Factors controlling the development of cold-climate dune fields within the central part of the European Sand Belt – insights from morphometry

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Abstract

The central part of the European Sand Belt is an area where intense aeolian processes led to the development of large dune fields in the Lateglacial. They have been studied principally in terms of their stratigraphy, with less attention given to their evolution and geomorphology. It is also uncertain whether large dune fields in cold areas arise analogously to those formed in other climatic zones. To fill this gap, we performed a morphometric analysis of 31 stabilized dune fields in Poland using high-resolution LiDAR data. We related the outcomes to the morphological zones associated with the extent of the ice sheet during the LGM, the position and basement shape of the dune fields. The results indicate that dune fields in cold areas evolve in the same way as in other climatic zones, as expressed in the preserved relation between crest length, spacing, and defect density. The study found that the investigated dune fields have simple patterns composed of single populations of transverse to parabolic dunes facing E-ESE, suggesting their simultaneous formation in the Younger Dryas. At the same time, the varying degree of dune fields pattern development indicates the different duration of aeolian processes that shaped individual dune fields. The dominance of transverse dunes transformed partially or completely into parabolic dunes reflects the increasing role of vegetation over time and the decreasing supply of sand. The development of the dune field patterns was not found to be correlated with the extent of the ice sheet during the LGM, the morphological position, and the basement shape of the dune fields.

Keywords: dune fields; aeolian processes; periglacial environment; pattern analysis; Late Glacial;

1. Introduction

The European Sand Belt (ESB), which extends from the Netherlands to Russia, is the relict of a harsh periglacial environment characterized by intensive aeolian activity. It developed under dry and windy conditions in front of the retreating Scandinavian Ice Sheet (SIS) at the termination of the Pleistocene (Koster, 1988, Zeeberg, 1998). The largest dune fields within the ESB are located in Poland, where they have been extensively studied. As a result, a stratigraphic model and depositional conditions have been established (Nowaczyk, 1986, 2000; Manikowska, 1991, 1995; Izmaiłow, 2001; Goździk, 2007; Zieliński, 2016). The latest studies reveal that aeolian dunes represent a final part of fluvio-aeolian succession deposited in the central part of the ESB from the Late Pleniglacial to the very end of the Last Glacial (Zieliński et al., 2014, Moska et al., 2022b).

Multiple factors, such as wind directions and strength, vegetation cover, and level of groundwater, play significant roles in the shaping of specific dunes and dune fields (Wasson and Hyde, 1983; Lancaster, 1995; Pye and Tsoar, 2009). They drive the dune type, size, and dynamics of aeolian processes. One specific factor that may have played an important role in the dune-forming processes during the final phase of the last glaciation within ESB was the presence and further degradation of permafrost. Under the periglacial climate high variability of wind speed and directions, low and periodical sediment supply, niveo-aeolian processes, and seasonal changes of surface moisture were postulated (McKenna-Neuman, 1990; Seppälä, 2004, Wolfe, 2010). Due to these conditions, parabolic dunes are the most frequent dune types across cold-climate inland dune fields (Seppälä, 1971; Collins, 1985; Dijkmans and Koster, 1990; Wolfe et al., 2004; Bernhardson and Alexanderson 2017, 2018; Baughmann et al., 2018).

The role of multiple dune transformations resulting from changing climatic conditions over time and the differentiation of dunes and dune fields within the ESB have been described (Izmaiłow, 2001; Zieliński, 2016). Most authors have emphasized that parabolic dunes predominate and were formed under conditions of low supply of sandy material and a significant role of vegetation cover. These assumptions were based on research from restricted areas without comparative morphological studies of specific dune fields within the ESB. Note also that most studies have been conducted outside of the main dune fields in Poland and have focused on particular elements, including paleosols, sedimentology, morphology, and stratigraphy (Nowaczyk, 1986, 2000; Manikowska, 1991, 1995; Izmaiłow, 2001; Zieliński, 2016).

To fill this gap and reconstruct the spatial variability of the depositional conditions controlling dune fields within the Polish part of the ESB, we applied two assumptions known from warm deserts: (i) the development of specific dune types is assumed to be linked to characteristic depositional conditions (wind direction and strength, sand supply, and vegetation; Wasson and Hyde, 1983; Lancaster, 1995; Pye and Tsoar, 2009); (ii) the dune field pattern (spatial organization of dunes) is a function of time due to the self-organizing nature of the aeolian forms (Werner, 1995, Werner and Kocurek, 1999; Ewing et al., 2006, 2015). The dune field pattern emerges through interactions of dunes (especially by merging and lateral linking of dunes) leading to simplification of the dune field pattern with time (Ewing and Kocurek, 2010a). This is reflected by changes in pattern parameters – the increasing crest lengths and spacing between dunes and a decrease in the defect density, defined as the number of the defect pairs (terminations of crests) per unit length of crestline (Werner, 1995, Werner and Kocurek, 1999). Initial dune fields are spatially poorly organized and consist of a large number of weakly developed dunes situated close together. In contrast, mature dune fields that develop over a long time exhibit a well-organized pattern of homogenous dunes (Werner, 1995, Werner and Kocurek, 1999; Ewing et al., 2006). The coexistence of a few dune field patterns within one area is linked to temporal or spatial variability of depositional conditions (e.g. precipitation, surface wetness, sand supply). This dependence has been observed in many deserts, including the Kalahari Desert, the Sonora Desert, California, and Australia (Thomas and Leason, 2005; Beveridge et al., 2006; Derickson et al., 2008; Hesse, 2011). Similar processes and their morphological effects can be expected in the ESB, where multiple phases of aeolian activity were documented (Crombé et al., 2020; Moska et al., 2022a, 2022b; Sokołowski et al., 2022).

The aim of this study was to apply pattern analysis to 31 representative dune fields in the Polish part of the ESB to: (1) reconstruct local and regional factors controlling dune-forming processes; (2) test whether the self-organization of dune fields formed under cold climate conditions is similar to their counterparts developed under warm climate conditions. This is the first application of pattern analysis to fixed cold-climate dune fields, making the dataset useful as a background for sedimentological studies and a supplement to previous studies.

