The Holland Paleosol: an informal pedostratigraphic unit in the coastal dunes of southeastern Lake Michigan

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Abstract: A very prominent buried soil crops out in coastal sand dunes along an ~200 km section of the southeastern shore of Lake Michigan. This study is the first to investigate the character of this soil — informally described here as the Holland Paleosol — by focusing on six sites from Indiana Dunes National Lakeshore north to Montague, Michigan. Most dunes in this region are large (>40 m high) and contain numerous buried soils that indicate periods of reduced sand supply and comcomitant stabilization. Most of these soils are buried in the lower part of the dunes and are thin Entisols. The soil described here, in contrast, is relatively well developed, is buried in the upper part of many dunes, and formed by podzolization under forest vegetation. Radiocarbon dates indicate that this soil formed between ~3000 and 300 calibrated years BP. Pedons of the Holland Paleosol range in development from thick Entisols (Regosols) with A–Bw–BC–C horizonation to weakly developed Spodosols (Podzols) with A–E–Bs–Bw–BC–C profiles. Many profiles have overthickened and (or) stratified A horizons, indicative of slow and episodic burial. Differences in development are mainly due to paleolandscape position and variations in paleoclimate among the sites. The Holland Paleosol is significant because it represents a relatively long period of landscape stability in coastal dunes over a broad (200 km) area. This period of stability was concurrent with numerous fluctuations in Lake Michigan. Given the general sensitivity of coastal dunes to prehistoric lake-level fluctuations, the soil may reflect a time when the lake shore was farther west than it is today. The Holland Paleosol would probably qualify as a formal pedostratigraphic unit if it were buried by a formal lithostratgraphic or allostratigraphic unit.

Résumé : Un sol enfoui, très caractéristique, affleure dans les dunes de sable côtières sur une section d'environ 200 km de la côte sud-est du lac Michigan. La présente étude est la première à examiner le caractère de ce sol — décrit ici de façon informelle en tant que paléosol Holland – en ciblant 6 sites entre le parc national Indiana Dunes National Lakeshore et Montague vers le nord, au Michigan. La plupart des dunes de cette région sont très grandes (> 40 m de haut) et contiennent de nombreux sols enfouis qui témoignent de périodes simultanées d'apport de sable réduit et de stabilisation. La plupart de ces sols sont enfouis dans la partie inférieure des dunes et consistent en des entisols minces. Le sol décrit ici est par contre relativement bien développé et est enfoui dans la partie supérieure de plusieurs dunes; ce sol a été formé par podzolitisation sous une végétation forestière. Les datations au radiocarbone indiquent que ce sol s'est formé entre environ ~3000 et 300 années avant le présent. Des pédons du sol enfoui Holland ont une plage de développement qui va d'entisols épais (regosols) avec une zonation horizontale A–Bs–BC–C à des spodosols mal développés (podsols) avec des profils A–E–Bs–Bs–BC–C. Plusieurs profils ont des horizons A surépaissis et/ou stratifiés, indiquant un enfouissement lent et épisodique. Les différences de développement sont surtout dues à la position dans le paléopaysage et aux variations paléoclimatiques entre les sites. Le paléosol Holland est important car il représente une période relativement longue de stabilité du paysage dans les dunes côtières sur une grande région (200 km). Cette période de stabilité était concurrente aux nombreuses fluctuations du lac Michigan. Étant donné la grande sensibilité des dunes côtières aux changements préhistoriques de niveau du lac, le sol peut refléter un temps où la rive du lac était plus à l'ouest que présentement. Le paléosol Holland pourrait probablement être qualifié d'unité pédostratigraphique formelle s'il était enfoui sous une unité lithostratigraphique ou allostratigraphique formelle.

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Introduction and background

Sand dunes, common within the Great Lakes region (Wolfe and Nickling 1997), are especially abundant and large along the eastern shore of Lake Michigan (Farrand and Bell 1982; Fig. 1). Dunes are present along the eastern Lake Michigan shore because (1) there is an extensive supply of glacial and lacustrine sands in the region, and (2) prevailing westerly winds have a long fetch across Lake Michigan (Dorr and Eschman 1970). North of the city of Manistee, Michigan the dunes typically occur in isolated fields "perched" on high (~90 m) headlands composed of glacial till (Dow 1937; Snyder 1985). South of Manistee, in contrast, the dunes form a semi-continuous, transgressive dune field about 0.5–1 km wide that mantles topographically lower lake plains. The largest dunes are massive parabolic to sub-parabolic dunes that are up to 60 m high (Arbogast et al. 2002). These large dunes directly front the lake, in many places forming a prominent bluff that continues uninterruptedly for kilometres. In other places, smaller (<10-m high), ephemeral foredunes lie between the larger dunes and the lake.

Despite the prominence of the semi-continuous large dunes, they did not begin to be systematically studied until the 1990s. Previously, their evolution was qualitatively linked to a pair of untested assumptions related to their age and the processes associated with their growth. With respect to the age of the dunes, it was assumed that they essentially formed during the highstand of the Nipissing Great Lakes (~6000–4000 years BP; Dorr and Eschman 1970; Buckler 1979), which were about 6 m higher than present lake level (Hansel et al. 1985). Regarding process, it was generally believed that the dunes must have developed during a relative lowstand within the overall high Nipissing stage. In this scenario, sands eroded from bluffs during a higher lake phase were later exposed on a broad beach during a lower lake stage, allowing for dune development (Dorr and Eschman 1970; Buckler 1979). This model was apparently derived by default from Olson's (1958*a*) foredune model, which accurately explains the ephemeral foredunes that lie between the lake and the larger dunes in many places.

