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NEW RADIOCARBON DATES FROM POLISH INLAND DUNES POINT TO PREVALENCE OF HUMAN IMPACT ON DUNE MOBILITY

Krzysztof Ninard* • Piotr Łapcik • Alfred Uchman

Faculty of Geography and Geology, Institute of Geological Sciences, Jagiellonian University, Gronostajowa 3a, PL-30-387 Kraków, Poland

ABSTRACT. The timeframes of Holocene anthropogenic dune remobilization in Central Europe remain less studied compared to those of Late Glacial climatically controlled dune formation. The present contribution aims to reinforce existing knowledge on the chronology of Late Glacial–Holocene dune activity and stability, as well as to reveal the scale of human impact on dune remobilization. Accelerator mass spectrometry radiocarbon (AMS ^{14}C) dating and calibration of the results are reported from paleosol horizons buried in inland dune deposits that occur in Central and Eastern Poland. Twenty-three new dates are based on charcoal samples collected at 13 sites. From each of the investigated sites, at least one AD date is obtained, indicating that buried paleosols of such young age are far more widespread in Polish dunes than reflected in previous studies. The widespread preservation of these paleosols under cover of aeolian sand reflects the extent of the anthropogenic dune formation phase that peaked during the Medieval and Early Modern periods.

KEYWORDS: charcoal, dunes, Holocene, paleosols, Poland.

INTRODUCTION

Research of aeolian dunes and coversands, which are a common constituent of the landscape of Central Europe, contributes significantly to the acquisition of knowledge on Late Pleistocene and Holocene environmental change. Radiocarbon (^{14}C) dating of paleosols buried in aeolian sandy deposits remains the centerpiece of such studies in Poland and adjacent countries for more than 40 years (Sokołowski et al. 2022 and references therein). However, as new outcrops become available, the need for conducting further ^{14}C age measurements persists (Tolksdorf and Kaiser 2012; Buró et al. 2019, 2022; Kappler et al. 2019; Moska et al. 2020, 2022; Sokołowski et al. 2022). New ^{14}C dates can help corroborate or reevaluate existing knowledge on the chronology of dune activity and stabilization. The present contribution also aims to shed light on the timeframes of anthropogenic impact on such processes.

The majority of pre-Holocene paleosols that occur in the European inland dune deposits are to date ascribed to relatively warmer pedogenic periods of the latest Pleistocene, Bølling (ca. 14.7–14.1 ka BP), and Allerød (ca. 13.9–12.9 ka BP) Interstadials. These periods were preceded by cooler and drier phases of dune formation (Kappler et al. 2019): at the end of the Late Pleniglacial (ca. 20–14.7 ka BP), the Older Dryas (ca. 14 ka BP), and the Younger Dryas (ca. 12.9–11.7 ka BP). Starting with the Early Holocene climate amelioration, remobilization of dunes interrupting the development of soils tends to be controlled by local factors, counting in human activity, rather than by climate (De Keyzer and Bateman 2018; Kasse and Aalbersberg 2019; Sokołowski et al. 2022). The record of Late Holocene (Subatlantic/Anno Domini) dune-forming phases in Central and Eastern Europe has long been overlooked. Only recently has the prevalence and scale of dune reactivation during the Late Holocene so-called "anthropogenic dune formation phase" (Twardy 2016) been recognized (Pierik et al. 2018; Hsieh et al. 2023). However, due to the limited scope of previous studies and the complexity of spatial and temporal Late Holocene dune activity patterns, more research is needed.

*Corresponding author. Email: krzysztof.ninard@uj.edu.pl

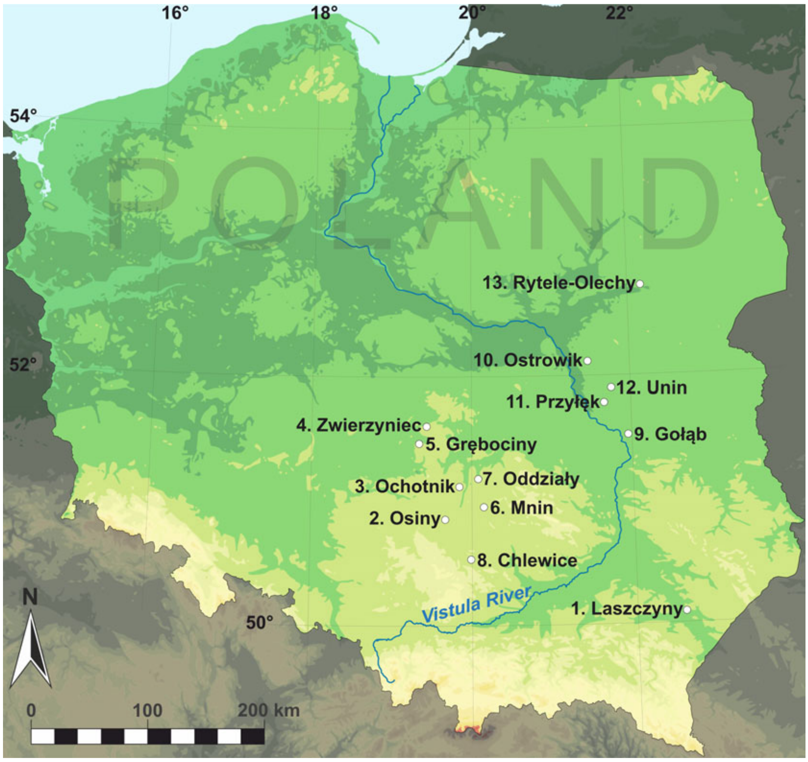

Figure 1 Location of sampling sites.