2. Timing and environmental framework of the European Sand Belt development

The European Sand Belt, due to its considerable latitudinal extension and the associated climatic gradient, is not uniform regarding the processes that took place and the forms that formed (Koster, 1988; Zeeberg, 1998). It reflects regional gradients of climate conditions (an increase of climate continentality towards the east) and local features such as glacioisostatic adjustment, sea level changes, and tectonic subsidence (Uścinowicz, 2003; Busschers et al., 2007). The existence of the ESB was related to the belt of periglacial conditions characterized by average annual temperatures below zero, 250-300 mm of annual precipitation in the foreland of the Scandinavian Ice Sheet (SIS) during the Late Pleniglacial (Huijzer and Isarin, 1997; Kasse, 2002; Vandenberghe et al., 2014). Such climate conditions hampered the development of dense vegetation cover and favoured intensive aeolian deflation and deposition. Stratigraphic models from different parts of the ESB differ (Schirmer, 1999). Stratigraphic scheme from the western part of the ESB basis on the combination of OSL and ^{14}C dating results (Vandenberghe et al., 2013; Kasse et al., 2020). Generally, three phases of aeolian activity spanning between the Late Pleniglacial and Early Holocene were distinguished in western Europe (Kasse, 2002). Phase I represents the Late Pleniglacial and only fluvio-aeolian and aeolian sand covers were deposited. Phase II took place at the very end of the Late Pleniglacial and during the Older Dryas (sand sheet and low-relief dunes). The aeolian activity was interrupted by the first climate amelioration during the Lateglacial connected to Bølling interstadial (Kasse, 2002). The next climate amelioration during the Allerød age is expressed by the Usselo Soil (Kaiser et al., 2009). Phase III - the main phase of dune formation took place during the second part of the Younger Dryas stadial (Kasse and Aalberberg, 2019; Kasse et al., 2020). The latest studies from lacustrine succession in NW Belgium suggest a more complicated model of aeolian activity with two phases of aeolian deflation and deposition during the Allerød interstadial (Crombé et al., 2020).

In NE Germany also three phases of aeolian deposition are reported from around 16.7 ka (mainly sand sheets), an early period of dune formation from 15.2 until 13.7 ka (peak around 14.4 ka), and a phase of dune formation and reactivation from 12.9 to 11.1 ka (peak around 12.0 ka; Hilgers, 2007; Kaiser et al., 2009, 2020). In the north-eastern part of the ESB continuous aeolian deposition took place between 15.9±1.0 ka and 8.5±0.5 ka without soil-forming periods (Kalińska et al., 2019).

Works conducted in the Polish part of ESB were indicating three aeolian phases related to the Oldest, Older, and Younger Dryas, separated by periods of fossil soil formation during the Bølling and Allerød interstadials (Nowaczyk, 1986, 2000; Manikowska, 1991, 1995). Recent studies showed that Lateglacial climate oscillations resulted in more complex stratigraphy of aeolian sediments (Zieliński et al., 2014, 2015; Moska et al., 2022b; Sokołowski et al., 2022). They confirmed that three lithofacial complexes (fluvial, fluvio-aeolian, and aeolian) represent common sedimentary succession from the final part of the Late Weichselian in the Polish part of the ESB (Zieliński et al., 2014, 2016). The fluvial complex was deposited during the Late Pleniglacial up to the beginning of the Lateglacial period (24-14 ka; Moska et al., 2022b). Remnants of aeolian activity during this period are inferred from textural analysis, especially from the aeolian abrasion of quartz grains (Woronko et al., 2015; Zieliński et al., 2019). The climate conditions in front of the SIS were severe, similar to a polar desert with continuous permafrost and limited vegetation cover (Latałowa, 2003b; Vandenberghe et al., 2014). During the SIS deglaciation formed ice-marginal valleys (IMV-s) and outwash plains with thick sandy units, that were undergoing deflation later (Vandenberghe et al., 1994; Starkel et al., 2015; Weckwerth, 2018).

Gradual improvement of climate conditions during the very end of the Late Pleniglacial (17-14 ka) caused the elongation of vegetation season and resulted in the development of tundra-type habitats (Simakova and Puzachenko, 2005). The low availability of material trapped by permafrost has resulted in the development of fluvio-aeolian covers, mainly on fluvial terraces (Zieliński et al., 2014, 2015). The climate amelioration at the beginning of the Lateglacial (the Bølling interstadial) caused the development of pine-birch forests and the formation of palaeosols (Simakova and Puzachenko, 2005).

The first phase of aeolian dune formation started from the Bølling interstadial as a response to rivers incision and formation of fluvial terraces (Vandenberghe et al., 1994; Starkel et al., 2015; Weckwerth, 2018). This phase was previously linked to the Older Dryas (Nowaczyk, 1986, 2000; Manikowska, 1991, 1995), but it was not confirmed in the new studies (Moska et al., 2022a, 2022b; Sokołowski et al., 2022). This phase was particularly well expressed in the unglaciated zone (sometimes referred to as the extraglacial), especially far from the retreating SIS (Nowaczyk, 1986, 2000; Moska et al., 2020). Moreover, an aeolian activity and dune formation were detected in the cold oscillations of Allerød interstadial, similarly to the last results from the western part of the ESB (Crombé et al., 2020). For this period, a westerly wind was postulated with a northern component, associated with katabatic winds (Kasse, 2002).

The last important dune-formation phase took place during the Younger Dryas, especially in the glaciated zone (Jankowski, 2012; Rychel et al., 2018; Moska et al., 2022a). This was favoured by the disappearance of permafrost over most of the area, the incision of rivers, and the release of large amounts of sand (Nowaczyk, 1986; 2000; Manikowska, 1991, 1995). However, aeolian processes could not play a significant role in many previously glaciated areas due to unfavourable lithology, ground moisture, and lack of available material (Błaszkiewicz et al., 2004, 2015). For this reason, dune fields in this zone are mainly located in IMV-s and on alluvial fans. Studies of lacustrine successions from Sweden, Germany, and Poland have shown that climatic seasonality particularly intensified during the Younger Dryas. Temperatures decreased at this time, notably in winter (by about 4-6°C), with a simultaneous decrease in humidity and length of the growing season (Schenk et al., 2018; Płóciennnik et al., 2022). This phase was characterized by the dominance of westerly winds blowing especially during the winter months (Böse, 1991; Zeeberg, 1998). Some authors also postulated the contribution of wind blowing from the SW (Zieliński, 2016).

The warming of the Early Holocene effectively terminated the development of dunes and dune fields, which were gradually stabilized by vegetation. During this time, the vegetation cover turned from being dominated by grasses, herbs, and shrubs to the dense boreal forest (Latałowa, 2003a). Permafrost occurred locally in the form of dead ice blocks (Błaszkiewicz et al., 2004; 2015). During the Early Holocene in central Europe dune fields underwent only limited transformations connected to forest fires and anthropogenic influence (Twardy, 2016; Lungershausen et al., 2018; Kappler et al., 2019).