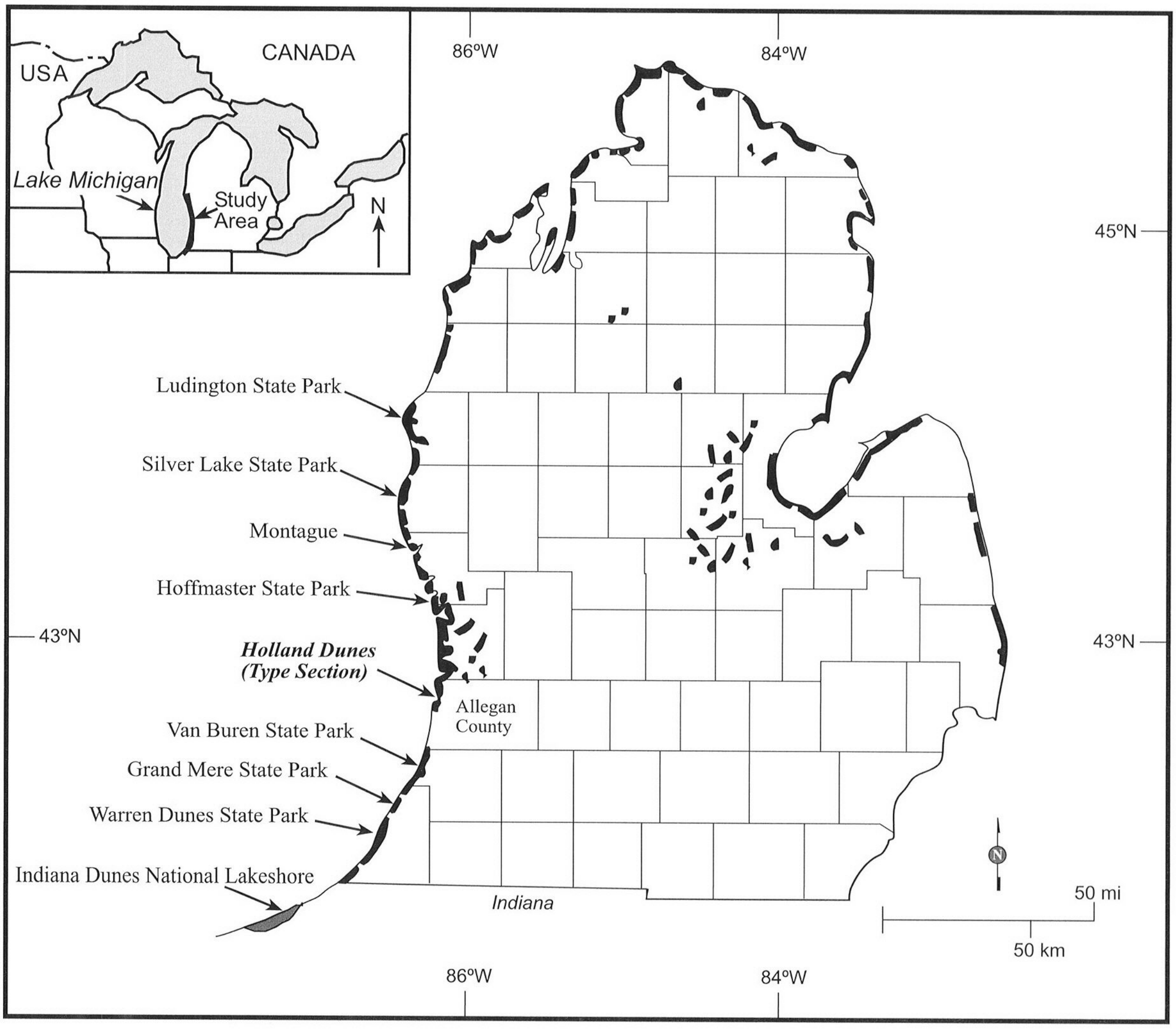
Within the past decade, there has been a systematic effort to test the age–process models associated with coastal dune development along the southeastern shore of Lake Michigan (Arbogast and Loope 1999; Van Oort et al. 2000, 2001; Arbogast et al. 2002). Initial research, conducted by Arbogast and Loope (1999), tested the Nipissing (age) hypothesis by investigating buried soils directly beneath dunes at four sites between Grand Haven and Muskegon, Michigan (Fig. 1). Their study indicated that dune building did not begin concurrently between sites and that the largest (~60-m high) dune (at the Rosy Mound Quarry; Fig. 1) began to form ~2900 years BP, well after the Nipissing highstand. A variety of buried soils were also observed at the Rosy Mound Quarry, indicating that the dunes formed episodically rather than during a narrow period of time.

Following the Arbogast and Loope (1999) study, reconnaissance data indicated that many of the large dunes along the southeastern shore of Lake Michigan contain buried soils. Systematic radiocarbon dating of these soils provided information regarding dune growth and stabilization periodicities. In this context, four dunes were studied near Holland, Michigan (Fig. 1; Arbogast et al. 2002). This cluster of large (>50 m high) dunes is noteworthy because (1) they lie within one of the most extensive dune fields along the southeastern shore of Lake Michigan, (2) the exposures are closely spaced, enabling detailed chonostratigraphic comparisons between them, and (3) each contains a variety of buried soils. The Holland dunes began to grow early in the post-Nipissing period (Arbogast et al. 2002). They grew the most (~75%) between about 4000 and 2500 calibrated (cal.) years BP, and enlarged only about 5–10 m in the past 500 years. During the early part of this evolution, growth correlates best with the post-Nipissing regression, which corroborates Olson's (1958*b*) foredune model relating dune growth to wide beaches and high sand supply. As the Holland dunes grew larger, however, episodes of enlargement corresponded better with high lake stages (Arbogast et al. 2002) reconstructed from beach-ridge sequences (Baedke and Thompson 2000). This high lake level – dune growth correlation best supports the perched-dune model (Marsh and Marsh 1987). According to this model, dunes grow during high lake stages when waves destabilize bluff faces by undercutting them, which, in turn, exposes the upper part of the bluffs to strong winds that can transport eolian sand to the adjacent plateau or lake plain. Subsequently, perched dunes stabilize when lake level falls and bluffs stabilize because waves no longer erode their base. This model has been applied to the headland dunes north of Manistee (Snyder 1985; Loope and Arbogast 2000) and along the southern shore of Lake Superior in Michigan's upper peninsula (Anderton and Loope 1995; Arbogast 2000). In a study of exposed buried soils in dunes at Van Buren State Park, 40 km to the south of Holland, Van Oort et al. (2001) found essentially the same history of dune activity as Arbogast et al. (2002) found near Holland.

During the Holland dunes study, many buried soils were discovered in the dunes. These Entisols (Regosols) indicate only brief periods of landscape stability and concomitant pedogenesis. Numerous Entisols were also observed in the perched dune fields north of Manistee by Loope and Arbogast (2000), who argued that they formed during ~150-year lowstands in Lake Michigan and were buried when the lake subsequently rose.

At Holland, Arbogast et al. (2002) also noted that each of the dunes contains a moderately developed buried soil in the upper part of the stratigraphic sequence (e.g., Fig. 2). The morphology of this soil points to a relatively long period of stability and pedogenesis in the dune system. Since the recognition of this buried soil at Holland, similar soils have been discovered in comparable landscape positions between Muskegon and Indiana Dunes National Lakeshore (Fig. 1; Van Oort et al. 2000; Arbogast et al. 2001) and likely also occur in other dune fields along the Great Lakes, including those in Canada (e.g., Wolfe and Nickling 1997). The extensive occurrence of this buried soil within an ~200-km-long stretch of coastal dunes along the southeastern shore of Lake Michigan implies that it represents a regional period of extended landscape stability and pedogenesis in the region. Given the prominence, traceability, and diagnostic character of this buried soil, and its likely presence elsewhere in coastal dune fields in the Great Lakes region, this paleosol would probably qualify as a geosol if the sediment above

Fig. 1. Distribution of sand dunes in lower Michigan, including the coastal dune system along Lake Michigan. Map shows the locations of the six sites sampled for this study. Also included are sites where the Holland Paleosol existed but was not sampled (P.J. Hoffmaster State Park) and sites where the buried soil is assumed to exist, but we were unable to locate a site suitable for sampling (Silver Lake Dunes and Ludington State Parks).



were a formally designated lithostratigraphic or allostratigraphic unit (North American Commission on Stratigraphic Nomenclature (NACSN) 1983). Nonetheless, we believe that it should be recognized informally. The purpose of this paper, therefore, is to (1) describe the physical and chemical characteristics of this buried soil, and (2) establish the period of time in which it formed and determine its geomorphic significance, and (3) informally name this buried soil the *Holland Paleosol.*

Study area

The study area is an ~200 km section of coastline that extends from Montague, Michigan to the Indiana Dunes National Lakeshore near Michigan City, Indiana (Fig. 1). Dunes here are very large (>40 m high), form a continuous but narrow (~0.5-km-wide) band of overlapping features that parallel the beach, and are well exposed in a series of lake-facing sections for most of the shore (e.g., Fig. 2). The dunes are cliffed (Olson 1958*b*), mantle lacustrine deposits (Farrand and Bell 1982) of probable Nipissing age (Hansel et al. 1985) and are parabolic with limbs facing generally perpendicularly to the shore.

The climate of the region is humid continental. Average annual temperature at Montague (Fig. 1) ranges from –4.9 °C in January to 20.2 °C in July, whereas data for Michigan City are –1.1 °C (January) and 28 °C (July). Average annual precipitation ranges from 851 mm at Montague to 1036 mm at Benton Harbor (Midwest Regional Climate Center 2002).