Here, we compile 23 new accelerator mass spectrometry (AMS) ^{14}C dates of charcoals from paleosols that occur in 13 inland dunes located in Central and Eastern Poland. Sample collection and dating were conducted during the period 2019–2022. Sixteen of the new dates indicate that the paleosols are not older than 1600 cal BP/350 AD, demonstrating the prevalence of human-induced dune remobilization during historical times. The remaining seven samples are dated to the Late Glacial–Early Holocene period and can be treated as reference markers. Several of the new dates (from sites 3, 6, 7, 9, and 12) were already referred to and put into paleogeographic context by Ninard et al. (2022) and Hsieh et al. (2023).

SAMPLE COLLECTION AND METHODS

Charcoal samples were collected from 23 distinct paleosol horizons exposed in 13 sand pits located in inland dune landforms (Figure 1; Table 1). The number of paleosols exposed varied from one (sites 4–8 and 12), through two (sites 1 and 2), three (site 11), four (site 13), five (site 10) up to six (sites 3 and 9). In case there is more than one sample dated from a particular site, each was collected from a separate paleosol horizon (Table 1; Figure 2). All investigated paleosols contain abundant charred plant remains ranging in diameter from less than 1 mm up to 4 mm. At least 20 charcoal grains of 2–4 mm in diameter per sample were collected and stored in polyethylene bags.

AMS ^{14}C dating of 23 samples was conducted entirely by Poznań Radiocarbon Laboratory (laboratory code designation Poz). The preparation of samples generally followed the

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Table 1 List of sampling sites with background information.

Site no.	Site name	No. of samples dated	GPS coordinates	Physiographic region	Present-day morphology	Present-day vegetation
1	Laszczyny	2	50°07′53″N 22° 28′13″E	Sandomierz Basin, SE Poland	Parabolic dune	Pine forest
2	Osiny	2	50°52′23″N 19° 37′04″E	Przedbórz Upland, Central Poland	Parabolic dune	Pine and birch forest
3	Ochotnik	4	51°08′02″N 19° 47′24″E	Przedbórz Upland, Central Poland	Parabolic dune	Grass, single pines, and birches
4	Zwierzyniec	1	51°29′47.4″N 19° 23′59.4″E	Southern Greater Poland Lowland, Central Poland	Parabolic dune	Pine forest
5	Grębociny	1	51°25′41.0″N 19° 15′35.5″E	Southern Greater Poland Lowland, Central Poland	Longitudinal dune	Birch and pine shrubbery
6	Mnin	1	50°58′52″N 20° 10′15″E	Przedbórz Upland, Central Poland	Parabolic dune	Pine forest
7	Oddziały	1	51°11′50″N 20° 00′30″E	Przedbórz Upland, Central Poland	Longitudinal dune	Grass and single pines
8	Chlewice	1	50°40′44.7″N 19° 59′37.1″E	Nida Basin, Central Poland	Parabolic dune	Pine forest
9	Gołąb	3	51°30′35″N 21° 55′20″E	Central Mazovia Lowland, E Poland	Complex dune	Pine forest
10	Ostrowik	2	52°06′13″N 21° 24′52″E	Central Mazovia Lowland, E Poland	Complex dune	Pine forest
11	Przyłęk	2	51°46′26″N 21° 39′17″E	Southern Podlasie Lowland, E Poland	Hummocky dune	Pine forest
12	Unin	1	51°52′43″N 21° 42′18″E	Southern Podlasie Lowland, E Poland	Parabolic dune	Pine forest
13	Rytele-Olechny	2	52°40′36″N 22° 09′55″E	Southern Podlasie Lowland, E Poland	Parabolic dune	Pine forest