3. Regional setting

The study area mainly covers the Polish Lowlands and selected parts of the Polish Highlands (Fig. 1). Test areas where dune fields were found were selected for detailed analysis. Their identification was based on a visual inspection of the hillshade model available on the Geoportal 2 website (mapy.geoportal.gov.pl/imap/Imgp_2.html). Sites were chosen with regard to sedimentary zones according to their relative location to the Last Glacial Maximum terminal moraines (LGM; glaciated/unglaciated), morphological setting (alluvial fan, ice-marginal valley (IMV), river valley, other), the dominant type of dunes (transverse, parabolic, superimposed), and the basement morphology. The flat surface below dune fields occurs over river terraces and alluvial fans, while climbing dune fields occur on valley edges. If a dune field is located in an area of varying topography, it was classified as *mixed*. Representative areas were selected to include vast or internally differentiated dune fields. A total of 31 sites within 23 dune fields were mapped (Fig. 1), covering an area of 289.9 km^2. 14 study sites are located in the glaciated zone, and 17 in the unglaciated zone (Tab. 1).

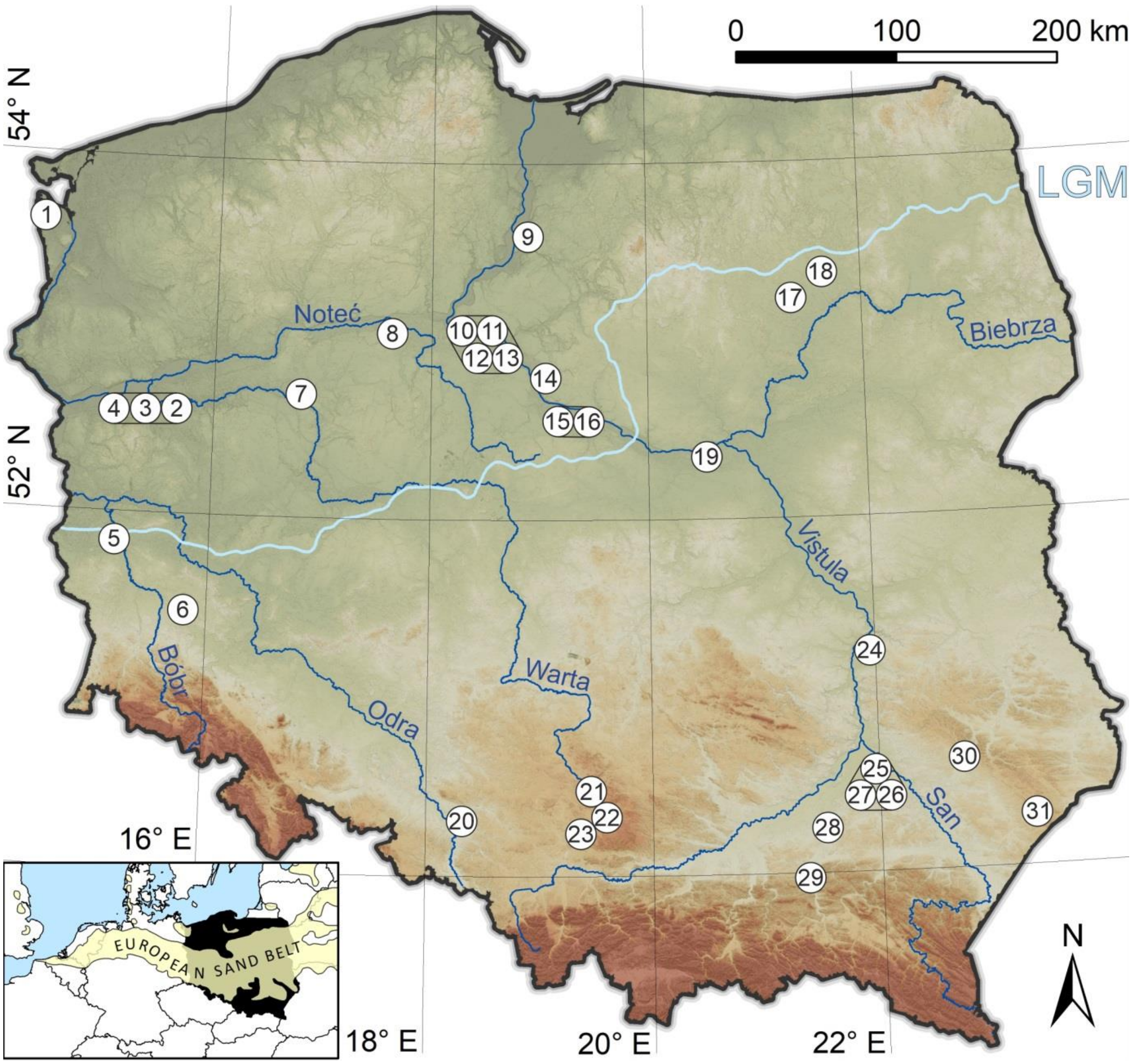

Fig. 1. Location of study sites in Poland. For the list of sites, see Tab. 1. Detailed maps of all sites are included in Supplementary Material. The maximum extent of the LGM is the boundary between the glaciated (to the north) and the unglaciated zone (to the south).

4. Methods

Landform analysis and terrain mapping were carried out in ArcMap 10.5.1 using a bare-earth 1 m Digital Elevation Model derived from airborne laser scanning (LiDAR), with 4–7 points per m^2. The mean vertical error does not exceed 0.15 m (Kurczyński et al., 2015). The original DEM was resampled to 5 m resolution to prevent the impact of small man-made topographic features. For further analysis, layers of surface slope and multi-directional hillshade model (Kokalj and Hesse, 2017) with three different illumination azimuths (1 – 350°, 2 – 15°, 3 – 270°) and sun altitudes (1 – 70°, 2 – 55°, 3 – 60°) were created. The use of multi-directional hillshade reduces the risk of mistakes during mapping due to azimuth biasing (Smith and Clark, 2005). The height of dunes was calculated using the procedure proposed by Baughmann et al. (2018): (1) aggregation of DEM into 50-cell resolution (250 m^2) using the minimum DEM cell values which determine the basement of the dune field (2) bilinear resampling of aggregated raster into previous resolution, (3) calculation of the difference between original dune field DEM and resampled DEM representing basement of the dune field. Dune crests were visually verified and extracted from automatically generated local watersheds. All crests were taken into consideration, including superimposed dunes and secondary crests. The obtained crests were simplified and smoothed to remove sharp angles derived from the original elevation raster.

