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The twentieth-century migration of parabolic dunes and wetland formation at Cape Cod National Sea Shore, Massachusetts, USA: landscape response to a legacy of environmental disturbance

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Abstract: Cape Cod, an early North American colony, was covered by mature forest prior to European contact but, with settlement in the late seventeenth century, aeolian processes dominated into the twenty-first century. An aerial photographic time series from AD 1938 to 2003 quantifies dune movement that reflects processes over centuries and documents accelerated parabolic dune movement at ~4 m/yr from 1938 to 1977 during a drier interval. In contrast, dune movement between 1987 and 2003 slowed to ~1 m/yr with wetter conditions. Wetlands expand post dune movement often forming in dune blowouts with seasonally wet conditions. Stratigraphic studies, coupled with optically stimulated luminescence ages, place erosion and burial of the pre-settlement forest soil by migrating dunes at AD 1690 ± 40 yr, with aeolian deposition continuing into the nineteenth and twentieth centuries, consistent with the historic record of land surface conditions. A threshold of landscape stability was exceeded in the late seventeenth to early eighteenth centuries, indicated by dune formation in response to human-induced land-cover changes, concomitant severe droughts and exposure to tropical storm/hurricane windfield. Dune orientation indicates preferential movement during winter with winds dominantly from the W–NW and with reduced vegetation cover. The present high biodiversity in interdunal wetlands is a legacy of aeolian processes from landscape disturbance initiated by European settlers in the seventeenth century.

Key words: Holocene aeolian activity, parabolic dunes, wetland formation, remote sensing, Cape Cod, historic landscape disturbance, Massachusetts.

Introduction

The outer coast of Cape Cod, Massachusetts (Figure 1), much of which is now the Cape Cod National Sea Shore (CCNS), was an area of early (1602–1620) European exploration (Kittredge, 1968: 10–12, 71; Chase, 1984; King, 1994) and was continuously occupied since the late seventeenth century (Rubertone, 1985). This area was mostly covered prior to European settlement by a mature forest but clear-cutting, grazing and agricultural practices by the eighteenth to nineteenth centuries eliminated much of this vegetation and apparently destabilized the ground surface (McCaffrey and Leatherman, 1979; Stilgoe, 1981; Cronon, 1983; Rubertone, 1985; Motzkin *et al*., 2002). Naturalist and author Henry David

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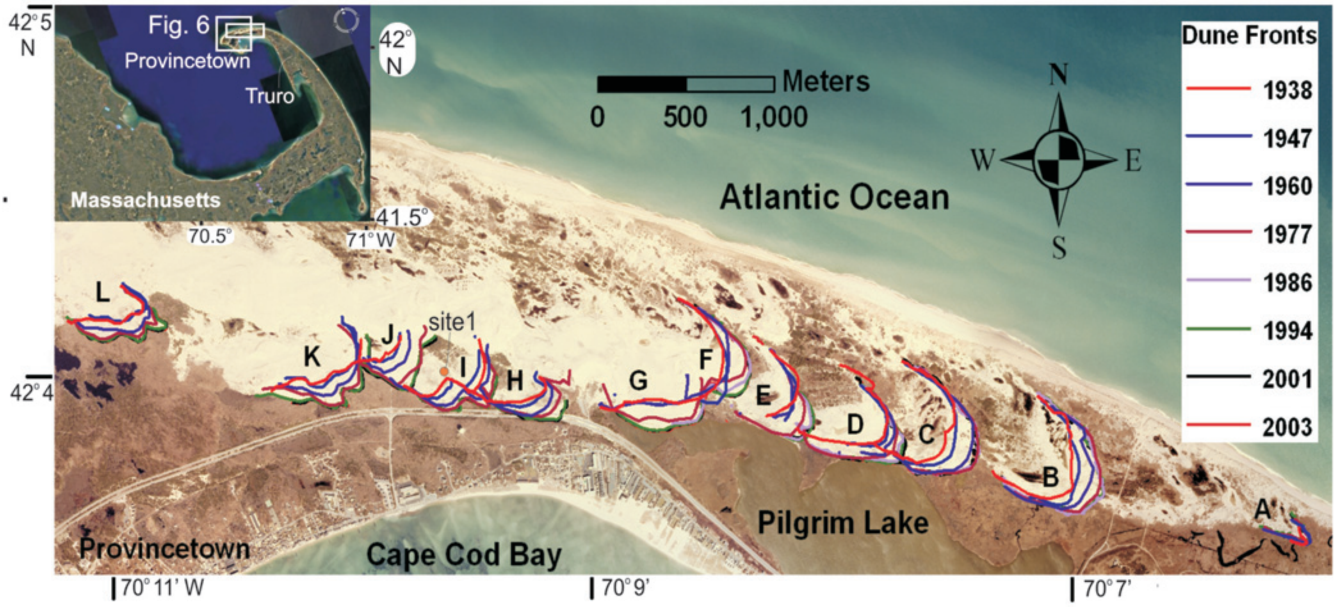

Figure 1 Aerial photographic mosaic (2001) of outer Cape Cod, Massachusetts showing position of parabolic dune fronts for various time periods in the twentieth and twenty-first centuries. Dark areas are wetlands and have formed and expanded with dune movement (Smith *et al.*, 2008)

Thoreau in October 1849 describes the lands between the towns of Truro and Provincetown (Figure 1) as desolate and barren with 'The greater part of land was a perfect desert of yellow sand, ripple-like waves by the wind, in only a little beach grass grew here and there' (Thoreau, 2004: 200). This landscape disturbance with settlement in the late seventeenth century initiated a complex response that persists into the twenty-first century, resulting in a sparsely vegetated landscape of migrating dunes and interdunal depressions. Thus, the Cape Cod landscape embodies the concept of legacy: current geomorphic and ecologic processes are dominantly governed by past events (eg, deforestation) that breach thresholds of apparent stability and result in unexpected states, such as pervasive dune migration (Swanson *et al.*, 1988). A striking landscape characteristic is broad, bowl-shaped depressions, often topographic lows, bounded by parabolic dune forms, that intersect the groundwater table for part of the year. These seasonally flooded wetlands, known as 'dune slacks', develop distinctive hydrophytic plant communities and are oases of biodiversity in an otherwise desert-like environment. Dune slacks are one of the last refuges on the outer Cape for species such as the insectivorous sundews (*Drosera* spp.) and orchids (*Calapogon tuberosus, Pogonia ophioglossoides*) and are critical habitat for the reproduction and survival of numerous invertebrates and amphibians such as the spadefoot (*Scaphiopus holbrookii*) and Fowler's toad (*Bufo fowleri*) (Smith *et al.*, 2008). This biologically diverse landscape, within a National Sea Shore, reflects a legacy of dramatic changes in landscape processes initiated by European settlers in the late seventeenth century.

