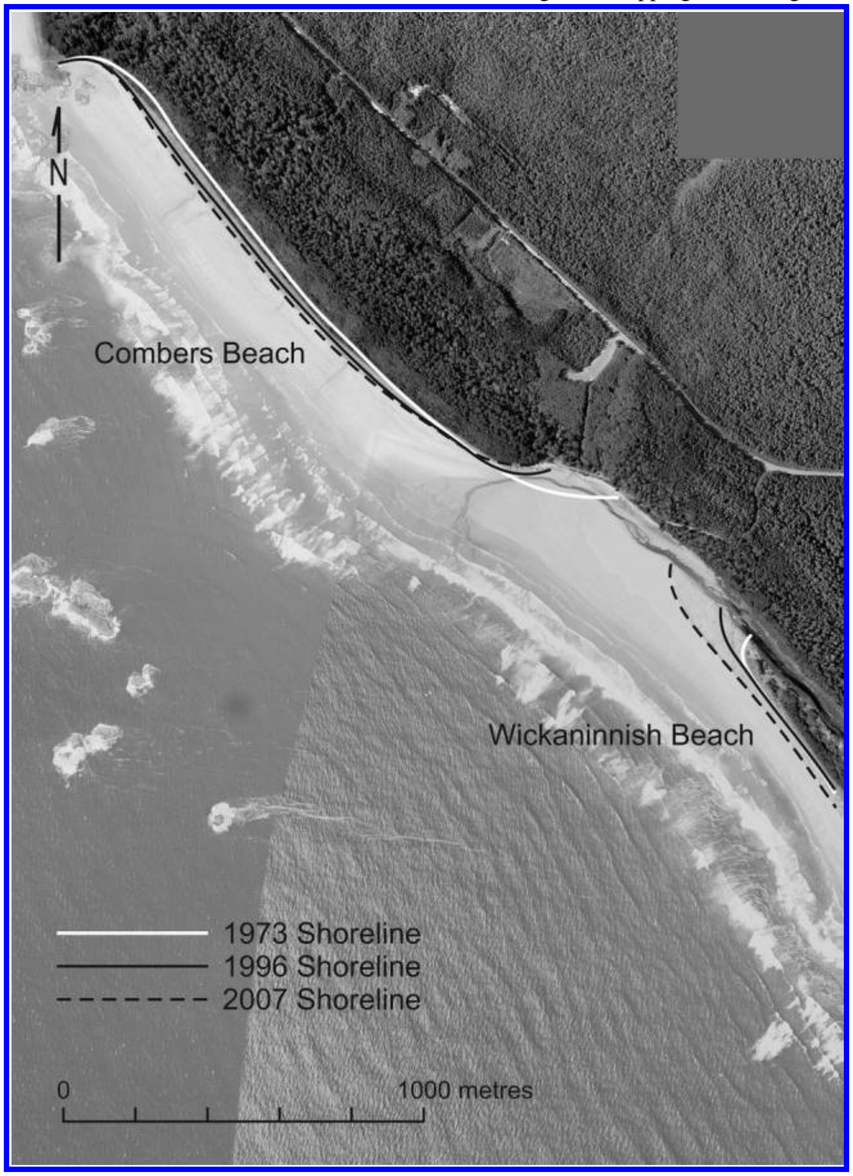


logs lost annually is difficult to estimate because losses and boom breakage are not typically tracked and recorded (BC Ministry of Sustainable Resource Management 2003). In the study area, there are only episodic accounts of major events, such as the grounding of the fully loaded log barge “Forest Prince” on Wickaninnish Beach in 1968. The barge was eventually removed by tugboat and the amount of wood that remained on the beach, although never recorded, was appreciable (Barry Campbell, Personal Communication, 2009).

Second, the forest industry has increased efforts to recover lost logs since the mid 1960s. For instance, in 1966 the BC Log Spill Recovery Cooperative Association (BCLS) was established following a move by the BC Legislature to give log salvage authority to the owner of escape logs or their agent (British Columbia Log Spill Recovery Co-operative Association 1998). Although the extent of log salvage in the study region is unknown, improvements in transportation technologies, combined with increased efforts to recover log spills and losses before they reach beaches in the study area, have contributed to a decline in log debris deposited on beaches in the study region and elsewhere in coastal British Columbia.