Vegetation is dominated by northern hardwoods, including American beech (*Fagus grandifolia*), red maple (*Acer rubrum*), sugar maple (*Acer saccharum*), white ash (*Fraxinus americana*), various species of oak (*Quercus* spp.), and shagbark hickory (*Carya ovata*) (Fig. 2). White pine (*Pinus strobus*) and eastern hemlock (*Tsuga canadensis*) are present in isolated localities. On active dunes, the sand is either entirely exposed or covered by scattered bunches of marram grass (*Ammophila breviligulata*; Bowman 1986).

Methods

Based on previous fieldwork (Gutschick and Gonsiewski

Fig. 2. View of the Lake Michigan coastal dunes, near Muskegon, Michigan. The Holland Paleosol is the prominent buried soil near the top of the dune (arrow).

1976, Arbogast et al. 2002), we became aware of several sites where a strongly developed paleosol exists within the Lake Michigan coastal dune system (Figs. 1, 2). We visited nine sites within the dune system but were able to sample the paleosol at only six. At one site (Silver Lake dunes) the landscape was so seriously disturbed by off-road vehicles that the paleosol could not be located, whereas at Ludington State Park, it is probably absent or buried by recent colluvium. We sampled and described the paleosol at P.J. Hoffmaster State Park but later rejected this pedon as atypical because it contained multiple A horizons, indicative of incremental, episodic burial.

At each of the six remaining sites, we sought to sample the best developed soil that still typified the overall setting. Most soils on dunes form on moderately to steeply sloping surfaces; we therefore avoided sites on crests and swales, where slopes are low. Because aspect is an important influence on soil development in the midlatitudes (Hunckler and Schaetzl 1997), we further constrained the sampling locations to geomorphic aspects between 305° and 45° azimuth (northwest- to northeast-facing slopes). At each of six dune outcrops, the paleosol was excavated by hand and described and sampled by horizon (Soil Survey Division Staff 1993; Schoeneberger et al. 1998; Fig. 1). The BC and C horizons, which were quite thick, were subdivided into lower and upper parts and subsampled. Although all horizons had formed in thick deposits of dune sand, subtle changes in sand size were deemed important enough to be designated as lithologic discontinuities (Beshay and Sallam 1995; Schaetzl 1998).

Horizon-based samples were air-dried and, as a precaution, sieved to remove coarse fragments (although, as expected, none were found). The fine earth fraction was analyzed in the laboratory for pH (2:1 water:soil) and texture by a modified particle-size method (Soil Survey Laboratory Staff 1996). Because the samples had almost no silt or clay, the content of silt + clay was determined gravimetrically, rather than by silt and clay fractionation by pipette. Organic matter content was determined by loss on ignition (8 h at 430 °C) (Davies 1974). Extractions for Al and Fe were performed on all horizons, except BC and C horizons, using acid ammonium oxalate (Fe_o, Al_o), sodium pyrophosphate (Fe_p, Al_p), and sodium citrate-dithionite (Fe_d, Al_d) (McKeague and Day 1966; Soil Survey Laboratory Staff 1996; McKeague et al. 1971; Parfitt and Childs 1988) and the extracts analyzed by atomic absorption spectrophotometry. Based on the literature, we made the following interpretations of extraction data: pyrophosphate extracts organically bound, amorphous forms of Al and Fe, oxalate extracts amorphous forms of Al and Fe, and both organic and inorganic and Al_d and Fe_d represent "free" amorphous and crystalline forms (McKeague and Day 1966). Weighted values of the data just discussed were calculated by multiplying the values (for each subhorizon) by its thickness in centimetres, and summing the total over the B horizon or solum. We did not need to multiply weighted horizon or solum data by bulk density values, as is preferred, because bulk densities of the soil horizons were nearly identical because of long-term burial in uniform sediment. Because the paleosol commonly exhibited podzolic morphology, illustrative of translocation of Al and Fe compounds, a POD Index was calculated for each site. The POD Index is a numerical index of spodic–podzolic development based on field-measured attributes; increasing POD values correlate to stronger soil development and, in many cases, greater soil age (Schaetzl and Mokma 1988; Arbogast and Jameson 1998; Wilson 2001; Schaetzl 2002).

Results and discussion

Paleosol characteristics and variability

We propose the informal name "Holland Paleosol" for the well-developed buried and exhumed soil in the upper part of the Lake Michigan coastal dune system, where it exists between (at least) Indiana Dunes National Lakeshore, Indiana and about Montague, Michigan (Fig. 1). The name can and should be carried onto sites outside and especially north of the aforementioned area, where it may exist but where we have not yet observed it. Within this area the paleosol is usually one of a suite of buried soils in the dune allostratigraphic complex. The Holland Paleosol is, however, almost always the best developed soil of the several that exist in these dunes.

We chose the name Holland Paleosol based on the soil exposed near the city of Holland, Michigan. The Holland type area (an informal stratotype) lies more-or-less geographically in the middle of the study area and exposes a buried soil that has been least modified by burial processes (see later in the text) (Tables 1, 2, 3). This site is located at 42°44′03″N latitude and 86°12′23″W longitude. It can easily be accessed from the city of Holland, which is ~9 km to the northeast and bordered to the east by US. Highway 31. To reach the site, one need only exit Highway 31 at East 32nd Street and proceed due west on that road for about 18 km to the intersection of 66th Street, which extends north and south along the coast, then turn south on 66th Street and proceed about 9 km to Gilligan Lake (Fig. 3), where informal parking is available on the east shoulder of the road. The site is about 50 m north of the northern end of Gilligan Lake and lies about 0.7 km west. Several hiking trails can be accessed in this area that lead to the beach.

The Holland Paleosol is everywhere formed in and buried by eolian sand. Sand in the dune complex is dominated by medium and fine sand, with the mean particle size falling in the medium sand fraction (Table 3). Most pedons had < 1.0% silt + clay, when determined on a profile-weighted basis (Table 3). Many also exhibited a slight increase in silt + clay in the upper profile (Table 1), possibly due to eolian influx. In swales on the paleolandscape, thin A and even O horizons exist above the paleosol, suggestive of episodic burial. The paleosol crops out as an exhumed soil on the sides of eroded dune faces within the coastal dune system. At the Green Mountain blowout (dune 4 in Arbogast et al. 2002), for example, the paleosol crops out in a wide arc across the base of the blowout.

The location of the informal stratotype (type section) for the Holland Paleosol (Fig. 3) lies between two lake-fronting sites (dunes 2 and 3; Arbogast et al. 2002), where radiocarbon dates have been obtained from it. At the stratotype, the paleosol exhibits the typical, pre-burial A–E–Bs–BC–C horizonation (Fig. 4). The profile is thinner, and the horizonation less complex, here than at the other sites, probably because only at the Holland site was burial initially rapid, closely preserving its original horizonation (Tables 1, 2). At the other five sites, including the one in P.J. Hoffmaster State Park, the upper profile has one or more transitional, slightly overthickened horizons (e.g., EB, BE, AB) in the upper profile, or an overthickened A horizon, manifested as A1 and A2 horizons (Van Buren). This type of horizonation usually indicates either (1) slow, continuous burial or (2) shallow burial followed by pedogenesis and welding of the newly forming surface soil with the buried soil, compounding and thickening the horizonation of both (Ruhe and Olson 1980; Kemp et al. 1998). In the former case, the soil surface accretes eolian sediment slowly and continuously, while the profile "grows" upward into the surrounding sediment by cumulization. In this case, cumulization involves eolian additions onto the soil surface, on a dune upland. Slow, gradual additions are usually implied as the surface aggrades, leading to overthickened, or cumulic A horizons (Riecken and Poetsch 1960; McDonald and Busacca 1990; Wang and Follmer 1998; Almond and Tonkin 1999). The Holland Paleosol at Van Buren State Park, for example, has a cumulic A horizon. Slower cumulization rates are implied for sites like Montague and Indiana Dunes, where pedogenesis was able to almost keep pace with dune growth, leading to overthickened A and E horizons (Table 1). Intermittent episodes of dune growth–cumulization, punctuated by periods of stability, the second scenario indicated earlier in this paragraph, may produce one or more, thin A horizons above the buried paleosol, as was the case at P.J. Hoffmaster State Park and, to a lesser extent, at the Holland stratotype (Fig. 4). When buried in this manner, the upper profile undergoes less cumulization, as exemplified by thinner A horizons but often with larger contents of organic matter (Table 2). Often, the paleosol exhibits many of these variations in morphology, depending on its location on the dune paleolandscape, as rates of burial of surface soils on dunes are highly variable in space and time. In sum, at the Holland stratotype, the profile is best preserved in its pre-burial form, i.e., at this site the burial process had the least impact on its morphology. For this reason and others, we chose that pedon as the stratotype.