This study quantifies rates of dune movement and wetland formation at CCNS from a time series of mosaicked and georeferenced aerial photographs for AD 1938 to 2003, which are representative of processes over the past *c*. 300 years. In turn, observations on land surface conditions of outer Cape Cod by explorers, settlers and naturalists from the seventeenth to nineteenth centuries provide a context to interpret dune migration rates in the twentieth century. The impact of other factors, such as moisture status monitored by the tree-ring derived Palmer Drought Severity Index (PDSI; Cook *et al.*, 2004), and tropical storm and hurricane intensity (Ludlum, 1963; Bosse *et al.*, 2001) are assessed on vegetation cover and associated aeolian transport. A stratigraphic assessment coupled with optically stimulated luminescence (OSL) dating identifies the pre-settlement land surface and dates the historic initiation of dune migration. The integration of historic observations, remote sensing analysis and stratigraphic studies yields new insights into the role of human activity and natural climate variability in landscape disturbance and propagation of wetland biodiversity.

Remote sensing

Remote sensing and Geographic Information Systems (GIS) techniques were used to monitor land surface changes and to quantify dune migration at CCNS over the past seven decades. A digital data base comprising 11 co-registered digital mosaics acquired (AD 1938, 1947, 1960, 1969, 1977, 1986, 1987, 1994, 1998, 2001 and 2003) over the study area was generated. Aerial photographs that were used in the generation of the mosaics were available in digital form from 1994 to 2003, whereas the aerial photographs from 1938 until 1987 were only available in hard copy and had to be scanned. Individual aerial photographs were scanned using the ScanMaker 9800XL Microtek TMA1600 scanner, with SilverFast Ai6 software, producing a TIFF file with original resolution of approximately 1 m/pixel.

All of the generated mosaics were rectified to the 2001 USGS orthomosaic, which was the base map. Approximately 20 ground control points (GCPs) were collected for each aerial photograph and were used to co-register it to the base map using ENVI, PCI Geomatica and Ortho Engine aerial photograph models. The average rectification ground root mean square errors (RMSE) for the aerial photographs from 1938 through 1977 is approximately 3 m, and for the aerial photographs from 1986 through 2003 is approximately 2 m. All mosaics were re-projected into a common projection (NAD 1983 State Plane Massachusetts Mainland FIPS 2001) and datum (North American 1983 datum).

Twelve parabolic dunes were identified from the mosaics (A through L, Figure 1). The front of each dune was defined as the point on the image where the avalanching advancing margin of the dune intersected the vegetation. This line of intersection with the vegetation was traced to define a forward arc of the parabolic dune. These lines were traced using ArcGIS. Most of the aerial photographs have sharp well-defined edges on the dune fronts. The definition of the dune in the 1938 image has additional uncertainties

Table 1 Parabolic dunes of Cape Cod National Seashore migration distances and rates from AD 1938 to 2003

Intervals	Number of years	Net migration of parabolic dunes (m)/ Migration rates for parabolic dunes (m/yr)																					
		B		C		D		E		F		G		H		I		J		K		L	
		m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr	m	m/yr
2001–03	2	1	0.5	2	1.0	3	1.5	3	1.5	1	0.5	3	1.5	1	0.5	3	1.5	2	1.0	3	1.5	3	1.5
1998–01	3	2	0.7	2	0.7	4	1.3	3	1.0	3	1.0	6	2.0	1	0.3	5	1.7	6	2.0	4	1.3	6	2.0
1994–98	4	1	0.3	1	0.3	8	2.0	7	1.8	3	0.8	6	1.5	1	0.3	5	1.3	3	0.8	4	1.0	3	0.8
1987–94	7	2	0.3	2	0.3	17	2.4	5	0.7	3	0.4	17	2.4										
1986–87	1	1	1.0	1	1.0	2	2.0	3	3.0	2	2.0	1	1.0	20	1.2	16	0.9	46	2.7	12	0.7		
1977–86	9	14	1.6	1	0.1	27	3.0	35	3.9	26	2.9	30	3.3									51	2.0
1969–77	8	14	1.8	4	0.5	6	0.8	43	5.4	3	0.4	40	5.0	18	2.3	3	0.4	28	3.5	27	3.4		
1960–69	9	40	4.4	34	3.8	18	2.0	50	5.6	32	3.6	44	4.9	55	6.1	27	3.0	49	5.4	40	4.4		
1947–60	13	46	3.5	92	7.1	31	2.4	19	1.5	67	5.2	19	1.5	67	5.2	73	5.6	62	4.8	66	5.1	74	5.7
1938–47	9	50	5.6	50	5.6	19	2.1	27	3.0	25	2.8	10	1.1	25	2.8	34	3.8	25	2.8	23	2.6	12	1.3
Total dune movement (m)		171		189		135		195		165		176		188		166		221		179		149	
Average			2.6		2.9		2.1		3.0		2.5		2.7		2.9		2.6		3.4		2.8		2.3

Figure 2 (a) Photograph showing burial of oak trees by advancing dune K front. (b) Top of trees remnants, buried by migrating dune K in the past decade

(approximately 1–4 m), because of the lower quality aerial photographs in comparison with the other available images.

To define the amount of movement of each dune, a line segment was drawn parallel to the direction of maximum movement and perpendicular to a tangent to the dune front. Distances along this line were measured in ArcGIS to determine the movement of each dune between two time periods (Table 1).

Geomorphic and climate context

A prominent feature of Cape Cod is the presence of kilometre-long parabolic dunes that elongate with winds from the west to northwest (Strahler, 1966: 82–89). At least eleven discrete parabolic dunes are recognised, which coalesce in places and show distinct arms, steep noses (25–30°) and blowout areas that form the interior landscape of the outer Cape. The dunes are composed of medium to coarse sand. These inland parabolic dunes are disjunct from the coastal transverse dune system, often separated by a forested area. Coastal dunes formed also parallel with the Atlantic shore, reflecting winds from the north and northeast.

There is ample evidence that the inland parabolic dunes are actively migrating landforms, with the avalanche slopes of dunes H, I, J and K currently burying an adjacent forest (Figure 2), similar to that observed by Thoreau in October 1849 (Thoreau, 2004: 160):

> In one place we saw numerous dead tops of trees projecting through the otherwise uninterrupted desert, where we afterward learned, thirty or forty years before a flourishing forest had stood and now the trees were laid bare from year to year, the inhabitants cut off the tops for fuel.