Third, sediment accretion and subsequent vegetation colonization can bury drift log debris. Research in areas of high onshore aeolian transport in northern BC has shown extensive aeolian deposition and complete burial of LWD can occur within months to a few seasons (Walker and Barrie 2006; Eamer and Walker 2010). This, coupled with rapid vegetation colonization, could effectively hide portions of LWD deposits and make interpretation of spatial and temporal variability in LWD from repeat aerial photography limited. There is evidence at each beach of historic LWD that has been buried and (or) stabilized by pioneer plant communities and Sitka spruce. To examine the depth and extent of historical LWD in the Wickaninnish Dunes complex, auguring to 3 m depth

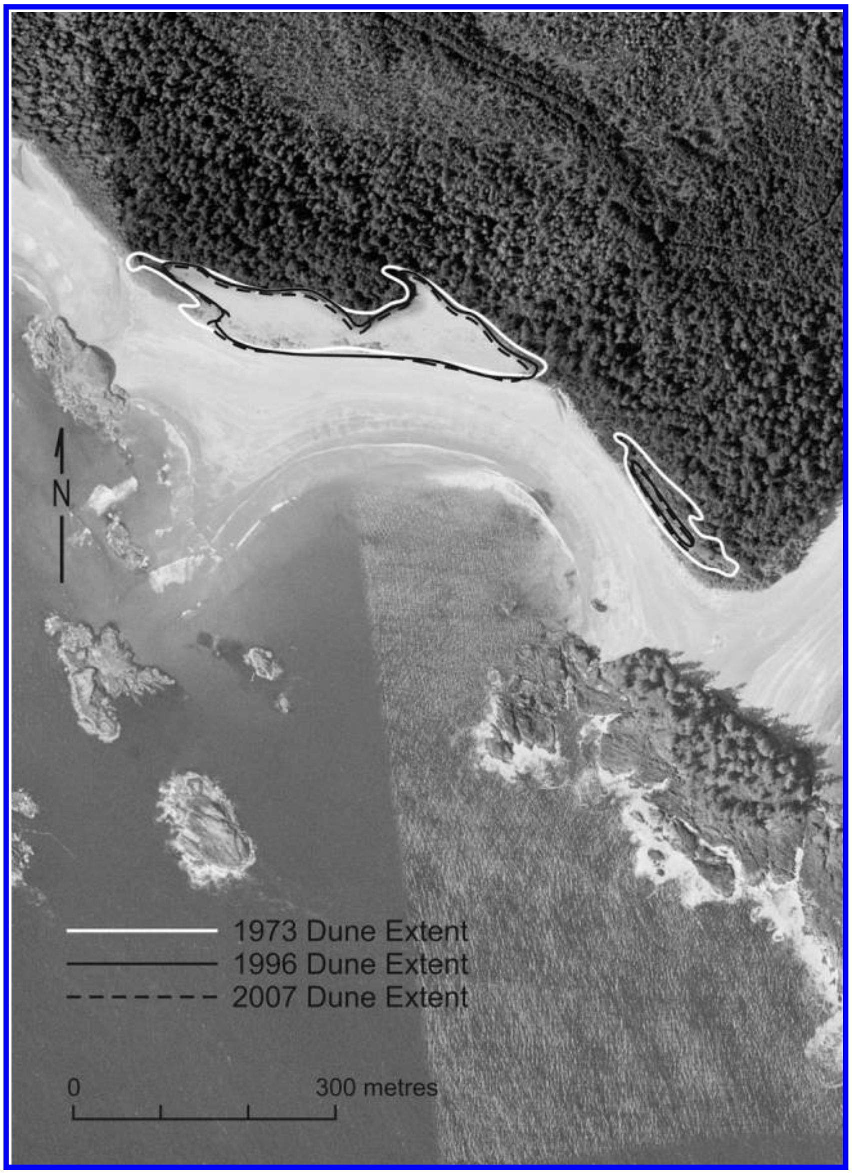
Fig. 5. Aerial photograph of southern Combers Beach at Sandhill Creek showing relative shoreline positions for 2007 (black dash), 1996 (black line), and 1973 (white line). The river channel has migrated northward in response to lateral extension and stabilization of the foredune plain on adjoining Wickaninnish Beach to the south. Consequently, the backshore near the outflow has eroded significantly, resulting in destruction of a former parking lot. A general progradation trend of +1.1 m·a^{-1} (or +35.7 m) is evident at Combers Beach over this time with highest advance occurring on the northern end (+50 ± 0.9 m). Photo credit: Integrated Mapping Technologies Inc. (2008).



in 5 m increments along several shore-normal transects was attempted. This method was unsuccessful in revealing any buried LWD beyond the established foredune, presumably because historical LWD is not consistent in extent. Ground penetrating radar is a more thorough alternative that could be used to explore historical buried LWD deposits.