As indicated by the six representative sites, the paleosol typically has A–E–Bs (or Bw)–BC–C horizonation, indicative of podzolization (Tables 1, 2). Its upper boundary ranges from abrupt to diffuse, assumedly depending on the rate at which it was buried, while its lower boundaries, like that of many similar soils at the surface, are diffuse, grading downward into clean dune sand. Based on this horizonation, we conclude that the Holland Paleosol was undergoing podzolization and eventually may have developed into a Spodosol (Podzol), had it not been buried. Podzolization is a pedogenic process bundle in which organic carbon, Fe^{+3} and Al^{+3}, in some combination, are translocated from the upper profile to an illuvial Bs or Bhs horizon (DeConinck 1980; Buurman and van Reeuwijk 1984; Lundström et al. 2000). It is best expressed under vegetation that produces acidic litter, such as coniferous forest or, as in this case, a mix of conifers and oaks; this type of vegetation currently covers stable dunes in the study area. Coarse-textured, sandy parent materials, such as dune sand, are especially conducive to podzolization in the cool, humid climate of southern Michigan, where there is an excess of precipitation over evapotranspiration (McKeague et al. 1983). Cool temperatures keep evapotranspiration rates low and inhibit decomposition of the acidic litter, facilitating the process. In general, climate and parent material are highly explanatory variables for podzolization intensity in the Great Lakes region, where soils exhibit increasing amounts of podzolic development to the north (Schaetzl and Isard 1991, 1996). Proximity to Lake Michigan may enhance the rate of soil

Table 1. Morphological and selected physical properties of the six Holland Paleosol pedons.[a]

Site[1] and horizon	Depth (cm)	Munsell color (moist)	Sand (50–000 µm)	Silt + cay (<50 µm) (%)	Coarse sand[b] (1.0–0.5 mm) (%)	Medium sand (0.5–0.25 mm) (%)	Fine sand (0.25–0.125 mm) (%)	Very fine sand (0.125–0.053 mm) (%)	USDA texture class
Montague									
A	0–4	5Y 2.5/1	94.7	5.3	0.3	42.6	35.8	15.9	Sand
E	4–14	10YR 5/2	96.7	3.3	0.3	47.5	40.1	8.8	Sand
EB	14–31	7.5YR 5/4	96.9	3.1	0.5	56.8	36.3	3.3	Sand
BE	31–52	7.5YR 5/6	98.4	1.6	0.5	61.1	35.2	1.7	Sand
Bs1	52–67	7.5YR 5/8	98.4	1.6	0.7	64.8	31.9	1.1	Sand
Bs2	67–97	7.5YR 5/8	98.5	1.5	1.6	71.3	25.3	0.3	Sand
Bw	97–114	10YR 5/6	98.9	1.1	0.6	64.6	32.9	0.8	Sand
BC1	114–142	10YR 4/6	98.0	2.0	0.3	73.9	22.9	0.8	Sand
BC2	142–168	10YR 4/6	99.1	0.9	0.2	65.3	32.9	0.7	Sand
BC3	168–200	10YR 4/6	99.3	0.7	0.8	73.3	24.8	0.4	Sand
C	200–215+	10YR 6/4	99.3	0.7	1.0	71.8	26.4	0.2	Sand
Holland Dunes									
A	0–8	2.5Y 3/2	98.3	1.8	0.3	43.4	54.2	0.4	Fine sand
E	8–10	10YR 4/3	98.3	1.7	0.3	43.3	54.5	0.3	Fine sand
Bs1	10–18	10YR 4/6	98.3	1.8	0.4	47.6	49.8	0.5	Sand
Bs2	18–49	10YR 4/6	98.6	1.4	0.4	48.4	49.4	0.3	Sand
BC	49–82	10YR 5/6	98.8	1.3	0.5	47.1	50.8	0.3	Fine sand
C1	82–150	2.5Y 6/4	99.4	0.6	0.7	47.0	51.4	0.3	Fine sand
C2	150–165+	2.5Y 6/4	99.6	0.4	1.2	53.6	44.7	0.2	Sand
Van Buren State Park									
A1	0–12	2.5Y 3/2	98.3	1.7	0.2	50.6	46.8	0.7	Sand
A2	12–32	2.5Y 3/3	98.3	1.7	0.2	53.9	43.8	0.4	Sand
BA	32–45	10YR 4/4	99.8	0.2	0.3	62.8	36.8	0.1	Sand
Bw1	45–78	10YR 6/6	98.1	1.9	0.3	63.5	34.2	0.2	Sand
Bw2	78–105	10YR 6/6	99.0	1.0	0.5	65.5	32.9	0.1	Sand
BC	105–156	2.5Y 5/4	99.3	0.7	0.3	58.5	39.5	1.0	Sand
C1	156–200	10YR 5/4	99.4	0.6	0.3	50.8	47.2	1.2	Sand
C2	200–215+	10YR 5/4	99.5	0.5	0.4	57.3	41.2	0.7	Sand
Grand Mere State Park									
A	0–6	2.5YR 3/1	97.4	2.6	0.3	53.2	43.3	0.8	Sand
AE	6–8	10YR 3/2	98.0	2.0	0.3	57.1	39.8	0.8	Sand
EB	8–15	10YR 3/3	98.1	1.9	0.3	54.1	42.5	1.3	Sand
2Bs	15–45	10YR 4/6	97.8	2.3	0.5	73.8	23.4	0.1	Sand
2Bw1	45–80	10YR 5/4	99.1	0.9	1.2	76.6	21.3	0.1	Sand
2Bw2	80–115	10YR 5/4	98.4	1.6	1.1	77.1	19.8	0.5	Sand
2BC	115–160	10YR 6/4	98.0	2.0	0.8	73.3	23.5	0.3	Sand
2C	160–175+	2.5Y 6/4	98.9	1.1	1.0	77.8	20.1	0.1	Sand
Warren Dunes State Park									
Oi	0–5	10YR 2/1	—	—	—	—	—	—	—
AB	5–12	10YR 3/3	99.3	0.7	0.2	52.5	46.3	0.3	Sand

Table 1 (*concluded*).