Cape Cod is a mesic environment with mean annual precipitation of 106.5 cm and with mean monthly totals relatively consistent between 7 and 11 cm (Provincetown: 1941–2000; National

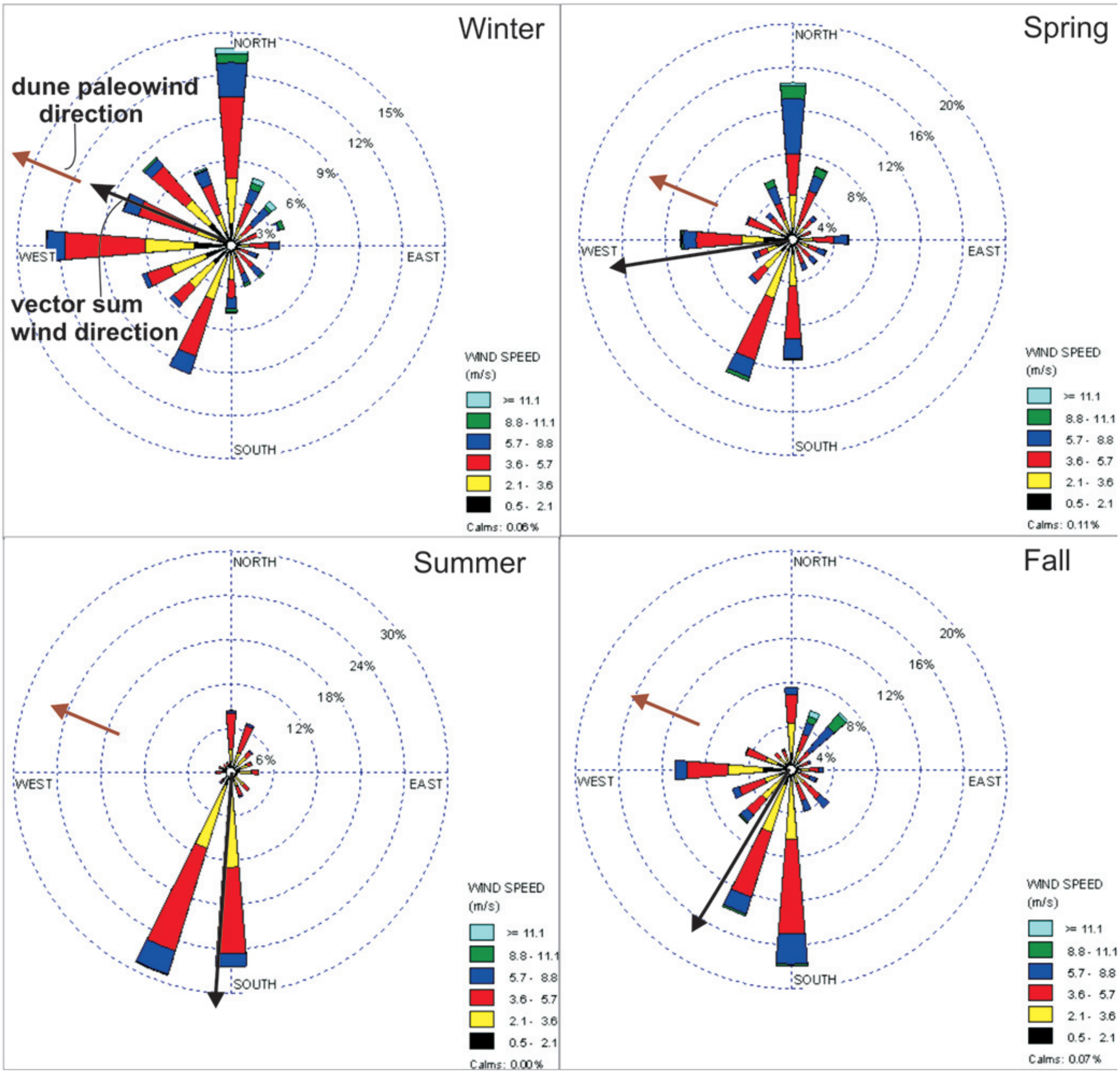

Figure 3 Winter (December, January and February), Autumn (September, October and November), Spring (March, April and May) and Summer (June, July and August) wind roses (2004–2005) and vector sum (black arrow) showing resultant prevailing winds. Winter winds are coincident with palaeowinds inferred from parabolic dune form (brown arrow)

Oceanic and Atmospheric Administration (NOAA), 2002). Most of the winter precipitation falls as snow with mean monthly temperatures <0°C. The wind climate of Cape Cod shows strong seasonality (Figure 3). Winds are almost exclusively from the south during the summer and autumn and less so for spring. Spring shows strong bi-directional winds from the north and south, with a weaker component from the west. On the other hand, winter shows wind directions dominating from the west and north (Figure 3), mirroring the orientation of migration of parabolic dunes on outer Cape Cod.

The Cape Cod dunes are dominated by American beach grass (*Ammophila breviligulata*), which promotes the vertical accretion and horizontal movement of dunes (eg, Disraeli, 1984; Maun and Lapierre, 1984; Maun, 1998; Maun and Perumal, 1999). Timothy Dwight, an erstwhile observer of American landscapes, in August, 1800 recognized the pivotal role of American beach grass in dune development (Dwight, 1969: 61):

> Where this covering is found, none of the sand is blown. On the contrary it is accumulated and raised continually, as snow gathers and rises among bushes or branches of trees cut and spread upon the earth. Nor does the grass merely defend the surface on which it is planted, but rises as that rises by new accumulations, and overtops the sand, however high may be raised by the wind.