Fourth, LWD is mobilized by high water level and (or) wave attack events that erode and redistribute existing log debris stored in the backshore. These events rework LWD seasonally to interannually and frequently shift the spatial distribution in varying patterns and quantities that may not be captured in aerial photographic "snapshots." Beaugrand (2010) used wave and water level data from 1970 to 1998 in the study area to estimate the recurrence interval of erosive events that breached the beach-dune junction elevation (~5.55 m above chart datum), which commonly delimits the seaward extent of LWD on the upper beach. Over this interval, 99 potentially erosive events occurred (3.53 a^{-1} long-term average), which, using a generalized extreme value (GEV) distribution block maxima approach, corresponds to a recurrence interval of 1.53 years, or a probability of 65% occurrence in any given year. Thus, it seems that erosive water level events are fairly common on the beaches of Wickaninnish Bay and the chance of major reworking and (or) removal of LWD deposits on a decadal scale (as spanned by the photo series) is highly probable. Erosive scarps containing LWD are common along the backshore from Long Beach to the southern end of Wickaninnish Beach. Some of these are fronted and (or) overridden by more recent LWD deposits, which indicates that LWD is eroded, transported, and redeposited frequently on these beaches. It remains unclear, however, how much of this reworked material is lost back to

Fig. 6. Aerial photograph of Schooner Cove foredune and transgressive dune complex showing sand surface extent for 2007 (black dash), 1996 (black line), and 1973 (white line). In general, the dune complex has stabilized and lost 308.0 $m^2 \cdot a^{-1}$ (or –0.66% a^{-1}) active sand surface over the past 34 years via colonization of both invasive grasses (*Ammophila* spp.) and woody vegetation. Photo credit: Integrated Mapping Technologies Inc. (2008).



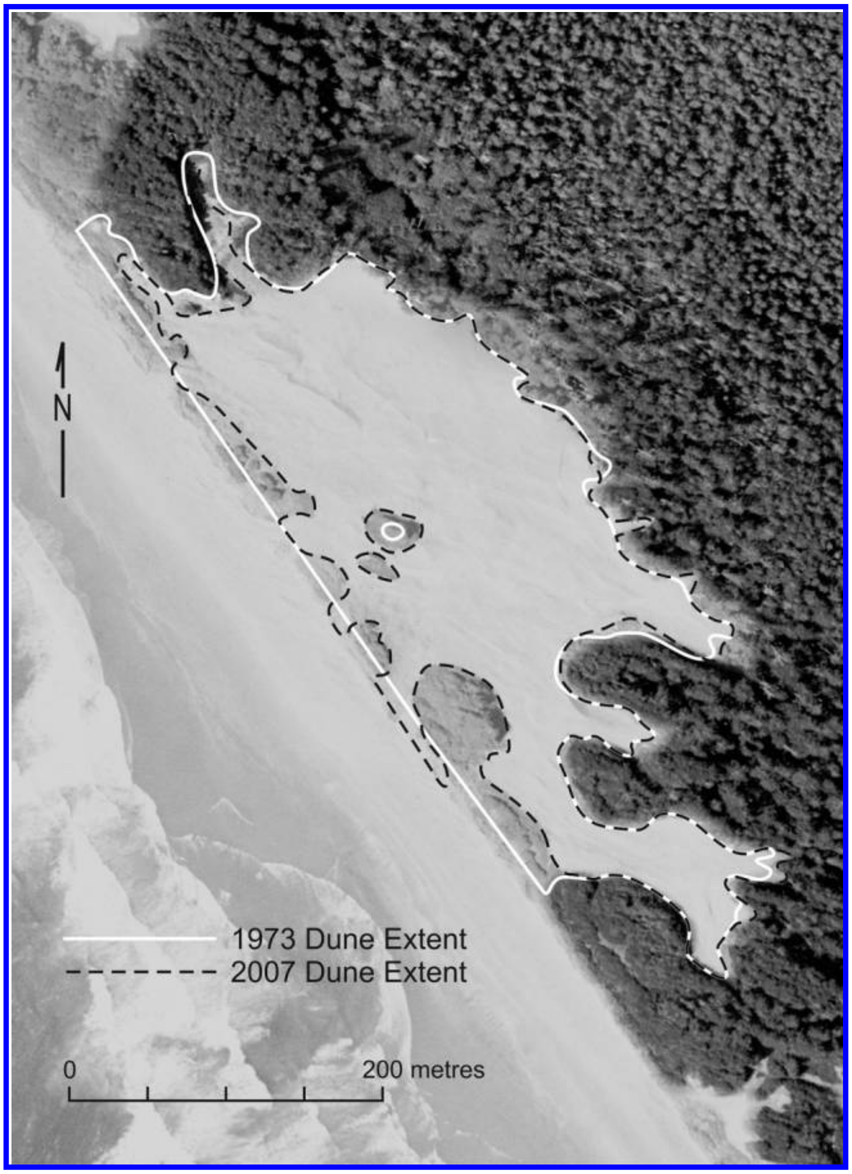
the ocean and how this contributes to declining trends in LWD in the study area.