Site[1] and horizon	Depth (cm)	Munsell color (moist)	Sand (50–000 μm)	Silt + cay (<50 μm) (%)	Coarse sand[b] (1.0–0.5 mm) (%)	Medium sand (0.5–0.25 mm) (%)	Fine sand (0.25–0.125 mm) (%)	Very fine sand (0.125–0.053 mm) (%)	USDA texture class
Warren Dunes State Park									
BA	12–20	2.5Y 4/3	99.3	0.8	0.2	52.7	46.1	0.3	Sand
Bw1	20–31	10YR 5/6	98.9	1.1	0.4	60.6	37.3	0.7	Sand
Bw2	31–55	10YR 5/6	99.0	1.0	1.3	76.3	20.9	0.5	Sand
BC1	55–70	10YR 6/4	99.2	0.8	1.3	81.7	15.8	0.3	Sand
BC2	70–105	10YR 6/4	99.3	0.7	0.9	75.1	22.8	0.4	Sand
C1	105–147	2.5Y 6/4	99.8	0.3	0.8	73.9	24.6	0.4	Sand
C2	147–162+	2.5Y 6/4	99.6	0.4	0.8	74.6	23.9	0.3	Sand
Indiana Dunes National Lakeshore									
A	0–7	2.5Y 2.5/1	99.1	0.9	0.3	30.8	66.8	1.2	Fine sand
AE	7–15	2.5Y 3/3	98.0	2.0	0.3	23.3	73.3	1.2	Fine sand
BE	15–24	10YR 4/4	98.2	1.8	0.3	28.2	68.6	1.2	Fine sand
Bs1	24–40	10YR 4/6	98.2	1.8	0.3	22.9	73.6	1.4	Fine sand
Bs2	40–54	10YR 4/6	98.8	1.2	0.2	20.4	76.7	1.6	Fine sand
BC1	54–81	10YR 6/6	99.7	0.3	0.2	17.7	80.5	1.3	Fine sand
BC2	81–135	10YR 6/6	100.0	0.0	0.1	19.8	79.3	0.8	Fine sand
C1	135–185	2.5Y 6/4	99.9	0.1	0.3	22.3	76.8	0.5	Fine sand
C2	185–200+	2.5Y 6/4	99.8	0.2	0.2	20.7	78.2	0.8	Fine sand

[a] Sites are arranged, within this and successive tables, from northernmost to southernmost.

[b] All samples lacked very coarse sand (1.0–2.0 mm diameter). This column was omitted for space reasons.

Table 2. Chemical properties of the six Holland Paleosol pedons.

Site and horizon	Depth (cm)	pH (2:1 water)	Organic matter based on LOI (%)	$\mathrm{Fe_o}$ (% of dry soil)	$\mathrm{Al_o}$ (% of dry soil)	$\mathrm{Fe_d}$ (% of dry soil)	$\mathrm{Al_d}$ (% of dry soil)	$\mathrm{Fe_p}$ (% of dry soil)	$\mathrm{Al_p}$ (% of dry soil)
Montague									
A	0–4	8.3	1.70	0.05	0.03	0.12	0.04	0.03	0.03
E	4–14	8.3	0.37	0.02	0.00	0.07	0.01	0.01	0.01
EB	14–31	8.2	0.29	0.04	0.01	0.08	0.01	0.02	0.01
BE	31–52	7.7	0.15	0.05	0.01	0.09	0.01	0.03	0.02
Bs1	52–67	7.8	0.14	0.05	0.03	0.07	0.02	0.05	0.03
Bs2	67–97	8.3	0.14	0.06	0.02	0.05	0.02	0.03	0.02
Bw	97–114	7.9	0.11	0.03	0.02	0.06	0.02	0.02	0.02
BC1	114–142	7.7	0.09	nd	nd	nd	nd	nd	nd
BC2	142–168	7.5	0.07	nd	nd	nd	nd	nd	nd
BC3	168–200	7.5	0.07	nd	nd	nd	nd	nd	nd
C	200–215+	8.0	0.06	nd	nd	nd	nd	nd	nd
Holland Dunes									
A	0–8	8.0	0.87	0.07	0.03	0.15	0.02	0.04	0.02
E	8–10	7.6	0.70	0.05	0.02	0.11	0.01	0.03	0.02
Bs1	10–18	7.7	0.54	0.08	0.03	0.12	0.02	0.04	0.02
Bs2	18–49	7.3	0.43	0.07	0.02	0.11	0.02	0.04	0.02
BC	49–82	7.2	0.31	nd	nd	nd	nd	nd	nd
C1	82–150	7.2	0.25	nd	nd	nd	nd	nd	nd
C2	150–165+	7.2	0.21	nd	nd	nd	nd	nd	nd
Van Buren State Park									
A1	0–12	7.8	1.02	0.15	0.03	nd	0.03	0.03	0.02
A2	12–32	7.8	0.58	0.11	0.02	nd	0.03	0.03	0.02
BA	32–45	7.5	0.24	0.13	0.02	0.10	0.02	0.05	0.02
Bw1	45–78	7.6	0.18	0.07	0.02	0.14	0.02	0.03	0.01
Bw2	78–105	7.6	0.16	0.07	0.02	0.10	0.01	0.02	0.01
BC	105–156	7.4	0.13	nd	nd	nd	nd	nd	nd
C1	156–200	7.5	0.16	nd	nd	nd	nd	nd	nd
C2	200–215+	7.4	0.06	nd	nd	nd	nd	nd	nd
Grand Mere State Park									
A	0–6	8.3	0.58	0.12	0.02	0.04	0.01	0.02	0.02
AE	6–8	8.5	0.38	0.13	0.02	0.12	0.02	0.03	0.02
EB	8–15	8.6	0.35	0.14	0.02	0.08	0.02	0.03	0.02
2Bs	15–45	7.8	0.18	0.08	0.01	0.12	0.02	0.03	0.01
2Bw1	45–80	7.9	0.14	0.04	0.02	0.02	0.01	0.02	0.01
2Bw2	80–115	8.0	0.18	0.04	0.01	0.08	0.02	0.02	0.01
2BC	115–160	8.6	0.17	nd	nd	nd	nd	nd	nd
2C	160–175+	8.8	0.15	nd	nd	nd	nd	nd	nd
Warren Dunes State Park									
Oi	0–5	7.0	nd	nd	nd	nd	nd	nd	nd
AB	5–12	7.6	0.44	0.14	0.02	0.09	0.02	0.03	0.02
BA	12–20	7.7	0.21	0.14	0.02	nd	0.02	0.03	0.01
Bw1	20–31	7.7	0.13	0.08	0.02	0.09	0.01	0.02	0.01
Bw2	31–55	7.8	0.11	0.04	0.01	0.11	0.01	0.01	0.01
BC1	55–70	7.7	0.11	nd	nd	nd	nd	nd	nd
BC2	70–105	7.7	0.12	nd	nd	nd	nd	nd	nd
C1	105–147	7.8	0.10	nd	nd	nd	nd	nd	nd
C2	147–162+	7.7	0.24	nd	nd	nd	nd	nd	nd
Indiana Dunes National Lakeshore									
A	0–7	7.5	0.97	0.08	0.03	0.09	0.03	0.02	0.02

Table 2 (*concluded*).

Site and horizon	Depth (cm)	pH (2:1 water)	Organic matter based on LOI (%)	Fe_o (% of dry soil)	Al_o (% of dry soil)	Fe_d (% of dry soil)	Al_d (% of dry soil)	Fe_p (% of dry soil)	Al_p (% of dry soil)
Indiana Dunes National Lakeshore									
AE	7–15	7.4	0.49	0.07	0.02	0.09	0.02	0.03	0.02
BE	15–24	7.6	0.31	0.08	0.02	0.14	0.02	0.04	0.02
Bs1	24–40	7.7	0.23	0.11	0.03	0.08	0.03	0.03	0.01
Bs2	40–54	7.3	0.16	0.08	0.04	0.12	0.02	0.03	0.02
BC1	54–81	7.4	0.11	nd	nd	nd	nd	nd	nd
BC2	81–135	7.2	0.09	nd	nd	nd	nd	nd	nd
C1	135–185	7.2	0.08	nd	nd	nd	nd	nd	nd
C2	185–200+	7.2	0.07	nd	nd	nd	nd	nd	nd

Note: nd, no data; LOI, loss on ignition.

development on the dune sands, explaining why most of our study sites contained a soil profile with a "complete" set of horizons, even though they had been subaerially exposed on a stable dune for probably < 2000 years.