Thoreau, in September 1849, echos Dwight's assessment and underscores the possible importance of winter processes (Thoreau, 2004: 161–62):

> Beach-grass during the spring and summer grows about two feet and a half. If surrounded by naked beach, the storms of autumn and winter heap up sands on all sides and cause it to rise nearly to the top of the plant. In the ensuing spring the grass sprouts anew; is again covered with sand in the winter; and thus a hill or ridge con-

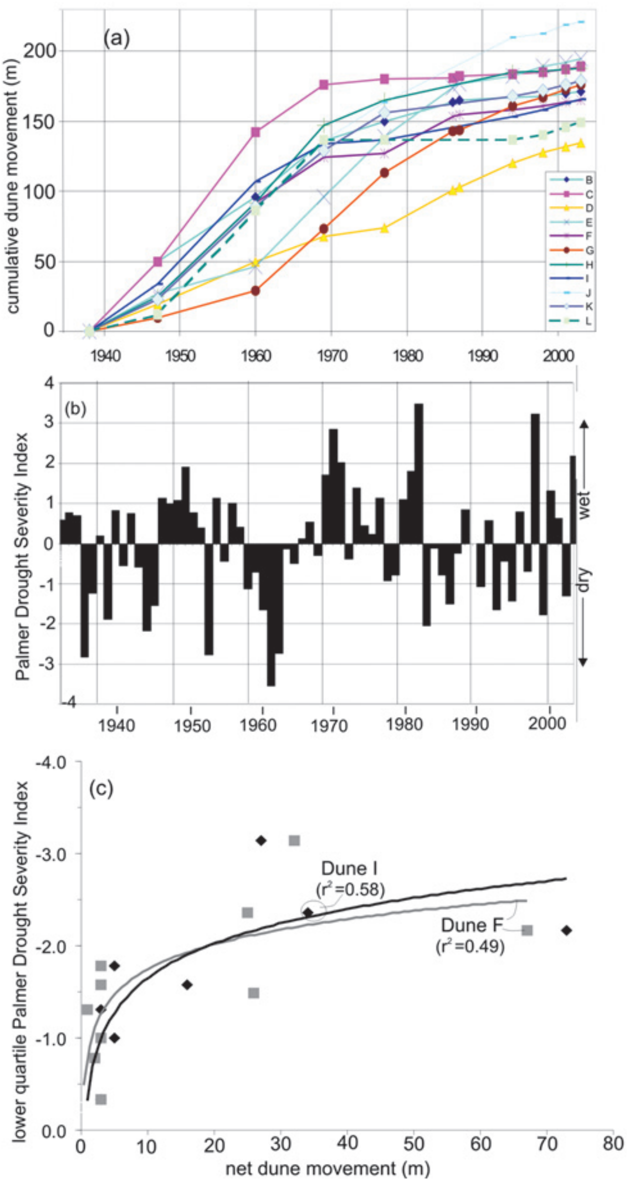

Figure 4 (a) Cummulative movement of parabolic dunes on outer Cape Cod, Massachusetts. Note that 70% of the dune movement occurred between 1940 and 1970, with <12% of movement since 1980. (b) Growing season (March–August) Palmer Drought Severity Index (PDSI) for outer Cape Cod (record 271 of Cook *et al*., 2004). Note correspondence of majority of dune movement to dry period between 1940 and 1970 with majority of years having negative PDSI. In contrast stabilization of dunes is associated with a majority of years with a positive PDSI. (c) The relation between dune (I and F) movement (m) and the lowest quartile PDSI. Note dune movement increases with a lower quartile PDSI <–2.0, which is associated with particularly dry conditions

tinues to ascend as long as there is a sufficient base to support it, or till the circumscribing sand, being also covered with beach-grass, will no longer yield to the force of the winds.

Field studies quantify these astute observations of Dwight (1969) and Thoreau (2004) and show that American beach grass thrives with annual sand additions of 5 to 40 cm/yr through vertical stem elongation, root formation on buried stems and vigorous rhizomal growth (Maun and Lapierre, 1984; Maun, 1998). However, grass density significantly decreases with sand depositional rates of 60 to 120 cm/yr, which limit shoot viability (Maun, 1998) and aeolian accretion dominates the landscape.

Migration of parabolic dunes in the twentieth and twenty-first centuries

The aerial photographic time series quantifies dune movement for the past 65 years that reflects processes over centuries (Figure 1; Table 1). Over 75% of dune migration occurred between AD 1938 and 1977 for 10 of the 11 monitored parabolic dunes (Figure 4). The average dune migration rate for this period is 4 m/yr, with peak rates for dunes B, E, F, G, H, I, J and K between 5 and 7 m/yr, surprisingly similar to rates of parabolic dunes from semi-arid environments (Marín *et al*., 2005). In contrast, <12% of the total dune migration occurred since 1987, with an average rate of 1 m/yr (Table 1; Figure 4a). Interdunal areas, sites for wetlands, propagate during accelerated dune movement, particularly between 1940 and 1965, and subsequently formed and expanded with ensuing wet conditions (Smith *et al*., 2008). Newly created wetlands are most evident in interdunal areas of dunes B and C (dark areas) with extension of parabolic dunes (Figure 1).

The total distance of migration for the 11 monitored dunes is fairly consistent, ranging from 130 to 221 m (Table 1). Dune D has the lowest total net migration (130 m), probably reflecting the limited source of sand with extensive vegetated and wetland surfaces upwind and partial termination into Pilgrim Lake. Dune J, with the highest total migration (221 m), is an interior dune with ample apparent sediment supply and no heavily vegetated surfaces (wetlands or forest) immediately upwind (Figure 1). Measured migration for dunes H and I that impinge onto a road may be an underestimate because of periodic removal of sand by highway authorities (McCaffrey and Leatherman, 1979).

Stratigraphic and chronologic context of dune migration

There is an abundance of stratigraphic exposures in areas of dune movement at CCNS. The formation of these dunes in places eroded and buried the pre-settlement forest soil (McCaffrey and Leatherman, 1979). Chronologic control for deposition of aeolian sand that buries this and other palaeosurfaces is by optically stimulated luminescence dating (OSL) on the quartz 425–500 µm fraction, similar to Forman *et al*. (2005, 2006). A 4 m exposure within the blowout area of dune I (Figure 1) shows two palaeosols buried by aeolian sand (Figure 5). The lowest most stratified aeolian sand (unit 1) yielded the OSL age of 2300 ± 190 yr (UIC1823) and contains a well-developed palaeosol, with a spodic horizon and a 70 cm thick buried B horizon with accumulation of sesquioxides characteristic of spodosols (Soil Survey Staff, 1999: 695–700). This well-developed palaeoforest soil is buried by stratified aeolian sand (unit 2) that yielded the OSL age of 310 ± 40 yr (UIC1822); aeolian deposition is interrupted, indicated by a weak palaeosol, resumes 150 ± 20 yr (UIC1825) ago and persists to at least 80 ± 10 yr (UIC1824) ago (Figure 5). This stratigraphic sequence with OSL ages indicates aeolian erosion and subsequent burial of the pre-settlement palaeosol (spodosol) by aeolian sand *c*. AD 1690 ± 40 yr with continued aeolian deposition into the nineteenth and twentieth centuries.