Shoreline progradation

Between 1973 and 2007, shorelines at study sites in Wickaninnish Bay showed average rates of seaward progradation from +0.2 $m \cdot a^{-1}$ to as high as +1.5 $m \cdot a^{-1}$ on the northern end of Combers Beach (Table 1, Fig. 5). This results from buried and stabilized LWD deposits coupled with dune stabilization by pioneering grasses and woody species (e.g., Sitka spruce) and a consistent onshore aeolian sand supply. Despite recent declines in LWD, however, which provide an important nucleus for incipient dune formation, shorelines in Wickaninnish Bay continue to prograde with punctuated erosion. This may also be a response to a regression in relative sea-level (–0.9 $mm \cdot a^{-1}$ or ~0.31 m over the 34 year study period) driven by tectonic uplift in the region (Wolynec 2004; Mazzotti et al. 2008). Although slow, this regression gradually limits the landward extent of high-water events and favours continued deposition and growth of incipient dunes in the backshore.

At Sandhill Creek, backshore sediments and relict coastal plain bluff deposits are reworked by the main channel and a network of shallow braided outlet channels on the beach (Fig. 5) provide an abundant sediment supply to Combers Beach and northern Wickaninnish Beach. This sediment is readily transported by competent southeast through west–northwest winds (Fig. 3) across a relatively wide beach fetch to be deposited in large incipient dunefields and LWD deposits on the upper beach. Over time, the stabilization of these features by vegetation has resulted in progradation at Combers Beach and the northern extension of the foredune complex on

Fig. 7. Aerial photograph of the Wickaninnish Beach dune complex showing active sand surface extent for 2007 (black dash), and 1973 (white line**).** For clarity of interpretation, the 1996 polygon is omitted, however, data from 1996 is included in Table 1. In general, sand surface has declined by 1561.7 $m^2 \cdot a^{-1}$ (or –0.83% a^{-1}) in the Wickaninnish Dunes owing to vegetation colonization, although a slight increase of 57.2 $m^2 \cdot a^{-1}$ occurred between 1996 to 2007 owing to increased blowout activity in the transgressive dunes. Photo credit: Integrated Mapping Technologies Inc. (2008).



Wickaninnish Beach, which, in turn, has forced the northward migration of Sandhill Creek.

Greater Wickaninnish Beach shows evidence for both shoreline erosion, in the central portion and progradation toward the north end near Combers Beach. Airphoto analyses show that rates of progradation have increased recently from +0.1 to +0.5 $m \cdot a^{-1}$ between 1996 and 2007 and most of this has occurred at the south end where LWD deposition has increased. This is supported by recent field observations since 2007 and anecdotal accounts that suggest that drift logs are mobilized frequently (i.e., seasonally to interannually) by erosion on central Wickaninnish Beach during high-water events and transported south toward the headland at Quisitis Point where they accumulate.