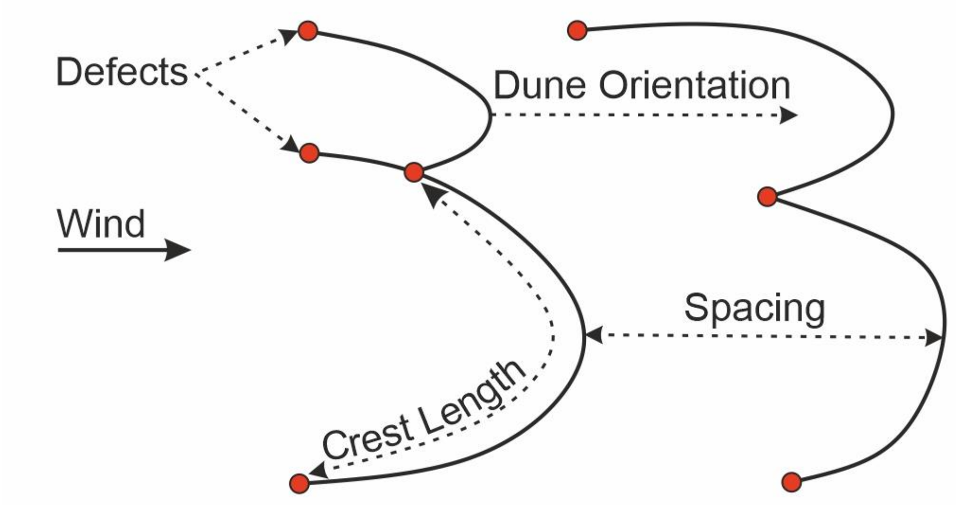

Fig. 2. Pattern parameters. Black lines represent vectorized dune ridges.

Pattern analyses were performed using the method proposed by Ewing et al. (2006; Fig. 2). Crest length was measured as the distance between two crestline terminations or junctions (defects). Defect density (ρ) was calculated for each site using the definition ρ=N/L, where N is the number of defect pairs per unit length of crestline (L) (Werner, 1995; Werner and Kocurek, 1999). Depending on the size of the study site, mean spacing between crests was measured along 5 to 9 elevation profiles parallel to the presumed transport direction. The elevation was sampled along profiles every 5 meters and exported into an Excel spreadsheet. Crestlines were identified as values higher than the mean of five preceding and following cell values. All crestlines were verified on a map to eliminate features that are not dunes (e.g. man-made structures). To identify the number of dune populations within each site, crest length and spacing were displayed on cumulative log frequency plots using the software Statistica 13.1 (StatSoft, 2009). In the case of a single, log-normally distributed population, data will plot as a straight line, while multiple populations within data will plot as line segments separated by inflection points (e.g. Jensen et al., 2000; Ewing et al., 2006).

The studied dune fields were divided into morphological groups using cluster analysis (dendrogram) based on Ward´s method and Euclidean distances (Kaufman and Rousseeuw, 2005). All the pattern properties studied (crest length, spacing, defect density, and mean dune height) were used as input variables. Statistical analyses were performed using the Statistica 13.1 software (StatSoft, 2009).

The orientation of the dunes (indicative of the direction of the paleo-wind forming the dunes) was measured manually on the base of DEM using the COGO toolbar

(ArcMap 10.3). Depending on the size of the dune field and the number of dunes, between 34 and 128 measurements were taken. The results were plotted on rose diagrams.

5. Results

Results of the analysis are shown in Tab. 1. The dune fields studied represent a wide variety of pattern properties, typical for dune fields in different stages of pattern development.

Tab. 1. Study sites. Description and results of the pattern analysis. *T – transverse; P – parabolic; S – superimposed. **For details see Fig. 3A.

No.	Name	Area (km²)	Zone	Setting	Dunes*	Basement	Crest Length (m)				Spacing (m)				Dune Height (m)		Defects		Dune Height to Spacing	Group**
							N	Mean	SD	Coef	N	Mean	SD	Coef	Max	Mean	N	Density		
1	Wkra Forest	7.2	Glaciated	Alluvial fan	T/P	Flat	646	138	134	0.97	91	179	94	0.53	18.5	7.6	584	0.0033	0.30	1
2	Gorzów Basin 1	8.6	Glaciated	IMV	T	Flat	98	322	413	1.28	101	203	128	0.63	27.1	9.8	130	0.0021	0.08	2
3	Gorzów Basin 2	3.5	Glaciated	IMV	T/P	Flat	99	234	216	0.92	86	178	107	0.60	22.2	9.4	104	0.0022	0.16	2
4	Gorzów Basin 3	3.4	Glaciated	IMV	T/P	Flat	146	182	151	0.83	70	178	78	0.44	22.4	12.0	156	0.0029	0.05	3
5	Bóbr Valley	5.0	Unglaciated	IMV	T/P	Flat	29	595	497	0.84	18	452	203	0.45	13.6	7.1	50	0.0015	0.08	4
6	Lower Silesian Forest	29.6	Unglaciated	Alluvial fan	T/P	Mixed	120	450	585	1.30	30	336	191	0.57	21.5	8.9	155	0.0014	0.47	4
7	Oborniki Wielkopolskie	6.2	Glaciated	Alluvial fan	P	Flat	216	173	173	1.00	103	171	99	0.58	24.8	10.5	224	0.0030	0.07	3
8	Nakło	4.6	Glaciated	IMV	T/P/S	Mixed	184	225	216	0.96	173	167	101	0.60	23.8	9.1	180	0.0022	0.02	2
9	Grudziądz	8.1	Glaciated	Other	T/P	Flat	209	224	234	1.04	97	180	117	0.65	22.3	8.3	266	0.0028	0.23	2
10	Toruń Basin1	9.9	Glaciated	IMV	P/S	Mixed	458	160	167	1.04	132	136	69	0.51	24.8	10.1	465	0.0032	0.13	3
11	Toruń Basin 2	30.2	Glaciated	IMV	P/S	Flat	1673	153	103	0.67	362	149	91	0.61	27.6	9.5	1608	0.0037	0.01	3
12	Toruń Basin 3	24.7	Glaciated	IMV	T/P	Flat	564	172	150	0.88	181	209	150	0.72	22.2	8.2	594	0.0031	0.11	2
13	Toruń Basin 4	17.2	Glaciated	IMV	P/S	Flat	1300	136	109	0.80	159	142	77	0.54	27.4	11.2	1229	0.0035	0.11	3
14	Lipno	8.0	Glaciated	Other	T/P	Mixed	212	200	190	0.95	82	204	95	0.47	24.4	10.4	270	0.0032	0.16	3
15	Płock Basin 1	4.0	Glaciated	IMV	T/P	Flat	170	198	165	0.83	73	143	74	0.52	26.9	9.3	199	0.0030	0.05	3
16	Płock Basin 2	3.2	Glaciated	IMV	T/P/S	Flat	185	158	136	0.86	78	153	71	0.46	23.1	9.9	200	0.0034	0.13	3
17	Kurpie 1	4.3	Unglaciated	Alluvial fan	T/P/S	Flat	333	129	108	0.84	61	205	123	0.60	18.4	7.9	384	0.0045	0.08	1
18	Kurpie 2	2.6	Unglaciated	Alluvial fan	P/S	Flat	309	108	88	0.82	68	136	75	0.55	15.5	6.4	277	0.0041	0.17	1
19	Kampinos	27.1	Unglaciated	IMV	T/P	Flat	451	265	272	1.02	196	324	308	0.95	21.6	8.5	470	0.0020	0.02	4
20	Racibórz Basin	5.3	Unglaciated	Alluvial fan	T	Flat	38	407	449	1.10	29	271	175	0.65	16.3	7.7	64	0.0021	0.19	4