Human-induced landscape disturbance and dune formation

The documented twentieth and twenty-first century movement of parabolic dunes on outer Cape Cod may ultimately reflect a land use philosophy and practices of seventeenth-century English settlers. A persistent belief of colonists was that activities to 'tame'

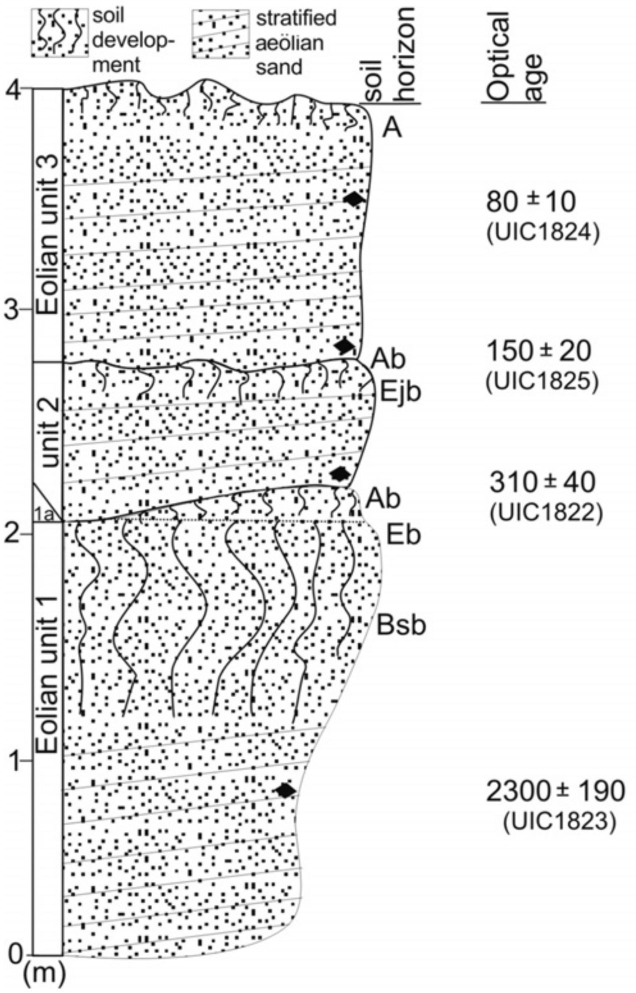

Figure 5 Stratigraphic section (site 1) exposing internal dune sand and associated buried soils for Provincetown dunes. Ages determined by optically stimulated luminescence using single aliquot protocols. Soil horizon designations follow those of Birkeland (1999: 348). This and other sites demonstrate reactivation of dune system in the past 300 years, consistent with historic accounts

nature yield improved weather and climate and are part of a divine plan to render the environment most suitable for habitation (Cronon, 1983: 108–20; Kupperman, 1984: 19–33). A common perception was that the removal of trees and agrarian activities would lead to warmer winters and summers and lengthen the growing season; the smoke and heat from fires in towns would broadly mitigate cold conditions. Indeed, there was a perception that the incidents of thunder, lightning, long droughts, severe rain and cold snaps decreased after colonization and agricultural expansion because of divine providence (Kupperman, 1984: 20). Thus, this perceived benefit of deforestation and cultivation on weather and climate and persistent economic needs with an expanding colonial population (Cronon, 1983: 110–26) led to inadvertent widespread landscape degradation particularly with expansion to less arable lands on outer Cape Cod *c*. AD 1660–1720 (Rubertone, 1985; King, 1994).

Early seventeenth-century explorer accounts for the outer Cape Cod prior to settlement indicate the clear dominance of dense vegetation and a stable land surface without moving or blowing sand. Samuel De Champlain, on 19 July 1605, described the area near Provincetown as 'There is a large extent of open country along the shore before reaching the woods, which are very attractive and beautiful' (Grant, 1952: 70). Henry Hudson, on a brief stop at the north end of Provincetown on 3 August 1609 'found goodly grapes and rose trees' (Young, 1971: 101). Captain John Smith observed in 1614 for the outer Cape 'headland of high hills of sand, overgrown with shrubbie pines, hurts and such trash; but an excellent harbor for all weather' (Arber, 1967: 205). The Pilgrims landed at the site of Provincetown on 11 November 1620 and found 'the ground or earth sand hills, much like the downs in Holland, but much better; the crust of the Earth, a spits depth (~20–30 cm), excellent black earth; all wooded with oaks, pines, sassafras, juniper, birch, holly, vines, some ash, walnut; the wood for most part open and with underwood, fit either to go or ride in' (Young, 1971: 123–24). A group of Pilgrims on 16 November 1620 explored southward from Provincetown toward Truro and described their passage through the thick vegetation as 'we marched through boughs and bushes, and under hills and valleys which tore our armor to pieces' (Young, 1971: 128). Later the Pilgrims encountered evidence for old cornfields and found more recent evidence for cultivation of 'new stubble they had gotten corn this year and many walnut trees full of nuts and a great store of strawberries and some vines' (Young, 1971: 132). In turn, the Pilgrims found near a house pits excavated in sand with large stores of 'full of very fair corn of this year, with some six and thirty goodly ears of corn, some yellow, and some red, and others mixed blue, which was a very goodly sight' (Young, 1971: 133). Historic accounts (Motzkin *et al*., 2002) and palaeoecologic studies (Parshall *et al*., 2003) concur that outer Cape Cod was largely forested by pine and oak woodlands and there is no evidence for blowing sand or migrating dunes at the time of European settlement.

The establishment of town and colonies by seventeenth-century settlers of New England resulted in widespread regional deforestation (Geller, 1974: 15–23; Cronon, 1983: 108–22). Deforestation was an early concern with the colonial government of Plymouth, passing laws in AD 1626 to conserve timber resources, but to no avail (Geller, 1974: 15). There is a wealth of written accounts and maps on changing land surface conditions, with colonization of the Provincetown area *c*. AD 1660–1720 (McManis, 1972; McCaffrey and Leatherman, 1979; Stilgoe, 1981; Cronon, 1983; Rubertone, 1985; Holmes *et al*., 1998) and with settlement in the eighteenth and the nineteenth centuries (Graham, 1838; Dwight, 1969: 57–67; McManis, 1972; McCaffrey and Leatherman, 1979; Stilgoe, 1981; Cronon, 1983; Rubertone, 1985; Holmes *et al.*, 1998; Thoreau, 2004: 139–215; Garver, 2006: 75). Much of the outer Cape was probably deforested by *c*. AD 1700, with Truro town records of AD 1701 and AD 1711/1712 indicating that municipal or court permission is needed to take firewood (Rubertone, 1985). Blowing sand emerged as a large concern to Cape Cod residents in the early 1700s (McCaffrey and Leatherman, 1979: 211; Cronon, 1983: 149–50; Rubertone, 1985; Holmes *et al*., 1998: 57–58). Large areas around the Province lands were described as 'deserts' in AD 1725, and in AD 1730 Truro and Provincetown meadows were covered in drifting sand dunes created by exposed soil nearby (McCaffrey and Leatherman, 1979; Cronon, 1983: 149; Holmes *et al*., 1998: 57). A Massachusetts Senate Document from AD 1714 indicates the severity of landscape denudation with the infilling of the Harbor (now Pilgrim Lake) by of blowing sand (from McCaffrey and Leatherman, 1979):