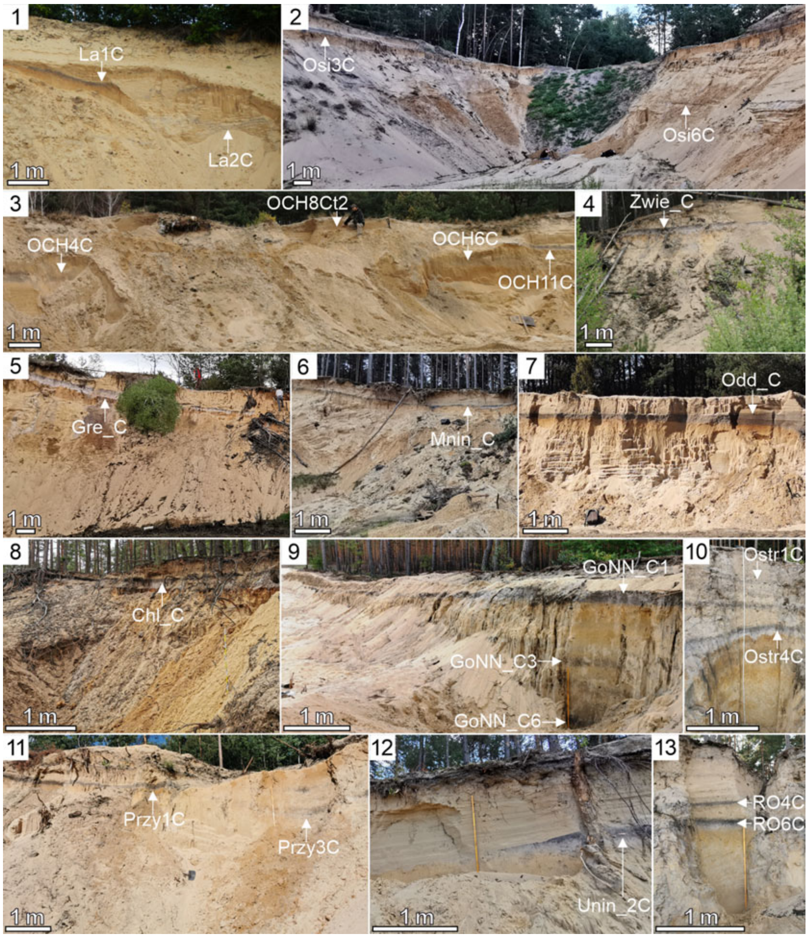

Figure 2 Studied sections with sample collection points marked. The numbers in the pictures correspond to the respective site numbers in Tables 1 and 2.

procedure used at the Oxford Radiocarbon Accelerator Unit. The sample material was sequentially treated with 1M HCl (80°C), 0.025–0.2M NaOH (80°C), 0.25M HCl (80°C) and rinsed with deionized water after each reagent. The first HCl treatment lasted until gas bubble emanation of the sample ceased, no less than 20 min, and the second HCl treatment was 1 hr long. NaOH treatment was repeated until no coloration of the solution was observed, each time for no less than 5 min. Combustion of the samples (900°C for 10 hr) was carried out in sealed quartz tubes in the presence of CuO and Ag. The subsequent graphitization process consisted of reduction of the CO_2 obtained in a reaction with H_2, in the presence of Fe powder as a catalyst. The resulting graphite target was pressed into an aluminum cathode holder.

The ^{14}C content in the samples was measured using a Compact Carbon AMS spectrometer produced by National Electrostatics Corporation. Measurement was based on a comparison between the intensities of ^{14}C, ^{13}C, and ^{12}C ionic beams, measured for each sample and for standard samples (modern standard: Oxalic Acid II and standard of ^{14}C-free carbon—coal). The conventional ^{14}C age calculation was corrected for isotopic fractionation based on δ^{13}C

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values measured using the AMS spectrometer. Conventional ^{14}C ages were reported with 1σ uncertainty, being the best estimate of total measurement uncertainties. The calibration of ^{14}C ages reported by the laboratory (Table 2) was performed using the OxCal v4.4.4 package (Bronk Ramsey 2009), with respect to the IntCal20 calibration curve (Reimer et al. 2020). Calibration results are reported at the 95.4% confidence level as BP and BC/AD age ranges (Table 2; Figure 3).

RESULTS OF THE ^{14}C DATING

Site 1: Laszczyny

The section is located in the central part of an up to 13 m high parabolic dune landform. Two dated paleosol horizons are inclined accordingly to the cross-stratification in sand. Charcoals from the upper paleosol (Rusty soil; Table 2: 1; Poz-133092) are collected ca. 2.1 m below the ground surface. The lower paleosol (incipient Arenosol; Table 2: 2; Poz-133094; dated also by Sokołowski et al. 2022; GdA-6327) is separated from the upper one by structureless 1.6-m-thick sand.

Site 2: Osiny

The section is located within the S arm of an up to 8 m high parabolic dune landform. The upper paleosol (Podzol; Table 2: 3; Poz-116770) occurs at a depth of 0.5–1 m. The lower paleosol (incipient Arenosol; Table 2: 4; Poz-116718; also dated by Sokołowski et al. 2022; GdA-6317) occurs 2–4 m below in cross-stratified sand, inclined according to stratification.

Site 3: Ochotnik

The section is located in the S part of an up to 5 m high parabolic dune landform. The topmost 0.8 m thick interval contains tetrapod and human footprints. The scattered charcoals in the lower part of this interval gave the youngest date (Table 2: 5; Poz-116758). Below, a Podzol (Table 2: 6; Poz-116769) with abundant cattle hoofprints occurs (Hsieh et al. 2023). In the lower part of the sedimentary succession, a suite of several laterally splitting Arenosols occurs. Two lowermost horizons, separated by a 0.6 m thick sand interval, were chosen for dating (organic matter-rich Arenosols; Table 2: 7; Poz-116757 and Table 2: 8; Poz-116771, respectively).

Site 4: Zwierzyniec

The section is located within the N arm of an up to 7 m high parabolic dune landform. A paleosol (Podzol; Table 2: 9; Poz-153782) occurs below ca. 0.5–1.2 m thick sand interval that contains abundant cattle hoofprints. A cemented orstein horizon underlies the paleosol.