Long Beach has experienced progradation rates that are approximately twice that of Wickaninnish Beach (0.4 $m \cdot a^{-1}$ versus 0.2 $m \cdot a^{-1}$) yet only 36% that of the intermediate Combers Beach (0.4 $m \cdot a^{-1}$ versus 1.1 $m \cdot a^{-1}$) over the observed time period (Table 1). From 1973 to 1996, the Long Beach shoreline prograded six times faster than Wickaninnish Beach (0.6 $m \cdot a^{-1}$ versus 0.1 $m \cdot a^{-1}$), but lost an average of 1.5 m of shoreline between 1996 and 2007 while Wickaninnish Beach continued to prograde by 5.0 m. This long-term difference in shoreline trends between these beaches is curious, as established foredunes or prograding sets of beach ridges are not evident along most of Long Beach. LWD accumulations have also declined significantly at Long Beach over the study period (–77.3% or –2.3% a^{-1}) to essentially the same amounts as on Wickaninnish Beach in 2007 (6999 m^2). Although speculative, these observations may indicate a recent increase in the frequency of, or exposure to, erosive events and (or) lesser onshore sand supply at Long Beach, compared to Wickaninnish. Anecdotal accounts suggest this may result from a shift in directionality in the storm wave regime, although this remains to be explored. Faster shoreline progradation rates and higher LWD amounts at intermediate Combers Beach most likely reflect greater protection from wave and current dynamics offered by nearshore islets, bedrock outcrops, and headlands at this site.

Overall, the shorelines of beaches within Wickaninnish Bay are experiencing a general progradation trend. Variability in progradation rates between sites is dependent on both unique geomorphic and geological controls (e.g., headlands, fluvial reworking), anthropogenic influences (e.g., LWD deposits), and varying rates of vegetation colonization, as well as ubiquitous regional processes, such as tectonic uplift and resulting sea-level regression and onshore wind and wave regimes that also control beach sediment supply and process–response dynamics.

Dune stabilization and restoration

Dune morphodynamics are controlled by various supply- and (or) transport-limiting factors. The former limit sand supply to the transport process (e.g., surface moisture and crusting) while the latter limit the ability of near-surface winds to entrain surface sediment via roughness effects (e.g., gravel lag deposits or LWD). Vegetation cover acts as both a supply- and transport-limiting factor and, thus, aeolian sand transport and deposition patterns and resulting dune morphology vary with plant canopy density and height, spacing, and seasonality (e.g., Ranwell 1972; Hesp 1989, 2002). This is because both increasing canopy density and height serve to decelerate near-surface airflow and result in increased sediment deposition within the vegetation. Alongshore variations in plant distributions, therefore, result in varying dune morphologies as sediment erosion and accretion respond locally to surface roughness. As such, plant ecology and morphology exert significant control on coastal dune morphodynamics and mobility. A fully vegetated dune is considered "fixed" or stabilized (Hugenholtz and Wolfe 2005; Tsoar 2005) and dune stabilization is defined as a reduction in active or open dune sand surface by colonizing vegetation.

Both transgressive dune systems at Wickaninnish Beach and Schooner Cove have experienced significant reductions in active sand surface area over the 34 year observation period (27.8% and 29.9%, respectively, Table 1, Figs. 6, 7). Field observations indicate that most of the transgressive dune sand surface was stabilized by encroaching Sitka spruce seedlings and Kinnikinnick, while the established foredune has been colonized rapidly by European and American beach grasses (*Ammophila arenaria* and *Ammophila breviligulata*, respectively). These beach grasses are introduced species that are prevalent along the Pacific Coast of North America. *A. arenaria* is more established on beaches in Wickaninnish Bay and was introduced via marine dispersal from Clayoquot Island near Tofino, where it was planted in the 1940s (Hubbard 1969; Page 2001) and possibly from other populations introduced in Oregon and Washington (Page 2001). *A. arenaria* is an effective invasive species as it can endure long distance marine dispersal in cold ocean water (Konlechner and Hilton 2009), low soil moisture, a wide range of soil pH, and extreme sand scour and burial at rates that many native dune species cannot tolerate (Heyligers 1985; Wiedemann and Pickart 1996; Hilton et al. 2005). Currently, *A. arenaria* plant communities are much more abundant than native Dune wildrye or "dune grass" (*Leymus mollis*) communities in the study area (Page 2003). *Ammophila* spp. colonization alters foredune morphodynamics and sediment budgets considerably via increased sand trapping efficiency and resulting dune growth (e.g., Heyligers 1985; Hesp 1989; Wiedemann and Pickart 1996; Hilton et al. 2005). In contrast, foredunes vegetated with *Leymus mollis* communities have lower plant densities (averaging 40.5% cover versus 61.6% for *A. arenaria*, Page 2003) and are less steep, hummocky, and more dynamic in form.