> *An Act for Preserving the Harbor at Cape Cod, and regulating that inhabitants and Sojourners there.* … the Harbour at Cape Cod … is in danger of being damified, if not made wholly unserviceable, by destroying the tress standing on the said Cape, (if not timely prevented), the trees and bushes being of great service to keep the sand from being driven into the Harbour by the wind.

It appears that some of the earliest attempts at landscape conservation and restoration may have occurred on Cape Cod. In AD 1728, cattle grazing and vegetation removal was prohibited along outer Cape Cod beaches because Provincetown officials realized that practices such as these aggravated sand exposure (McCaffrey and

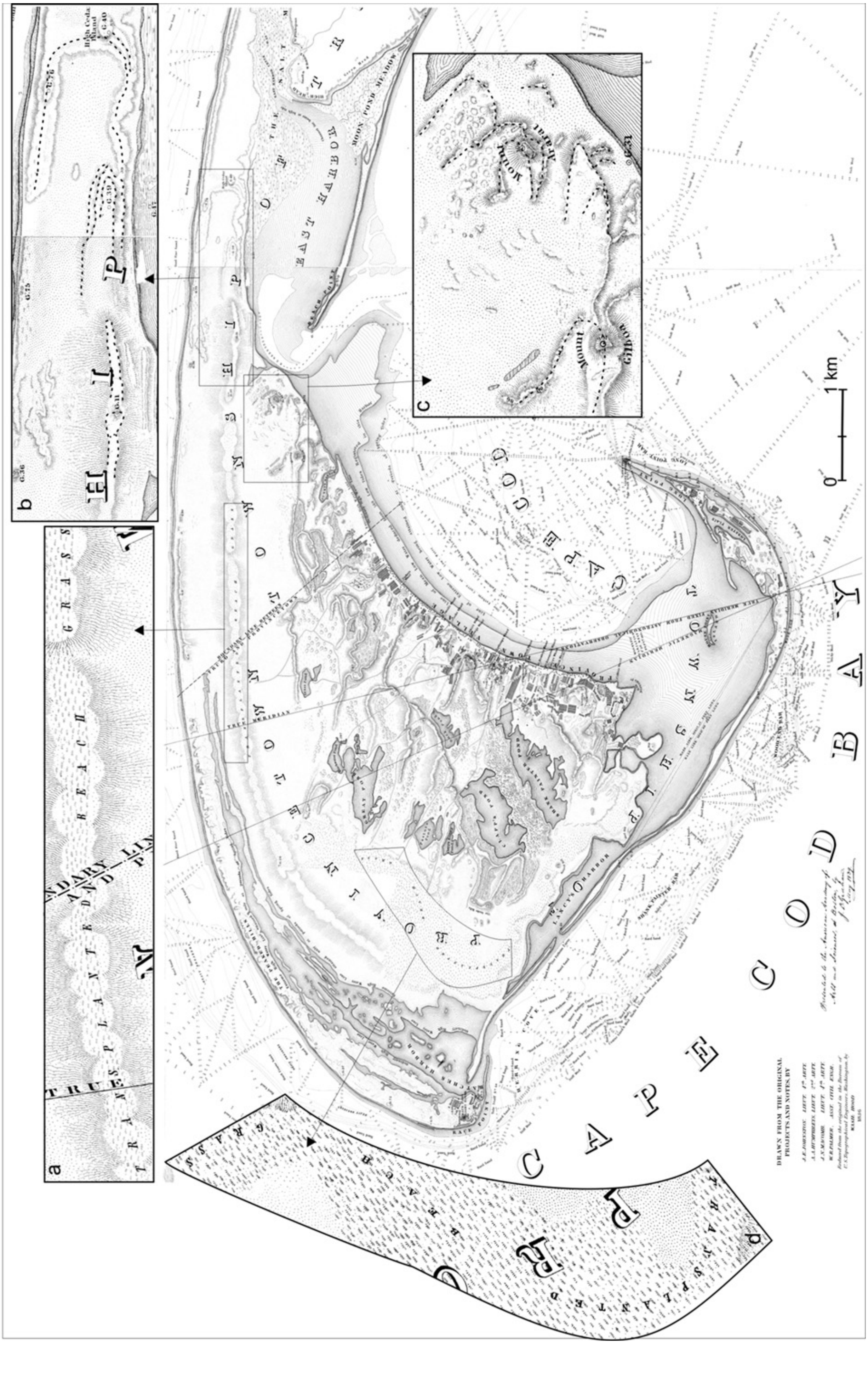

Figure 6 Portion of AD 1838 shaded relief map of outer Cape Cod showing areas artificially planted with beach grass to stabilize blowing sand and morphologies with parabolic-like dune forms (Graham, 1838). (a) Bare sand area with transplanted beach grass (most likely *Ammophila breviligulata*). (b) Bare sand area with distinctive parabolic forms outlined by dashed line; possible dunes. (c) Bare sand area with many parabolic forms outlined by dashed line and closed depressions, potentially blowouts. (d) Bare sand area with transplanted beach grass