Site 5: Grębociny

The section is located in the central part of a 10 m high longitudinal dune landform. Similarly to the nearby Zwierzyniec site, a paleosol (Podzol; Table 2: 10; Poz-153801) occurs below an interval of thickness varying from 0.2 m to 1.5 m, which contains abundant cattle hoofprints. A cemented orstein horizon underlies the paleosol.

Table 2 Radiocarbon dating and calibration results.

Sample no.	Site no.	Site name	Sample name	Lab no.	Sample collection depth (± 0.1 m)	^{14}C age (BP)	Calibrated age IntCal20 curve 95.4% confidence level	Climato-stratigraphic stage
1	1	Laszczyny	La1C	Poz-133092	2.1 m	1615 ± 30	1540–1410 cal BP (95.4%)	Subatlantic
2	1	Laszczyny	La2C	Poz-133094	3.7 m	12180 ± 60	14320–13980 cal BP (86.3%) 13940–13860 cal BP (8.8%) 13305–13820 cal BP (0.3%)	Bølling
3	2	Osiny	Osi3C	Poz-116770	0.9 m	370 ± 30	500–420 cal BP (52.3%) 400–320 cal BP (43.1%)	Subatlantic
4	2	Osiny	Osi6C	Poz-116718	3.6 m	11310 ± 50	13300–13110 cal BP (95.4%)	Allerød
5	3	Ochotnik	OCH8Ct2	Poz-116758	0.6 m	345 ± 30	480–310 cal BP (95.4%)	Subatlantic
6	3	Ochotnik	OCH11C	Poz-116769	1.8 m	1255 ± 30	1280–1170 cal BP (68.2%) 1170–1120 cal BP (21.5%) 1100–1070 cal BP (5.8%)	Subatlantic
7	3	Ochotnik	OCH6C	Poz-116757	2.4 m	11450 ± 60	13460–13230 cal BP (88.6%) 13220–13180 cal BP (6.8%)	Allerød
8	3	Ochotnik	OCH4C	Poz-116771	2.8 m	11700 ± 60	13750–13680 cal BP (9.2%) 13670–13450 cal BP (86.2%)	Allerød
9	4	Zwierzyniec	Zwie_C	Poz-153782	0.8m	535 ± 30	630–600 cal BP (20.8%) 560–510 cal BP (74.7%)	Subatlantic
10	5	Grębociny	Gre_C	Poz-153801	1.4 m	925 ± 30	920–770 cal BP (91.4%) 760–750 cal BP (4.0%)	Subatlantic
11	6	Mnin	Mnin_C	Poz-112287	1.2 m	55 ± 30	260–230 cal BP (27.2%) 140–30 cal BP (68.2%)	Subatlantic
12	7	Oddziały	Odd_C	Poz-122285	0.7 m	40 ± 30	260–230 cal BP (28%) 140–30 cal BP (67%)	Subatlantic
13	8	Chlewice	Chl_C	Poz-153802	0.5 m	1260 ± 30	1280–1170 cal BP (74.6%) 1160–1120 cal BP (17.3%) 1100–1080 cal BP (3.5%)	Subatlantic
14	9	Gołąb	GoNN_C1	Poz-112281	0.9 m	465 ± 30	540–490 cal BP (95.4%)	Subatlantic
15	9	Gołąb	GoNN_C3	Poz-112282	1.2 m	9020 ± 50	10250–10120 cal BP (82.5%) 10070–10010 cal BP (5.9%) 9990–9960 cal BP (5.8%) 9940–9920 cal BP (1.2%)	Boreal
16	9	Gołąb	GoNN_C6	Poz-112283	1.7 m	9930 ± 50	11610–11530 cal BP (10.5%) 11510–11420 cal BP (12.2%) 11410–11230 cal BP (72.7%)	Preboreal
17	10	Ostrowik	Ostr1C	Poz-133097	0.45 m	110 ± 30	270–210 cal BP (25.7%) 200–190 cal BP (1.1%) 150–10 cal BP (68.6%)	Subatlantic

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Table 2 (*Continued*)

Sample no.	Site no.	Site name	Sample name	Lab no.	Sample collection depth (± 0.1 m)	^{14}C age (BP)	Calibrated age IntCal20 curve 95.4% confidence level	Climato-stratigraphic stage
18	10	Ostrowik	Ostr4C	Poz-133098	1.1 m	620 ± 30	650–550 cal BP (95.4%)	Subatlantic
19	11	Przyłęk	Przy1C	Poz-133218	0.7 m	575 ± 30	650–590 cal BP (61.3%) 570–530 cal BP (34.2%)	Subatlantic
20	11	Przyłęk	Przy3C	Poz-133099	1.9 m	11530 ± 60	13570–13560 cal BP (1.1%) 13510–13300 cal BP (94.4%)	Allerød
21	12	Unin	Unin_2C	Poz-112286	1.1 m	1490 ± 30	1410–1310 cal BP (95.4%)	Subatlantic
22	13	Rytele-Olechny	RO4C	Poz-133095	0.9 m	140 ± 40	280–170 cal BP (38.3%) ≤150 cal BP (57.2%)	Subatlantic
23	13	Rytele-Olechny	RO6C	Poz-133096	1.1 m	435 ± 30	530–450 cal BP (92.8%) 350–340 cal BP (2.7%)	Subatlantic