21	Ogrodzieniec	6.3	Unglaciated	Alluvial fan	T/P	Climbing	144	266	235	0.88	64	152	77	0.51	14.8	6.4	182	0.0024	0.08	3
22	Olkusz Highland	3.9	Unglaciated	Valley	T/P	Mixed	77	245	239	0.98	18	214	125	0.58	32.5	9.8	94	0.0025	0.55	2
23	Jaworzno	3.6	Unglaciated	Alluvial fan	T/P	Mixed	72	262	193	0.74	32	187	91	0.49	18.1	6.6	92	0.0024	0.07	3
24	Karczmiska	5.6	Unglaciated	Other	T/P	Climbing	203	184	178	0.97	94	156	89	0.58	20.0	8.4	278	0.0037	0.20	1
25	Sandomierz Forest 1	15.3	Unglaciated	Valley	T/P	Flat	378	224	202	0.90	162	187	110	0.59	24.7	9.0	421	0.0025	0.19	2
26	Sandomierz Forest 2	9.8	Unglaciated	Valley	T	Flat	162	261	292	1.12	53	253	162	0.64	17.3	7.4	196	0.0023	0.13	4
27	Sandomierz Forest 3	5.3	Unglaciated	Valley	T/P	Mixed	95	235	210	0.89	46	189	120	0.63	22.0	8.1	114	0.0026	0.31	2
28	Mielec	17.3	Unglaciated	Valley	T/P	Flat	504	206	181	0.88	118	206	131	0.64	23.9	10.1	528	0.0025	0.15	2
29	Pilzno	2.4	Unglaciated	Alluvial fan	P	Climbing	111	136	130	0.96	76	116	57	0.50	10.6	4.3	146	0.0049	0.21	1
30	Solec Forest	4.7	Unglaciated	Valley	T/P/S	Mixed	172	187	183	0.98	52	212	114	0.54	18.5	9.2	181	0.0028	0.23	3
31	Eastern Roztocze	3.0	Unglaciated	Valley	T/P	Mixed	89	194	162	0.84	30	218	180	0.83	22.2	10.5	118	0.0034	0.24	3

On the basis of the hierarchical clustering (dendrogram, Fig. 3A), four morphological groups of dune fields were distinguished and assumed to reflect varying stages of development (Fig. 3B): initial (Group 1), poorly-organized (Group 2), well-organized (Group 3), and mature (Group 4).

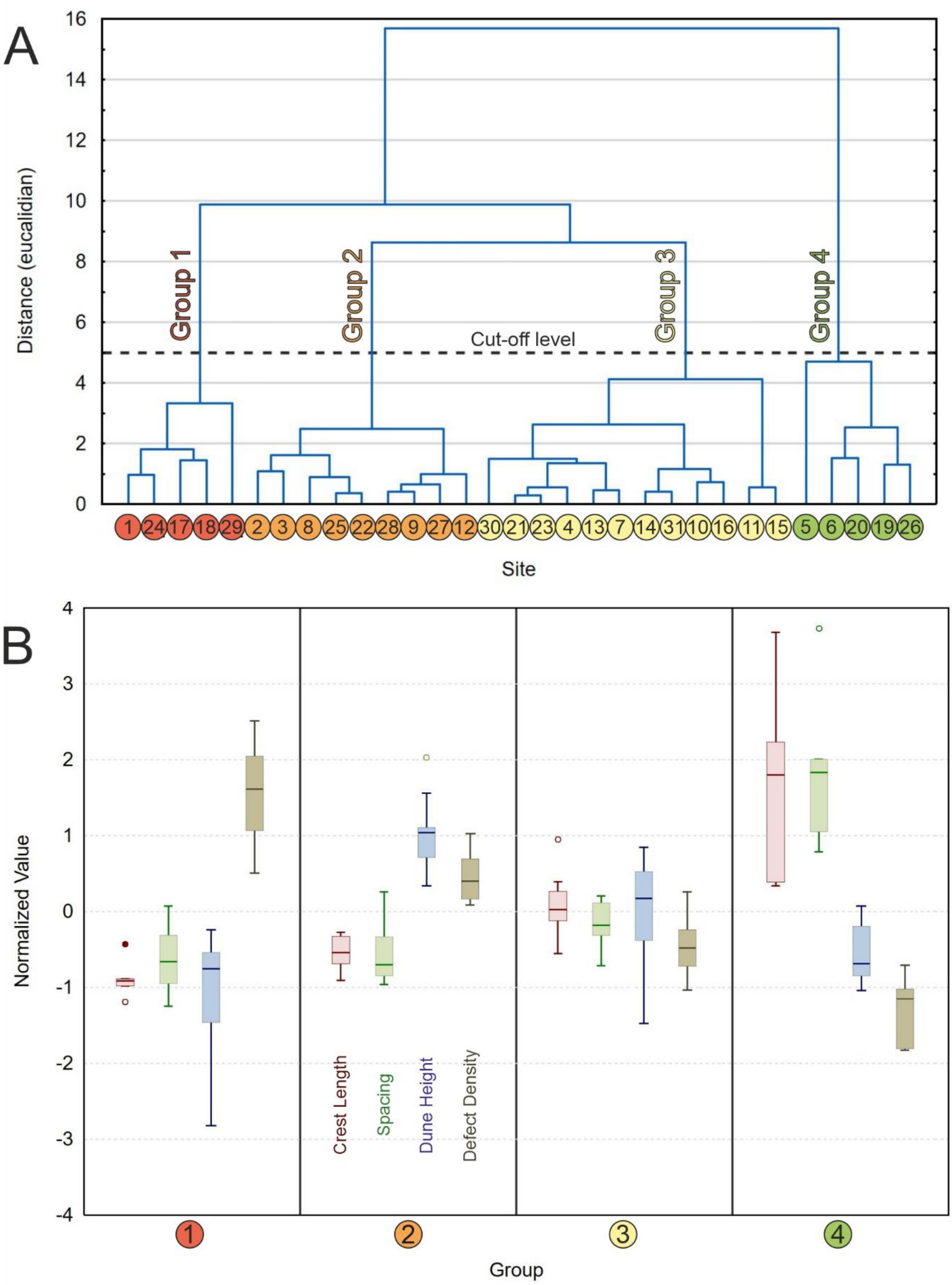

Fig. 3. A – Results of the hierarchical clustering (dendrogram) for all sites, B - Box plots showing differences in pattern parameters for distinguished morphological groups of dune fields.