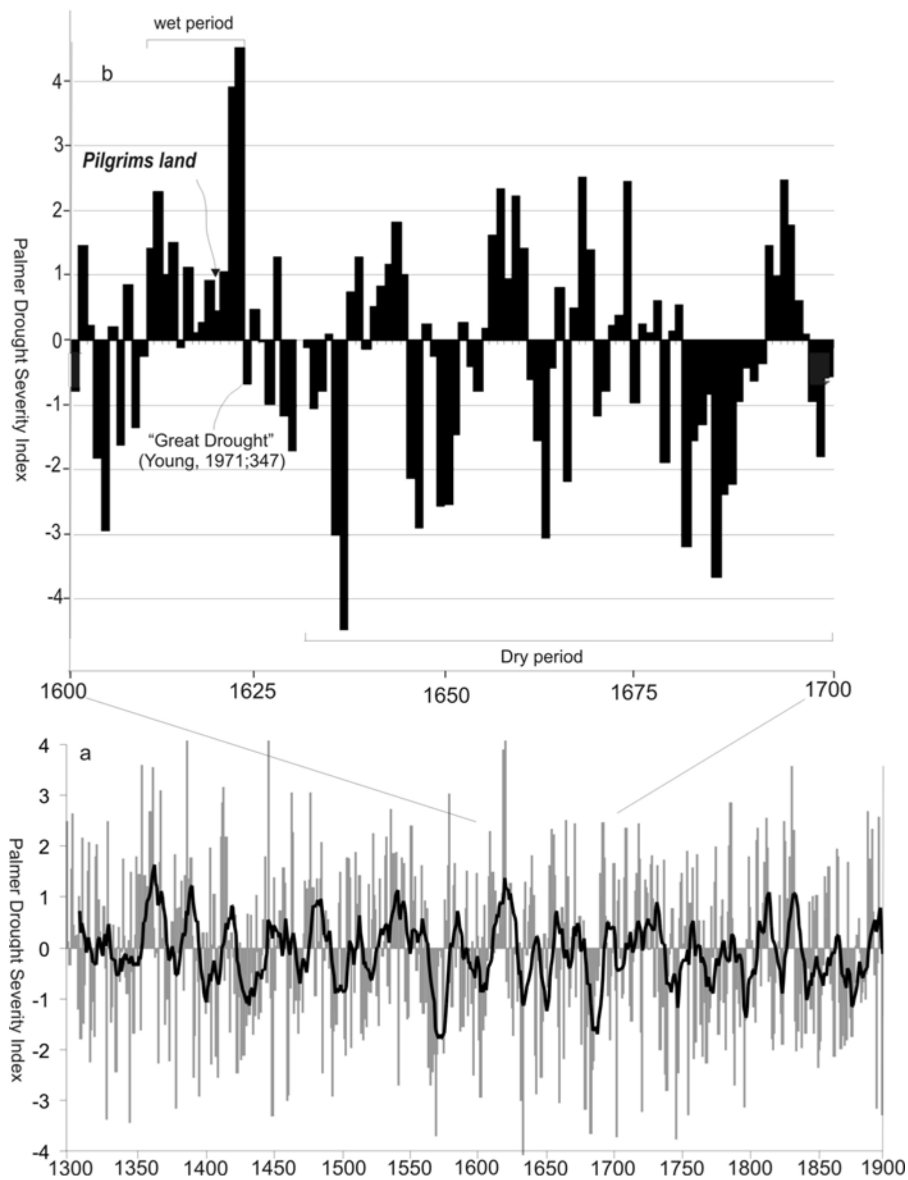

Figure 7 (a) Annual Palmer Drought Severity Index (PDSI) for outer Cape Cod from AD 1300 to 1900 (record 271 of Cook *et al*., 2004). (b) Annual PDSI record for AD 1600 to 1700. Pilgrims landed on Cape Cod in AD 1621 during a pronounced wet period, the third wettest interval in the past *c*. 970 years. In contrast the ensuing 75 years in the seventeenth century are noticeably drier and exacerbate landscape denudation triggered by early settlers. Early historic accounts indicate significant landscape disturbance and loss of soil and timber resources

Leatherman, 1979: 211). The Massachusetts General Court passed an act in AD 1739 that prohibited grazing in denuded areas and went on to require in AD 1744 that local Cape Cod residents plant (American) beach grass each spring, along with Scotch broom, native pines, bayberries and buckwheat, in an effort to control drifting sand dunes (Rubertone, 1985; Holmes *et al*., 1998: 57). It appears that these legislated efforts did not arrest land degradation. Timothy Dwight, an early and perceptive observer of American landscapes, in August 1800 graphically described the aeolian landscape between Truro and Provincetown as (Dwight, 1969: 59):

> This remarkable object is an enormous mass of sand, … fine light of yellowish hue and the sport of every wind. It is blown into plains, valleys and hills. The hills are of every height from ten to two hundred feet. Frequently they are naked, round and extremely elegant; and often rough, pointed, wild and fantastical, with the varied forms which are seen as times of drifts of snow.

Henry David Thoreau approximately 50 years later (AD 1849) repeatedly referred to the landscape between Truro and Provincetown as 'the Desert' (Thoreau, 2004: 150, 152, 157, 159, 165), and described (Thoreau, 2004: 162):

> Sand-hills formed … are one hundred feet high and of every variety of form, like snowdrifts, or Arab tents and are continually shifting.

A shaded relief map produced in AD 1838 from land surveys in AD 1833, 1834 and 1835 (Figure 6) clearly shows extensive areas planted with beach grass to stabilize the land surface and features with parabolic-like dune forms (Graham, 1838); this is 'the Desert' described by Thoreau (2004: 150, 152, 157, 159, 165). Public documents and maps attest to persistence of a denuded landscape and continued dune migration through the nineteenth and into the twentieth centuries, despite numerous attempts to stabilize dunes with American beach grass and other plants (McCaffrey and Leatherman, 1979). The breadth of historic accounts spanning the past *c*. 300 years indicate that tree removal, agricultural and grazing practices initiated in the middle to late seventeenth century (McCaffrey and Leatherman, 1979; Rubertone, 1985) lead to widespread landscape denudation and subsequent dune movement that continued mostly unabated into the nineteenth, twentieth and twenty-first centuries. Palaeoecologic studies of lake cores from the outer Cape Cod show a dramatic increase in charcoal and non-arboreal pollen *c*. 300 years ago, associated with widespread forest clearance (Parshall *et al*., 2003). Thus, dune migration documented from the aerial photographic time series for the past 65 years reflects landscape denudation processes for the preceding *c*. 300 years.

Dune migration and climate variability

Documented variable rates of dune migration on outer Cape Cod (Figure 4; Table 1) reflect changes in windfield and availability and supply of sand (Kocurek and Lancaster, 1999) on decadal to multidecadal timescales. Parabolic dune migration in the past *c*. 65 years may be enhanced by heightened winds and extensive tree blowdowns associated with tropical storms and hurricanes. An analysis of hurricane climate and ecological impacts in the past 370 years indicates that Cape Cod has the lowest (85 years) reoccurrence of Fujita Force 2 winds (182–253 km/h) in New England, which could lead to substantial forest destruction and further landscape denudation (Bosse *et al*., 2001). There are a number Fujita Force >2 hurricanes in the seventeenth century that would have impacted the outer Cape Cod, specifically during 1635, 1638 and 1675 (Ludlum, 1963; Bosse *et al*., 2001). The heightened exposure of Cape Cod to storm-generated winds is probably a factor in impeding forest recovery and also perpetuating dune movement.