The range of characteristics for the Holland Paleosol, along 13 sedimentologic and pedogenic axes, is provided in Table 3; the Holland Paleosol at its type section never ranks first on a series of developmental and sedimentologic criteria and ranks last only in solum thickness. As explained earlier in the text, the thinner solum probably is due to more rapid burial than at the other sites. Along most axes reported in Table 3, the Holland Paleosol ranks 3rd or 4th, and thus can be considered the modal profile from among the six.

The Holland Paleosol can be considered a weakly developed Spodosol (Podzol), although it fails to meet the quantitative criteria for this soil order (Soil Survey Staff 1999). It is likely that the requisite spodic properties have been partially lost because of post-burial alteration, because spodic properties develop quickly in soils (Barrett and Schaetzl 1992) but also fade rapidly (Hole 1975; Barrett and Schaetzl 1998). Indeed, among its characteristics, only gross horizonation of the lower profile has likely been retained more-or-less completely from the period of time when it formed. Thus, data on profile and B horizon thickness can be meaningfully compared with surface soils with reasonable assurance of their utility. Profile thicknesses, which range from roughly 50 to 110 cm, compare favorably with strongly developed Entisols (Regosols) or Entic Haplorthods in Michigan. Contents of illuvial Fe and Al compounds are minimal, again suggestive of a Udipsamment or an Entic Haplorthod (Table 3). Other chemical characteristics, such as pH, have been changed because of post-burial modification. Finally, the POD Index, a quantitative index of soil development that was developed for Spodosols, is zero for all pedons. In most soils, POD values below 2 are indicative of Entisols (Schaetzl and Mokma 1988).

Age of the Holland Paleosol

The Holland Paleosol has been dated at 15 exposures along the southeastern shore of Lake Michigan, ranging from Montague to Indiana Dunes National Lakeshore (Fig. 1). Table 4 lists the dates that have been obtained thus far for the Holland Paleosol and from the soils that lie directly (stratigraphically) below it. Most of these ages have been derived from charcoal; a few are from wood. Regardless, either of these sources is considered to provide highly reliable ages (Libby 1955) and, in this case, collectively provide bracketing estimates for the pedogenic interval of the Holland Paleosol. Given that the buried soils below the Holland Paleosol are weakly developed Entisols, they frequently do not contain a sufficient amount of material for radiocarbon dating. Thus, we have acquired dates from the underlying Entisols at only five exposures where the Holland Paleosol has been dated, including the type section. Nevertheless, we believe that there is enough data to confidently determine when the paleosol began to form and was subsequently buried.

Radiocarbon data suggest that the Holland Paleosol formed largely between ~3000 cal. years BP, and 300 years BP. Data from the Holland area (including the type section), Van Buren State Park, and Indiana Dunes National Lakeshore (Fig. 1) provide a basic chronology (Fig. 5). In the Holland area, the underlying Entisol was buried by sand that would become the paleosol parent material sometime between ~3000 and 2500 cal. years BP. At two sites in the Holland area (dunes 1 and 3), burial of the Holland Paleosol occurred ~1000–900 cal. years BP (Arbogast et al. 2002), whereas at the type section Holland Paleosol pedogenesis terminated at ~400 cal. years BP. The onset of pedogenesis in a blowout (Dune 4) at Holland began somewhat later, specifically between about 1900 and 1500 cal. years BP in the blowouts core (Hansen et al. 2004). This later start apparently occurred because the blowout is a local feature that was periodically active and migrating. Subsequently, the paleosol in the blowout was buried about 900 cal. years BP on its northern limb and about 400 cal. years BP elsewhere. Farther south, it appears that the Holland Paleosol formed during a shorter period of time. At both Van Buren State Park and Indiana Dunes National Lakeshore, the underlying Entisol was buried ~2100 cal. years BP by deposits of eolian sand that became the parent material for the Holland Paleosol. Subsequent to this period of dune growth, no significant additional deposits of eolian sand accumulated at these sites until ~300 cal. years BP ($2\sigma = \pm \sim 100$ years).

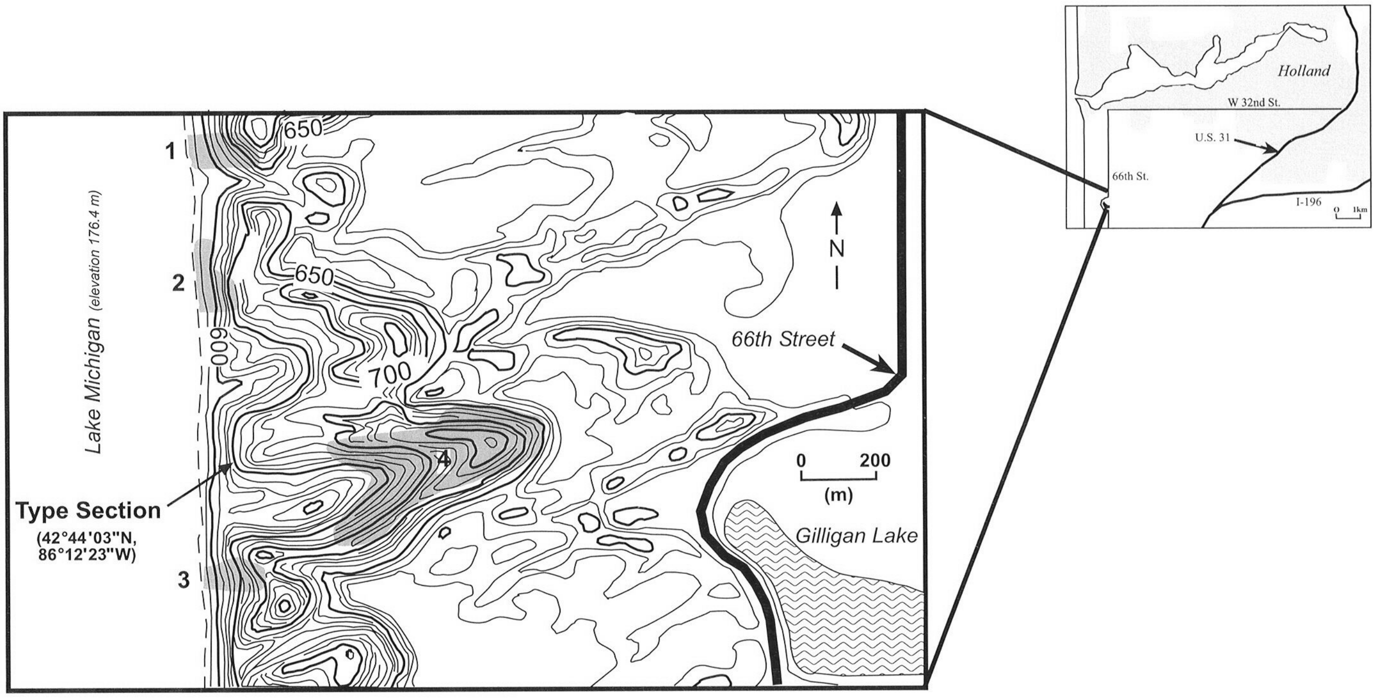
Although the Van Buren and Indiana Dunes data provide a basic temporal pattern of pedogensis for the Holland Paleosol, the evidence suggests that there was some variability between sites in the timing of its formation. This variability is not surprising given that coastal dunes are inherently sensi-

Table 3. Comparisons and rankings of the six Holland Paleosol pedons along sedimentologic, pedogenic, geomorphic, and site-specific criteria.