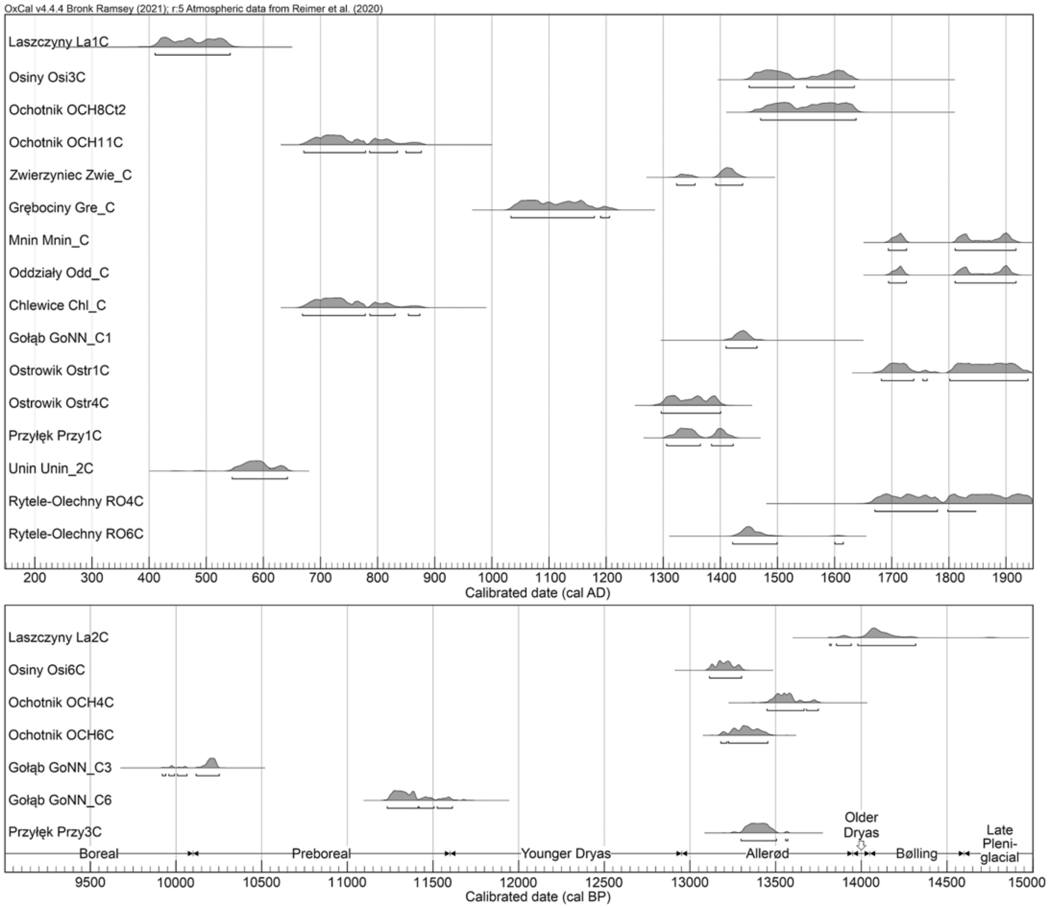

Figure 3 Calibrated 95.4% range probability distributions of the Late Holocene (cal AD; upper plot) and Late Glacial/Early Holocene (cal BP; lower plot) dates.

Site 6: Mnin

The section is located within the N arm of an up to 6 m high parabolic dune landform. Strongly bioturbated, organic matter-rich paleosol (Podzol; Table 2: 11; Poz-112287) is covered by 1–1.2 m sand layer with very abundant cattle and occasional human footprints, documented by Hsieh et al. (2023).

Site 7: Oddziały

The section is located within the S arm of an up to 5 m high parabolic dune landform. Similarly to the nearby Mnin site, the paleosol (weakly developed Podzol; Table 2: 12; Poz-122285) is covered by a sand layer up to 1 m thick with cattle and human footprints. A cattle metal chain link was found directly above the paleosol (Hsieh et al. 2023).

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Site 8: Chlewice

The section is located in the central part of an up to 6 m high parabolic dune landform. A paleosol (Podzol; Table 2: 13; Poz-153802) occurs below an interval of thickness varying from 0.4 to 1 m that contains few tetrapod footprints. A cemented orstein horizon underlies the paleosol.

Site 9: Gołąb

The section, documented in detail by Ninard et al. (2022), is located in the N margin of up to 6 m high transverse dune landform. Late Glacial paleosol horizons, dated by Zieliński et al. (2019) and Sokołowski et al. (2022) were exposed several hundred meters to the NE. The uppermost part of the section displays undisturbed stratification. Below 0.08 m thick recent paleosol (Brunic Arenosol), seven distinct paleosols (uppermost, Podzol, the rest, strongly bioturbated Arenosols) occur within the 3.5 m thick top part of the section. Paleosols are separated from each other by 0.79, 0.12, 0.18, 0.1, 0.12, and 0.25 m massive sand intervals, respectively. Radiocarbon dates are obtained from the first (Podzol; Table 2: 14; Poz-112281), third and sixth paleosols (Arenosols; Table 2: 15; Poz-112282 and Table 2: 16; Poz-112283, respectively).