Group 1 contains the initial dune fields, which pattern formed over a short period of time. The pattern of initial dune fields is irregular and consists of various dune types (mainly parabolic and initial). Dunes interact in many ways, colliding with each other and merging into bigger ones through lateral linking. The irregular distribution of dunes within the dune field and the varying orientation of the ridges in the windward direction indicate a not fully organized airflow within the dune field. The site Kurpie 1 is representative of this group (Fig. 4A). Group 2 comprises poorly organized dune fields that have formed long enough to develop a regular pattern. This group is characterized by transitional shapes between transverse and parabolic dunes with multiple thin and short trailing arms. Crest lengths and defect density are controlled by the number of secondary ridges. The site Gorzów Basin 3 is an example of this group (Fig. 4B).

Tab.2. Pattern parameters of morphological groups.

Group	Pattern description	Number of sites	Crest Length [m]		Spacing [m]		Defect Density		Dune Height [m]	
			Mean	Range	Mean	Range	Mean	Range	Mean	Range
1	Initial	5 (16%)	139	108-184	159	117-206	0.0041	0.0033-0.0049	6.9	4.3-8.4
2	Poorly-organized	9 (29%)	173	136-198	167	136-219	0.0032	0.0029-0.0037	10.4	9.3-12.0
3	Well-organized	12 (39%)	233	172-322	191	167-215	0.0025	0.0021-0.0031	8.7	6.4-10.1
4	Mature	5 (16%)	396	261-595	328	254-453	0.0018	0.0014-0.0023	7.9	7.1-8.9

Group 3 includes well-organized dune fields that have a regular pattern of homogenous dunes. Secondary ridges are rare, and the inter-dune areas are devoid of small initial dunes. The site Grudziądz is representative of this group (Fig. 4C). The most organized dune fields (mature) compose Group 4. Most mature patterns consist of large transgressive ridges or U- and V-shaped parabolic dunes without secondary ridges. The Bóbr Valley site is an example of this group (Fig. 4D).

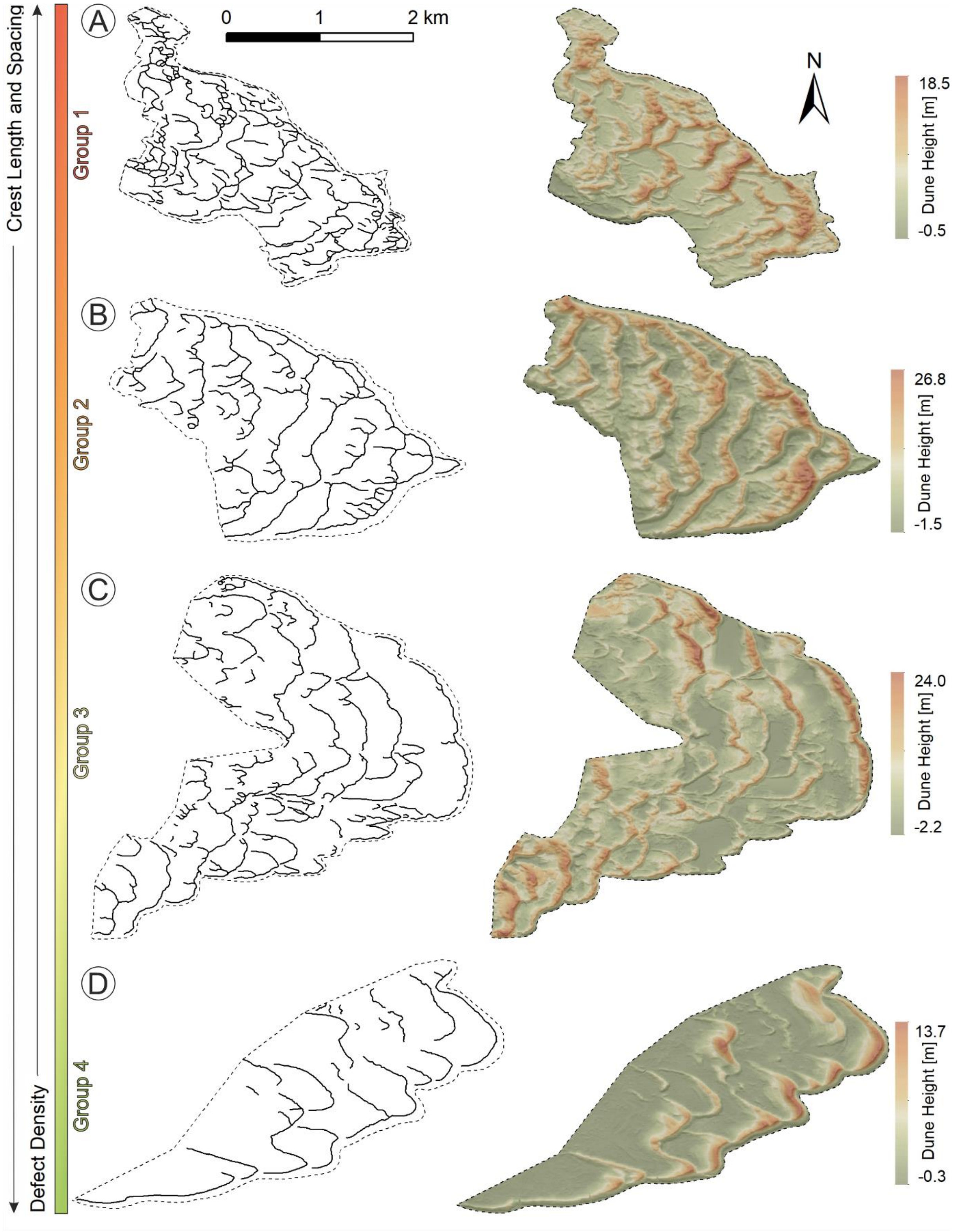

Fig. 4. Variation in morphology the dune field groups identified: A – initial site Kurpie 1 (No. 18, Figs. 1 and 5), B – poorly-organized site Gorzów Basin 3 (No. 4, Figs. 1 and 5), C – well-organized site Grudziądz (No. 9, Figs. 1 and 5), D – mature dune field in site Bóbr Valley (No. 5, Figs. 1 and 5). Maps of all sites are included in Supplementary Material.