Criteria (units)	Montague value (rank)	Holland Dunes value (rank)	Van Buren value (rank)	Grand Mere value (rank)	Warren Dunes value (rank)	Indiana Dunes value (rank)
	northernmost —					— southernmost
Criteria related to sedimentology						
Mean particle size (weighted solum value, µm)	303 (3)	277 (5)	295 (4)	315 (2)	318 (1)	229 (6)
Content of silt + clay (weighted solum value, %)	1.59 (2)	0.89 (4)	0.99 (3)	1.68 (1)	0.63 (5)	0.50 (6)
Criteria related to soil development						
Solum thickness (cm)	114 (2)	49 (6)	105 (3)	115 (1)	55 (4)	54 (5)
B horizon thickness (cm)	83 (2)	43 (4)	73 (3)	100 (1)	43 (4)	39 (6)
Organic matter content (%): A horizon value	1.70 (1)	0.87 (4)	1.02 (2)	0.58 (5)	0.44 (6)[3]	0.97 (3)
Organic matter content (solum-weighted value, %)	34.41 (3)	37.42 (2)	51.78 (1)	33.01 (4)	22.23 (6)	32.08 (5)
Criteria related to pedogenesis and podzolization						
Maximum content of free iron (% Fe_d) within a B horizon	0.09 (6)	0.12 (3)	0.14 (1)	0.12 (3)	0.11 (5)	0.14 (1)
Maximum content of amorphous iron (% Fe_d) within a B horizon	0.06 (6)	0.08 (4)	0.13 (2)	0.08 (4)	0.14 (1)	0.11 (3)
Maximum content of organically bound iron (% Fe_p) within a B horizon	0.05 (1)	0.04 (3)	0.05 (1)	0.03 (5)	0.02 (6)	0.04 (3)
Total content of Fe_d, Fe_p, and Fe_o (B horizon-weighted value)	16.14 (3)	13.61 (4)	21.68 (1)	18.46 (2)	9.46 (6)	11.81 (5)
Total content of Al_d, Al_p, and Al_o (B horizon-weighted value)	6.29 (1)	4.00 (5)	6.01 (2)	5.27 (3)	2.00 (6)	4.02 (4)
Reddest and darkest B horizon	7.5YR 5/8 (1)	10YR 4/6 (3)	10YR 6/6 (6)	10YR 4/6 (3)	10YR 5/6 (5)	10YR 4/4 (2)
E (and transitional E) horizon thickness (cm)	48 (1)	10 (3)	0 (5)	9 (4)	0 (5)	17 (2)

Note: Ties are indicated by two or more pedons with the same rank. Highest rank indicates coarsest mean particle size. The pedon at Warren Dunes is the only one that has an O horizon.

Fig. 3. Detailed site map and stratigraphic section of the stratotype area for the Holland Paleosol. Shaded areas are sites reported in Arbogast et al. (2002). The type section is located between two sites (dunes 2, 3), where radiocarbon dates were obtained in the earlier study. Modified from the Saugatuck, Michigan (1981) quadrangle. Contour interval = 10 ft (1 foot = 0.3048 m).



tive landforms that depend upon the intricate relationships among the nearby water body, vegetation, and sand supply (Bauer and Sherman 1999). In addition, they can easily be disturbed on a local scale through blowout formation (e.g., Fraser et al. 1998; Hansen et al. 2001). At Holland (Fig. 1), for example, the onset of pedogenesis at dune 1 began shortly after 3390–2860 cal. years BP, and ended sometime between 1190 and 730 cal. years BP. Data from the southernmost site at Holland, dune 3, indicate that the Holland Paleosol formed between 2710–2330 and 530–140 cal. years BP. At dune 4, the paleosol was buried sometime between 930 and 470 cal. years BP on the north side of the blowout, between 510 and 320 cal. years BP in the core of the blowout, and between 280 and 0 cal. years BP on the south side of the blowout. This latter age is similar to the age (290–0 years BP) derived from one of the sites at Indiana Dunes National Lakeshore. Overall, however, the data indicate that the Holland Paleosol was buried between ~400 and 300 cal. years BP, as the median and mean ages (310 and 348 cal. years BP, respectively) from radiocarbon dates suggest.

In addition to potential temporal variability that exists within sites, such as at Holland, there may be a time-transgressive pattern that exists from north to south across the study area. For example, the paleosol was buried at Montague at ~500 cal. years BP at Montague, 300 cal. years BP at Van Buren State Park, and within the past 250 cal. years BP at Indiana Dunes National Lakeshore (Table 4). This spatio-temporal hypothesis needs to be tested further.

Regional significance of the Holland Paleosol

The widespread occurrence of the Holland Paleosol reflects a major period of late Holocene landscape stability in coastal dunes along the southeastern shore of Lake Michigan. According to Arbogast et al. (2001, 2002), dunes in this region began to grow ~5000 cal. years BP during the Nipissing transgression, when a large supply of reworked bluff sand was probably available (Chrzastowski and Thompson 1992) for dune growth. The dunes grew rapidly until sometime between ~2500 and 2200 cal. years BP, at which time they were ~30 m high. This period of dune growth was punctuated by brief periods of stability during which Entisols formed. Burial of these Entisols appears to temporally correlate with periods of high lake level (Arbogast et al. 2001, 2002).

Following the major period of dune growth, most coastal dunes along the southeastern shore of Lake Michigan stabilized for ~3000 to 2500 cal. years BP. This period of stability resulted in the formation of the Holland Paleosol. As noted previously, radiocarbon data (Table 4) suggest that some spatial and temporal variability existed with respect to the onset and termination of this period of stability and pedogenesis. Nevertheless, it is clear that the overall coastal dune system was in a period of relative stability, especially given the inherent sensitivity of this environment, and that this period is marked by the Holland Paleosol. This stable period ended approximately 300 cal. years BP.

It remains unclear as to why this long period of stability and pedogensis occurred. The widespread nature of the Holland Paleosol suggests that dunes along the southeastern shore of Lake Michigan basin responded to some regional environmental factor in the late Holocene that caused them to stop growing and stabilize; what was this variable? One possibility is that there was a decrease in the frequency and intensity of strong storms that are needed to mobilize large amounts of eolian sand. It seems unlikely, however, that such a decrease in storm frequency and character would have lasted almost two millennia. Another scenario involves

Fig. 4. Images of the Holland Paleosol. (A) Cross-sectional view of the type section, showing the depth of burial and some of the paleotopography of the geosol (arrow). (B) Profile of the Holland Paleosol. These images were taken a few months after our initial field work and do not reflect the exact pedon that was sampled at that time.

Table 4. Radiocarbon dates from the Holland Paleosol and underlying Entisols.

Location	Soil	Lab number	Radiocarbon age (1σ)	Calibrated age[a] (2σ)
Montague	Holland Paleosol	Beta-172560	420±60	540–310
Holland (dune 1)[b]	Holland Paleosol	NSRL-10488	1050±65	1190–730
Holland (dune 1)[b]	Entisol	NSRL-10489	2980±55	3390–2860
Holland (dune 2)[b]	Holland Paleosol	NSRL-10347	430±55	570–280
Holland (dune 3)[b]	Holland Paleosol	NSRL-10494	310±50	530–140
Holland (dune 3)[b]	**Entisol**	NSRL-10495	2390±65	2710–2330
Holland (dune 4)[b, c]	Holland Paleosol	Beta-132389	130±50	280–0
Holland (dune 4)[b, c]	Holland Paleosol	Beta-132390	320±50	490–290
Holland (dune 4)[b, c]	Holland Paleosol	Beta-132391	390±40	510–320
Holland (dune 4)[b, c]	Holland Paleosol	Beta-132392	930±40	930–740
Holland (dune 4)[c]	Holland Paleosol	Beta-175384	1800±40	1720–1540
Holland (dune 4)[c]	Holland Paleosol	Beta-163524	1940±40	1930–1740
Holland (type section)	Holland Paleosol	Beta-179044	390±40	520–320
Holland (type section)	Entisol	Beta-175383	3090±40	3380–3220
Van Buren (north)[d]	Holland Paleosol	NSRL-11932	165±30	290–0
Van Buren (central)[d]	Holland Paleosol	NSRL-11937	modern	390–0
Van Buren (central)[d]	Entisol	Beta-144632	2090±40	2145–1955
Van Buren (south)[d]	Holland Paleosol	NSRL-11935	235±35	420–5
Indiana Dunes	Holland Paleosol	Beta-159509	240±40	420–0
Indiana Dunes	Holland Paleosol	Beta-159508	160±40	290–0
Indiana Dunes	Entisol	Beta-159506	2070±40	2140–1930
Indiana Dunes	Holland Paleosol	Beta-159504	50±50	modern
Median age	Holland Paleosol		**310**	
Mean age	Holland Paleosol		**348**	

[a] Calibrated from conventional δ^{13}C-corrected radiocarbon age to calendar years using a tree-ring curve. All calibrations reported here were based on the 20-year atmospheric curve (e.g., Linick et al. 1985; Stuiver et al. 1986). The program used is discussed in Stuiver et al. (1998).