Site 10: Ostrowik

The section is located in an up to 12 m high complex dune landform. Five paleosol horizons were excavated at the N margin of the dune slope. The upper three (incipient Arenosols; the uppermost one, Table 2: 17; Poz-133097) occur at depths of 0.45 m, 0.55 m, and 0.7 m, respectively. The fourth paleosol (Podzol; Table 2: 18; Poz-133098) occurs at a depth of 1.1 m. The lowermost paleosol, a strongly bioturbated Arenosol, occurs within the spodic horizon of overlying Podzol at a depth of 1.4 m.

Site 11: Przyłęk

The section, located in the central part of the up to 6 m high complex dune landform, displays three paleosol horizons. The uppermost one (weakly developed Podzol, Table 2: 19; Poz-133218) occurs at a depth of 0.7 m. Two lower paleosols (incipient Arenosols; the lower one, Table 2: 20; Poz-133099), occur at depths of 1.5 m and 1.9 m. Both Arenosols display a concave-up geometry, reflecting the morphology of an interdune depression.

Site 12: Unin

The section is located in the central part of up to 14 m high parabolic dune landform. A paleosol (weakly developed Podzol; Table 2: 21; Poz-112286) occurs at depths ranging from 0.8 to 2.5 m. The topmost part of the paleosol and the laminated sand overlying contain abundant tetrapod footprints (Hsieh et al. 2023). The paleosol is erosionally truncated to the east.

Site 13: Rytele-Olechny

The section is located within the S arm of an up to 6 m high parabolic dune landform and contains four paleosol layers in total. Two uppermost (thin incipient Arenosols) occur at depths of 0.5 m and 0.7 m, respectively. The third paleosol (well-developed Arenosol; Table 2: 22; Poz-133095), occurs at a depth of 0.9 m and the lowest one (weakly developed Podzol; Table 2: 23; Poz-133096) at a depth of 1.1 m.

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DISCUSSION

A widespread paleosol, the so-called Usselo-type soil, is found in dunes and coversands throughout Western and Central Europe. It is typically developed as Arenosol with possible signs of podzolization. The Usselo-type soil serves as a marker horizon—in principle for Allerød, with several cases dated to the Younger Dryas and the earliest Holocene (Kaiser et al. 2009). Among the sites described in the present paper, paleosols corresponding to pedological properties and the age of the Usselo-type soil occur in sites 2 (Osiny; the lowermost paleosol; sample Poz-116718), 3 (Ochotnik; two lowermost paleosols; Poz-116771 and Poz-116757), 9 (Gołąb; five lowermost paleosols of which two have been dated; Poz-112282 and Poz-112283) and 11 (Przyłęk; two lowermost paleosols of which one has been dated; Poz-133099). The lower paleosol at site 1 (Laszczyny; Poz-133094) visually resembles the Usselo-type soil. However, dating indicates its Bølling age, in contrast to previously known Usselo-type soils, which are younger (Kaiser et al. 2009).

Buried Podzols occur at sites 2–10 (samples Poz-116770, Poz-116769, Poz-112287, Poz-122285, Poz-112281, Poz-133098, Poz-133218, Poz-112286, and Poz-133096) and are distinguished by ages ranging from 7th–8th century to 18th–early 20th century. It should be noted that paleosols can, in fact, be younger than dated charcoals, as the redeposition of charcoals from older soils cannot be excluded. In all the sites that display more than one paleosol horizon, only one is a Podzol. An explanation for the better development of Medieval paleosols compared to Late Glacial–Early Holocene and Modern period–recent soils possibly lies in warmer climate or longer, anthropogenically induced periods of surface stabilization during the Middle Ages (Sevink et al. 2018; Kappler et al. 2019; Moska et al. 2020).

^{14}C dates reported in the present contribution, except for those falling in the Late Glacial–Early Holocene period, are clustered in the 5th–6th to 18th–19th century interval. Notwithstanding the fact that paleosols ranging in age from Boreal through Atlantic to Subboreal were recorded in multiple sites spread throughout Central and Western Europe (Konecka-Betley and Janowska 2005; Tolksdorf and Kaiser 2012; Twardy 2016; Lungershausen et al. 2018; Pierik et al. 2018; Kappler et al. 2019), such dates are not present at all among our new results.

Soils develop on the dunes during the conditions of nondeposition and stabilization of the land surface by vegetation, which remained the case throughout most of the Holocene (Kappler et al. 2019). Conversely, the burial of soils by dune sands occurs due to surface destabilization caused by vegetation depletion. Human-induced intensification of aeolian activity could also result in soil material being winnowed away and not preserved in the sedimentary record. Assuming purely anthropogenic determinants of dune remobilization that locally interrupted Holocene soil development (Tolksdorf and Kaiser 2012; Lungershausen et al. 2018; Pierik et al. 2018), lack of such interruptions, recorded as sand layers covering the paleosols, could simply stem from human activity not being intensive enough to force surface destabilization.