Examined dune field patterns differ between sites and within the whole central part of the ESB, but their distribution does not show spatial regularities (Fig. 5A). Well- and poorly-organized dune fields coexist in close vicinity (e.g. sites of the Gorzów Basin (No. 2-4, Fig. 5A) or the Sandomierz Forest (No. 25-27, Fig. 5A). Spatial variability of crest length (Fig. 5B), spacing (Fig. 5C), and defect density (Fig. 5E) are linked strictly to relationships between these features. Conversely, mean dune height is an independent feature connected to local sand availability, which was the largest in IMVs (Fig. 5D).

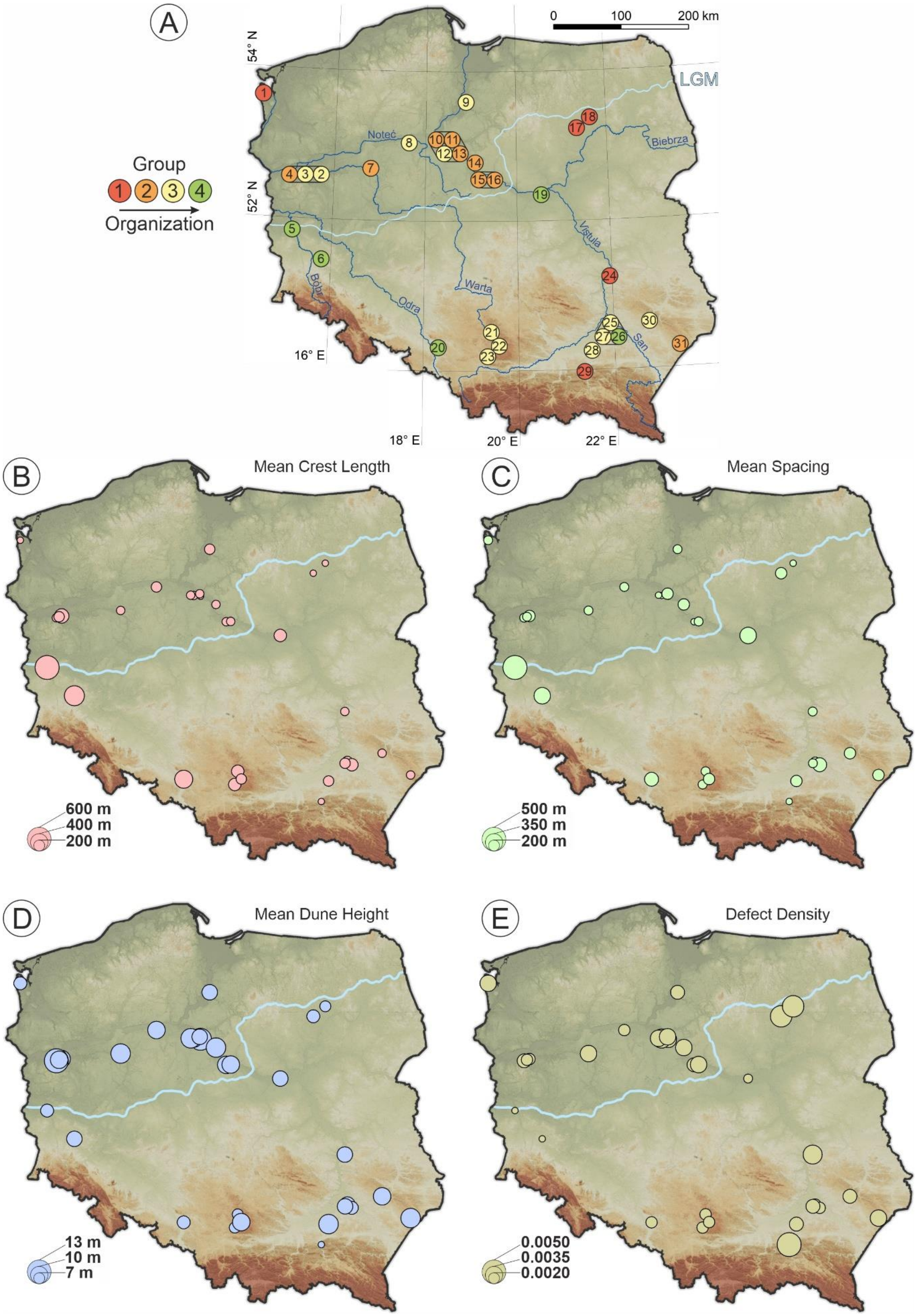

Fig. 5. Spatial distribution of morphological groups (A) and spatial variation of morphological properties (B-D).

The glaciated zone (north to the maximum LGM extent, 14 study sites) is dominated by dune fields classified as Group 2 (8/14), with a minor presence of Group 3 (5/14) and one site from Group 1 (Fig. 5A). In the unglaciated zone (17 study sites), dune fields from all four morphological groups are found, with Group 3 (7/17) being the most common. All well-developed dune fields (Group 4, 5/17) are situated in this zone, as well as 4 of the 5 dune fields of Group 1. It should be mentioned that the differences in the dune patterns from the different settings and locations relative to the LGM limit are relatively slight. Dunes developed in the glaciated zone are more similar to each other and less organized than in the unglaciated zone (Fig. 6B). Dune fields developed on alluvial fans represent all stages of development but are significantly smaller than dunes in other morphological positions (Fig. 6C). Additionally, dune fields on alluvial fans are less common and cover a smaller area compared to dune fields in IMVs, where dune fields are large and more homogenous (Fig. 6C, Tab. 1). Dune fields located in other morphological settings (e.g. in valleys, on moraines or loess plateaus) do not differ from the previously mentioned sites (Fig. 6C). Dune fields located on morphologically varied (mixed) surfaces do not differ from those located on flat areas but are more homogeneous. The results for the climbing dune fields are not relevant due to their small amount (3/31; Fig. 6D).