[b] Reported in Arbogast et al. (2002).

[c] Date derived from specific point along geosol axis in blowout.

[d] Reported in Van Oort et al. (2001).

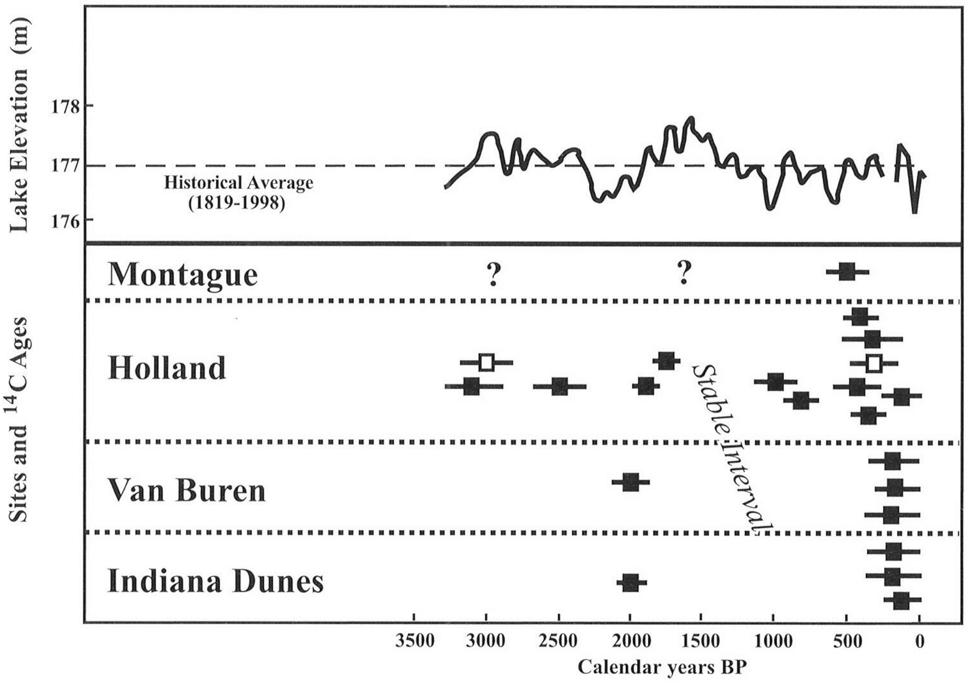
a subtle climatic shift to more effective moisture in the coastal dunes region, which would have contributed to pedogensis through increased (denser) vegetation, as well as through its impact on stabilizing the dune system. Local pollen evidence (Zumberge and Potzer 1956), however, indicates that no significant climate shift has occurred in the region during the past ~3000 cal. year BP. However, subtle changes in vegetation, especially along the coastal dunes, may not have been captured in the pollen data.

Given the rapid growth of the dunes from 4000 to 2200 cal. years BP, it appears that the Holland Paleosol formed because the supply of sand to this part of the dune system was markedly diminished. The dunes along the southeastern coast of Lake Michigan are essentially perched dunes that grow when sand blows from wave-destabilized bluffs to dune crests during high lake level (Snyder 1985; Loope and Arbogast 2000). Thus, the Holland Paleosol represents a change in the relationship between the dunes and the lake, one that significantly reduced sand supply to dune crests. In this context, a logical assumption is that the Holland Paleosol formed during a period of relatively low lake level. According to Baedke and Thompson (2000), however, the highest post-Nipissing level in Lake Michigan occurred within the period of time (~1700 cal. years BP) in which the Holland Paleosol was forming and that the lake fluctuated greatly throughout this entire temporal interval (Fig. 5).

Given the reconstructed fluctuations of Lake Michigan between ~2200 and 300 cal. years BP (Baedke and Thompson 2000) and the apparent consistent climate of that time span, some other unknown variable may have resulted in the formation of Holland Paleosol. A potential hypothesis for this lengthy interval of regional dune stability is that the dunes were somehow protected from wave undercutting and thus sand was not supplied to dune crests (e.g., Snyder 1985; Anderton and Loope 1995; Loope and Arbogast 2000). This protection may have occurred because the active shorezone was farther to the west between ~3000 and 1000 cal. years BP.

According to Chrzastowski and Thompson (1992), large volumes of littoral sediment flowed into the southern part of the Lake Michigan basin during this interval of time. These sediments were eroded from sites like the steep bluffs north of Manistee (Fig. 1), causing rapid progradation of the Toleston Beach in Indiana and Illinois. Beach progradation may have also occurred along the rest of the shore at least to Montague, thereby creating a buffer (e.g., Thompson et al. 2001) that allowed the dunes to stabilize and the Holland Paleosol to form. In this scenario, beach progradation hypothetically dominated as lake level fell between ~3000 and

Fig. 5. Comparison of radiocarbon ages from the Holland Paleosol and underlying Entisols with the late-Holocene lake-level curve (modified from Baedke and Thompson 1999 and Arbogast et al. 2002). Open and closed boxes represent ages derived from the type section and other sites, respectively.



2000 cal. years BP (Fig. 5). When the lake began to rise again ~1000 cal. years BP, the strand plain may have been progressively eroded such that cliffing of the dunes by waves resumed, and sand was supplied to dune crests. This hypothesis is supported by dip measurements on most exposures of the Holland Paleosol, which are at or near the angle of repose (Arbogast et al. 2003). These steep dips strongly imply that the paleocrests of the dunes were more lakeward at some point in time. If this scenario is valid, cliffing hypothetically began sooner in the Holland area than it did elsewhere, causing the Holland Paleosol to be buried earlier (~1000 cal. years BP) there. All of the dunes were apparently being cliffed by ~500–300 cal. years BP, which resulted in burial of the Holland Paleosol at most sites along the coast.

Conclusions

The Holland Paleosol, as informally recognized here, commonly occurs within the upper 5–10 m of the large coastal dunes along the southeastern shore of Lake Michigan between Montague and Indiana Dunes National Lakeshore. Despite having undergone pedogenesis for only about ~2500 years, the Holland Paleosol exhibits a remarkably well-developed profile, typically with A–E–Bs (or Bw)–BC–C horizonation, indicative of podzolization. In the cool, coastal region, the soil was able to develop more rapidly than would normally be expected, attaining a morphology that is characteristic of a Spodosol (Podzol) at many sites.

The Holland Paleosol is significant because it represents a period of regional landscape stability in the coastal dunes over at least a ~200-km reach of the Lake Michigan shore. This period of pedogenesis lasted from ~3000 to 300 cal. years BP, with some temporal and spatial variability occurring between sites. Although this period of stability is relatively short when compared with inland localities, it nonetheless represents ~50% of the time during which dunes have been present in this area. Thus, the Holland Paleosol is a significant stratigraphic marker in coastal dunes of the region and would probably qualify as a formal geosol if it were overlain by a formal lithostragraphic or allostratigraphic unit. Future research should be directed toward locating, dating, and describing this soil elsewhere within the region.

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