Deforestation and agricultural activities have occurred in Europe with intensity varying in both time and space since the Bronze Age. While the Roman Period marked an increase in anthropogenic impact, the Early Middle Ages were characterized by their relative decrease, which, in turn, resulted in partial restoration of primeval forest vegetation (Tolksdorf and Kaiser 2012). Compared to Western Europe, its Central-Eastern part was subjected to limited human habitation and land use throughout the Bronze Age, Iron Age, and Roman Period (Tolksdorf and Kaiser 2012; Twardy 2016; Kappler et al. 2019; Kasse and Aalbersberg 2019). Especially in the barren areas covered by aeolian sands in Central and Eastern Poland, the development of the rural settlement network remained delayed prior to the High Middle Ages. A significant expansion of deforestation and agriculture in these areas began no earlier than during the 10th to 12th centuries, still occurring at a slower rate compared to western and southern Poland (Buko 2007). Furthermore, it cannot be excluded that older Holocene paleosols might have been eroded during the Late Holocene intensification of dune mobility, while the pre-Holocene deposits building the lower part of the dunes remained in place. However, such erosion events would expectedly be recorded as erosional truncation surfaces in the intervals underlying the Late Holocene paleosols, which were not noticed in the studied sections.

Apparently, soil development and burial occurred almost synchronously and, at least in some cases, were not restricted to certain localities or dune fields. A comparable age of paleosols is observed between sites located within the same region, but several dozen kilometers apart: site 2 (Osiny, Poz-116770) to site 3 (Ochotnik, Poz-116758)—31 km apart; site 3 (Ochotnik, Poz-116769) to site 8 (Chlewice, Poz-153802)—52 km apart; site 6 (Mnin, Poz-112287) to site 7 (Oddziały, Poz-122285)—27 km apart; site 10 (Ostrowik, Poz-133098) to site 11 (Przyłęk, Poz-133218)—40 km apart; site 9 (Gołąb; Poz-112281) to site 13 (Rytele-Olechny; Poz-133096)—130 km apart. Presumedly, such "dune formation sub-phases" of regional extent occurred in response to spatiotemporal variation in settlement and land use.

The dating of samples from Laszczyny and Osiny sites was independently conducted by Sokołowski et al. (2022) with results similar to those presented in this paper. Laszczyny La2C (Poz-133094) sample dated to 12,180 ± 60 BP corresponds to 12,200 ± 70 BP (GdA-6327) obtained by Sokołowski et al. (2022), which confirms the Bølling Interstadial age of the paleosol. Likewise, the Osiny Osi6C (Poz-116718) sample age of 11,310 ± 50 BP virtually equals the result of 11,310 ± 70 BP (GdA-6317) of Sokołowski et al. (2022), which falls in the middle part of the Allerød Interstadial. On the contrary, new dates from the Gołąb site do not coincide with previous results, from which only Late Glacial paleosols have been reported to date (Zieliński et al. 2019; Poz-52907; Sokołowski et al. 2022; GdA-6319, GdA-6321, GdA-6322, GdA-6323). A suite of Holocene (Preboreal and Boreal to Subatlantic/Medieval) paleosols recognized in this study was accessible only temporarily in the marginal part of the dune.

A decrease in the concentration of dates in the Early and Middle Holocene noticed by Sokołowski et al. (2022) also coincides with the scarcity of radiocarbon ages in the same time interval among those reported in the present contribution. However, an underrepresentation of Late Holocene dates among those reported by Sokołowski et al. (2022) is hardly explicable. The above applies, in particular, to the younger paleosols at the Laszczyny and Osiny sites, which Sokołowski et al. (2022) did not account for. The notability of the Laszczyny site for studies of anthropogenic impact on dune activity is derived from the presence of human and ungulate footprints in the Early Medieval paleosol (Hsieh et al. 2023).

CONCLUSION

Most of the radiocarbon dates acquired in Poland from inland dune paleosols fall in the Late Glacial to the earliest Holocene period. Consequently, it could be implied that dune activity was insignificant throughout the remaining part of the Holocene. On the contrary, the present contribution shows that much younger paleosols occur commonly over vast areas. Out of 23 dated buried paleosols, 7 incipient horizons documented at 5 of the investigated sites were dated to the Late Glacial–Early Holocene period. The remaining majority, 16 dates obtained from relatively well-developed buried paleosols, indicate soil formation during the last two millennia. As the remobilization of dunes in Europe during Holocene is assumed to have occurred independently of climatic conditions, burial of the soils by aeolian sand may be ascribed to anthropogenic factors: deforestation and land cultivation in areas adjacent to investigated sites. Therefore, the prevalent occurrence of paleosols buried during the Medieval to Modern periods marks the peak of the anthropogenic dune formation phase in Central and Eastern Poland.

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REFERENCES

Bronk Ramsey C. 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51(1):337–360.

Buko A. 2007. The archaeology of Early Medieval Poland: discoveries–hypotheses–interpretations. Leiden: Brill.