Another factor impacting dune movement is moisture status, as monitored by nearby tree-ring derived Palmer Drought Severity Index (PDSI) (Cook *et al*., 2004, site 271). There is an apparent relation between accelerated dune migration *c*. 1940–1965 and particularly dry conditions, with 16 years registering negative Palmer Drought Severity Index (PDSI) (Cook *et al*., 2004, site 271) (Figure 4b). Dune movement accelerates when the lower quartile monthly PDSI values are <–1.5 to –2.0 (Figure 4c), indicative of particularly dry conditions in the winter and spring. In contrast, deacceleration of dune movement occurs during wetter conditions between 1970 and 1990 with only 3 years of negative PDSI (Figure 4b). Wet conditions enhance dune stability through expansion of interdunal wetlands into topographic lows that serve as blowout propagation areas in drier conditions. In turn, the higher water-table through capillary action and a possible perched water-table (Chen *et al*., 2004) in the adjacent vertically accreted dune further stabilizes dune fronts. In contrast, drought conditions would reduce above- and below-ground primary productivity (cf. Mangan *et al*., 2004) and shrink wetland areas. In areas where the vegetation cover is reduced below 25% the efficiency of wind entrainment of sand dramatically increases (Kuriyama *et al*., 2005). Aeolian processes dominate during the winter, indicated by dune orientation coincident with winter wind directions from the west-northwest. The dominance of winter conditions may reflect snow-assisted movement of sand grains up snow ramps within the blowout areas of dunes, decreasing the angle of accretion (eg, Dijkmans, 1990), and with the common exceedance of threshold wind velocities (>3.6 m/s) for aeolian entrainment. Low vegetation cover and drier moisture status of the dune landscape in winter further enhances aeolian transport. Burial of beach grass and other plants by 60+ cm of dune sand will severely restrict plant viability in the spring (Disraeli, 1984; Maun, 1998), resulting in a reduction of vegetation cover. In turn, spring and summer drought limit vegetation cover in marginal areas, near wetlands, further expanding the footprint of moving sand.

Initial colonization of New England at *c*. AD 1620 occurred during a 13-yr interval (AD 1610–1622) of particularly wet conditions, with average PDSI of +2 (Figure 7) and may be reflected in early explorer accounts of lush vegetation cover (eg, Arber, 1967: 205; Young, 1971: 122–33). Pronounced wet conditions are registered for outer Cape Cod in AD 1622 with PDSI of +4.5, the third highest PDSI of the 965-yr record (Cook *et al*., 2004, record 271). However, in the succeeding year of AD 1623 William Bradford, Governor of the Plymouth Colony, registered a ‘great drought’ in the spring and was portrayed as (Young, 1971: 347–48):

> In the midst of April we began to set the weather being then seasonable which much encouraged us, giving us hopes of after plenty. The setting season is good till the latter end of May. But it pleased God, for our further chastisement, to send a great drought; in so much as in six weeks after the latter setting there scarce fell any rain … both (corn) blade and stalk … judged utterly dead.

This ‘great drought’ of William Bradford in AD 1623 is registered as a modest drought year with an average PDSI of –0.6 (Cook *et al*., 2004; record 271). This perceived drought reflects a significant shift in moisture status with a change in PDSI values between AD 1622 and 1623 of –5 PDSI units. The PDSI record since AD 1630 shows similar shifts in moisture status, though with more severe droughts, which in comparison to William Bradford’s account, may have yielded an even drier conditions.

A threshold in landscape stability on Cape Cod was exceeded sometime in the late seventeenth to early eighteenth centuries, indicated by historic accounts on the ubiquity of blowing sand and migrating sand masses (McCaffrey and Leatherman, 1979; Cronon, 1983: 149; Holmes *et al*., 1998: 57) and a stratigraphic assessment that documents burial of the pre-settlement land surface by aeolian sand at *c*. AD 1690 ± 40 years (Figure 5). In turn, palaeoecologic studies infer widespread deforestation *c*. 300 years ago (Parshall *et al*., 2003). The dominance of aeolian surface processes is probably in response to human-induced land cover changes. However, this landscape disturbance was concomitant with one of the severest and prolonged droughts in the past 1000 years, between AD 1681 and 1691, with an average PDSI of –2 (Figure 7). Indeed, the climate of the late seventeeth century (AD 1625–1700) is drier than previous and succeeding centuries, with 40 of 75 years registering negative PDSI (Figure 7) and includes the driest year (AD 1635) on record with a PDSI –4.5 (Cook *et al*., 2004). In turn, Cape Cod’s heightened exposure to >2 Fujita Force winds is another factor that enhances aeolian transport and denudation, with forest blow down (Bosse *et al*., 2001). The juxtaposition of this extreme climate variability with rapid and pervasive landscape denudation probably resulted in an irrevocable shift from forested terrain to actively moving dunes. Climate variability on outer Cape Cod, indicated by the PDSI (Cook *et al*., 2004, record 271), has been insufficient in the past 300 years to fully stabilize this dune system.

Conclusion

Aerial photographic analysis of migration of 11 parabolic dunes indicates that during drier periods, dune migration rates accelerate to 4 to 7 m/yr, whereas dune movement decreases to ≤ 2 m/yr in wetter intervals. Dune orientation indicates preferential movement during the drier winter with reduced vegetation cover and dominant winds from the west-northwest. Thus, the currently active inland dune system of Cape Cod reflects a complex response to landscape denudation by early European inhabitants, natural moisture variability, storm-generated winds, and a seasonal wind-field and aeolian processes. The unique biodiversity of interdunal wetlands (Smith *et al*., 2008) does not reflect the antiquity of the landscape but rather the recent development of these habitats, with aeolian activity in response to human disturbance starting *c*. 300 years ago. Thus, current ecologic and landscape processes on Cape Cod reflect dominantly a legacy of landscape disturbance initiated by European settlement. It is unclear if wetter conditions in the past 30 years, with low parabolic dune migration rates (<1 m/yr) and reduced hurricane occurrence (Bosse *et al*., 2001) if ensuing, may result in stabilization of dune forms and succession to forest, similar to the landscape encountered by the Pilgrims.

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