Continued shoreline progradation at Wickaninnish Beach, combined with the increasing extent and density of invasive *Ammophila* spp., will alter the morphodynamics and sediment budgets of the large transgressive dunes in the backshore. These factors, coupled with observed declines in active sand surface, suggest increasing vegetation stabilization (Wiedemann and Pickart 1996) within the large and regionally distinct transgressive backshore dune complexes at Wickaninnish and Schooner Cove beaches.

Recent efforts are underway by Parks Canada Agency to "restore" foredune systems within the study area by mechanically removing (by backhoe) invasive *Ammophila* spp. The goal of this program is to restore dune dynamics and aeolian activity so as to promote more favourable habitat for endemic and endangered species including native *Leymus mollis* and others of conservation significance, such as Grey beach peavine (*Lathyrus littoralis*), Yellow sand-verbena (*Abronia latifolia*), Beach carrot (*Glehnia littoralis*) and the SARA-listed Pink sand-verbena (*Abronia umbellata var breviflora*). In September 2009, Parks Canada mechanically restored over 150 m of foredune and an intensive maintenance and monitoring program is underway to limit *Ammophila* spp. regrowth and to assess geomorphic and sediment budget implications. This follows various smaller scale initiatives, mostly hand pulling, that were of limited success (Barry Campbell, Personal Communication, 2009) and the program will continue until 2014 with extension of restoration sites and related monitoring each year.

Conclusions

This study examines and interprets trends in LWD, active dune sand surface, shoreline changes, and associated geomorphic responses within beach-dune systems in Pacific Rim National Park Reserve, British Columbia using field surveys, GIS analyses of aerial photography dating back to the 1970s, and local accounts. This research improves understanding of the geomorphic significance of LWD in sandy beach–dune systems and contributes to ongoing assessment of coastal dune dynamics and new foredune restoration initiatives in collaboration with Parks Canada. The key findings of this research are:

1. The extent of LWD on beaches in Wickaninnish Bay has declined by an average of 61% over the 34 year observation period (1973–2007). Combers Beach had the greatest

total reduction in LWD areal extent (–1236.1 $m^2 \cdot a^{-1}$), despite being the smallest site analyzed, while the largest site, Long Beach, showed the greatest total percentage decline in LWD (–77.3% or 700.4 $m^2 \cdot a^{-1}$). Amounts vary depending on site size, beach aspect and other geomorphic and geological features that affect log transport, deposition, and (or) removal in the backshore. The general decline in LWD coverage is attributed to four factors: (*i*) a less active coastal logging industry and more efficient methods of transporting and storing felled logs, (*ii*) increased efforts to recover lost logs since the mid 1960s, (*iii*) sediment accretion and vegetation colonization that bury and stabilize LWD in the backshore, and (*iv*) removal by frequent high water events over the period of observation.

2. The shoreline throughout Wickaninnish Bay is prograding seaward at an average rate of +0.2 $m \cdot a^{-1}$ to as high as +1.5 $m \cdot a^{-1}$ on the northern end of Combers Beach over the period of observation. This results from stabilized LWD deposits and foredune progradation under a continued onshore aeolian sand supply in combination with a regression in relative sea level of –0.9 $mm \cdot a^{-1}$. Erosive events do occur frequently and vary in location on each beach. However, dune recovery is relatively rapid and only two sites (southern Combers Beach near Sandhill Creek and central Long Beach) exhibited long-term erosional trends.
3. The large landward transgressive dunes at Wickaninnish Beach and Schooner Cove have stabilized rapidly with respective losses of 27.8% and 29.9% active sand surface area, which translate to respective stabilization rates of –1561.7 $m^2 \cdot a^{-1}$ (–0.83% a^{-1}) and –308.0 $m^2 \cdot a^{-1}$ (or –0.66% a^{-1}) over the 34 year study period. There has been slight expansion of active sand surface at Wickaninnish Dunes due to enhanced blowout activity, however, continued shoreline progradation, combined with reduced sand supply to the transgressive dunes from colonization of invasive *Ammophila* spp. on the foredunes, suggest continued stabilization within the regionally distinct transgressive dunes at Wickaninnish Beach and Schooner Cove. New restoration efforts are underway to mechanically remove invasive beach grasses so as to restore aeolian activity and promote more favourable habitat for endemic and endangered species within the dunes.

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