Buró B, Lóki J, Győri E, Nagy R, Molnár M, Négyesi G. 2019. New radiocarbon data from the paleosols of the Nyírség blown sand area, Hungary. Radiocarbon 61(6):1983–1995.

Buró B, Négyesi G, Varga T, Sipos G, Filyó D, Jull AT, Molnár M. 2022. Soil organic carbon dating of paleosoils of alluvial fans in a blown sand area (Nyírség, Hungary). Radiocarbon 64(1):1–19.

De Keyzer M, Bateman MD. 2018. Late Holocene landscape instability in the Breckland (England) drift sands. Geomorphology 323:123–134.

Hsieh S, Ninard K, Uchman A, Łaska W, Łapcik P. 2023. Mammal tracks record anthropogenic environmental influence in late-Holocene inland dunes of the European Sand Belt, Poland. The Holocene 33(1):61–80.

Kaiser K, Hilgers A, Schlaak N, Jankowski M, Kuehn P, Bussemer S, Przegiętka K. 2009. Paleopedological marker horizons in northern central Europe: characteristics of Lateglacial Usselo and Finow soils. Boreas 38:591–609.

Kappler C, Kaiser K, Küster M, Nicolay A, Fülling A, Bens O, Raab T. 2019. Late Pleistocene and Holocene terrestrial geomorphodynamics and soil formation in northeastern Germany: a review of geochronological data. Physical Geography 40:405–432.

Kasse C, Aalbersberg G. 2019. A complete Late Weichselian and Holocene record of aeolian coversands, drift sands and soils forced by climate change and human impact, Ossendrecht, the Netherlands. Netherlands Journal of Geosciences 98:E4.

Konecka-Betley K, Janowska E. 2005. Late Glacial and Holocene stratotype profile of palaeosols in the Warsaw basin. Studia Quaternaria 22:33–16.

Lungershausen U, Larsen A, Bork HR, Duttmann R. 2018. Anthropogenic influence on rates of aeolian dune activity within the northern European Sand Belt and socio-economic feedbacks over the last ~ 2500 years. The Holocene 28(1):84–103.

Moska P, Jary Z, Sokołowski RJ, Poręba G, Raczyk J, Krawczyk M, Skurzyński J, Zieliński P, Michczyński A, Tudyka K, Adamiec G, Piotrowska N, Pawełczyk F, Łopuch M, Szymak A, Ryzner K. 2020. Chronostratigraphy of Late Glacial aeolian activity in SW Poland—a case study from the Niemodlin Plateau. Geochronometria 47:124–137.

Moska P, Sokołowski RJ, Jary Z, Zieliński P, Raczyk J, Szymak A, Krawczyk M, Skurzyński J, Poręba G, Łopuch M, Tudyka K. 2022. Stratigraphy of the Late Glacial and Holocene aeolian series in different sedimentary zones related to the Last Glacial maximum in Poland. Quaternary International 630:65–83.

Ninard K, Łapcik P, Uchman A, Stachacz M. 2022. 3D sine wave-like geometry of soft sediment deformation structures: Possible record of the Late Pleistocene seismic activity over the Teisseyre-Tornquist Zone. Terra Nova 34(1):54–61.

Pierik HJ, van Lanen RJ, Gouw-Bouman MT, Groenewoudt BJ, Wallinga J, Hoek WZ. 2018. Controls on late-Holocene drift-sand dynamics: The dominant role of human pressure in the Netherlands. The Holocene 28(9):1361–1381.

Reimer P, Austin W, Bard E, Bayliss A, Blackwell P, Bronk Ramsey C, Butzin M, Cheng H, Edwards R, Friedrich M, et al. 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4):725–757.

Sevink J, van Geel B, Jansen B, Wallinga J. 2018. Early Holocene forest fires, drift sands, and Usselo-type paleosols in the Laarder Wasmeren area near Hilversum, the Netherlands: implications for the history of sand landscapes and the potential role of Mesolithic land use. Catena 165:286–298.

Sokołowski RJ, Moska P, Zieliński P, Jary Z, Piotrowska N, Raczyk J, Mroczek P, Szymak A, Krawczyk M, Skurzyński J, Poręba G, Łopuch M, Tudyka K. 2022. Reinterpretation of fluvial-aeolian sediments from last glacial termination classic type localities using high-resolution radiocarbon data from the Polish part of the European Sand Belt. Radiocarbon 64(6):1387–1402.

Tolksdorf JF, Kaiser K. 2012. Holocene aeolian dynamics in the European sand-belt as indicated by geochronological data. Boreas 41(3):408–421.

Twardy J. 2016. Antropogeniczna faza wydmotwórcza w środkowej Polsce = Anthropogenic phase of dune-forming processes in central Poland. In: Święchowicz J, Michno A, editors. Wybrane zagadnienia geomorfologii eolicznej. Poland: IGiGP UJ. P. 157–184.

Zieliński P, Sokołowski RJ, Jankowski M, Standzikowski K, Fedorowicz S. 2019. The climatic control of sedimentary environment changes during the Weichselian—an example from the Middle Vistula Region (eastern Poland). Quaternary International 501:120–134.