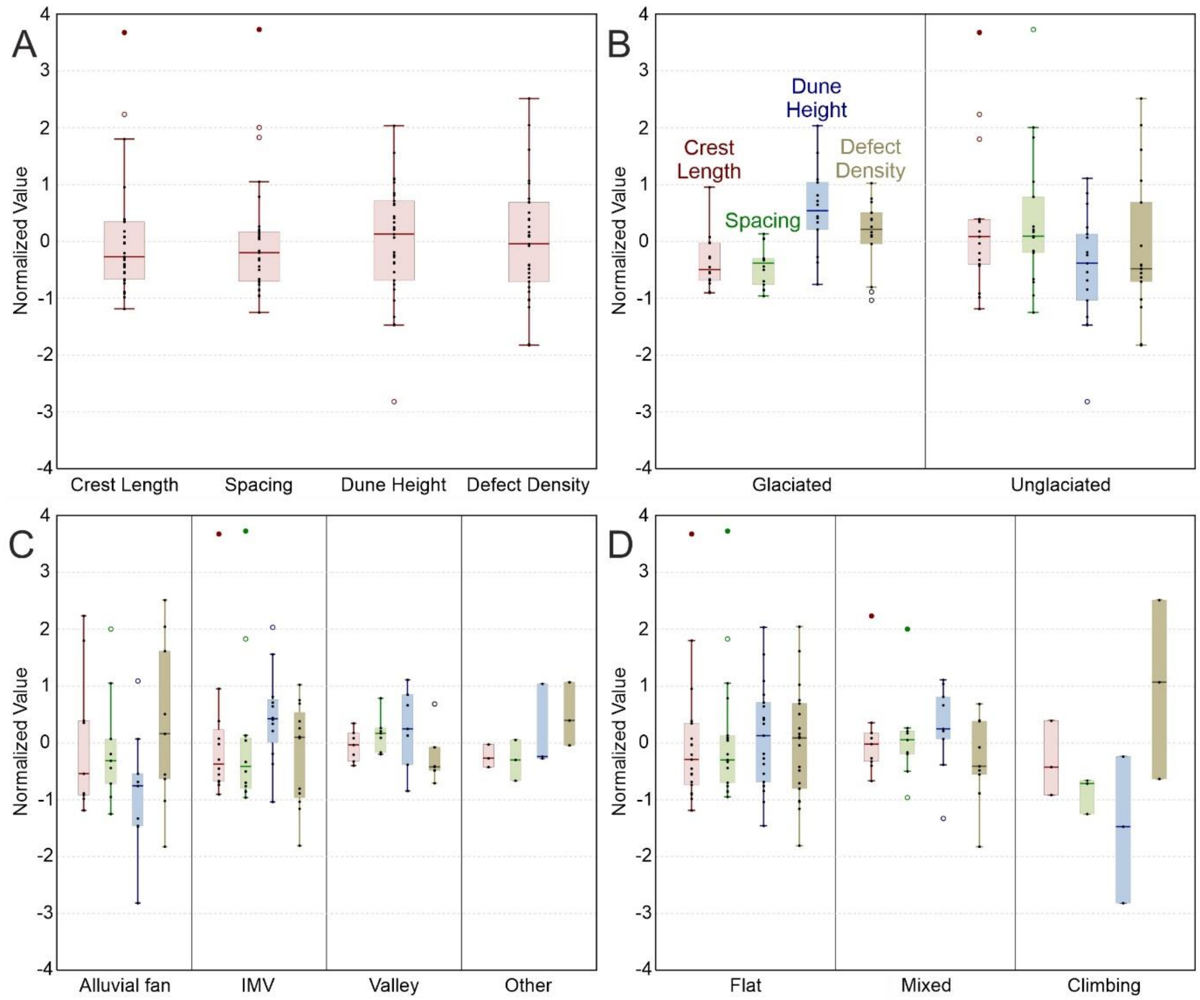

Fig. 6. Normalized crest length, spacing, dune height, and defect density in general (A), in relation to Last Glacial Maximum zones (B), setting (C), and shape of dune field basement (D).

Cumulative frequency plots of crest lengths (Fig. 7A) and dune spacing (Fig. 7B) indicate that examined dune fields comprise single populations of crest length and spacing. All sites consist of simple patterns of individual populations of dunes.

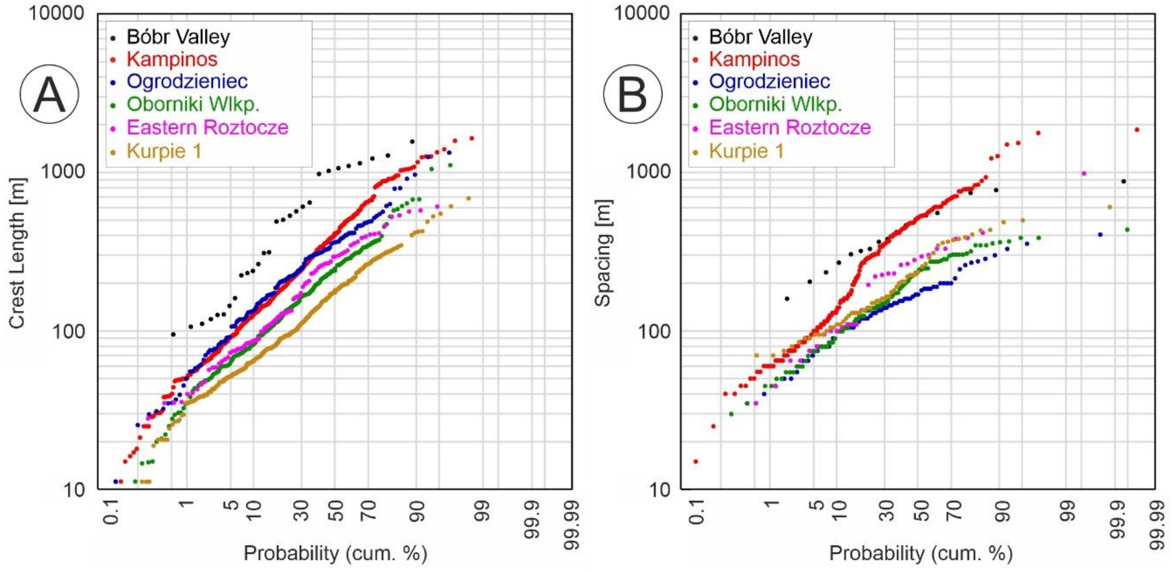

Fig. 7. Cumulative probability plots of crest length (A) and dune spacing (B). Selected sites present different stages of pattern development. For all plots, see Supplementary Material.

87% of the dunes are oriented in the E-ESE direction, indicating the dominance of dune-forming winds from the west (Fig. 8). Singular ridges are directed in the ENE and SE directions, comprising up to 20% of all dunes within individual dune fields.

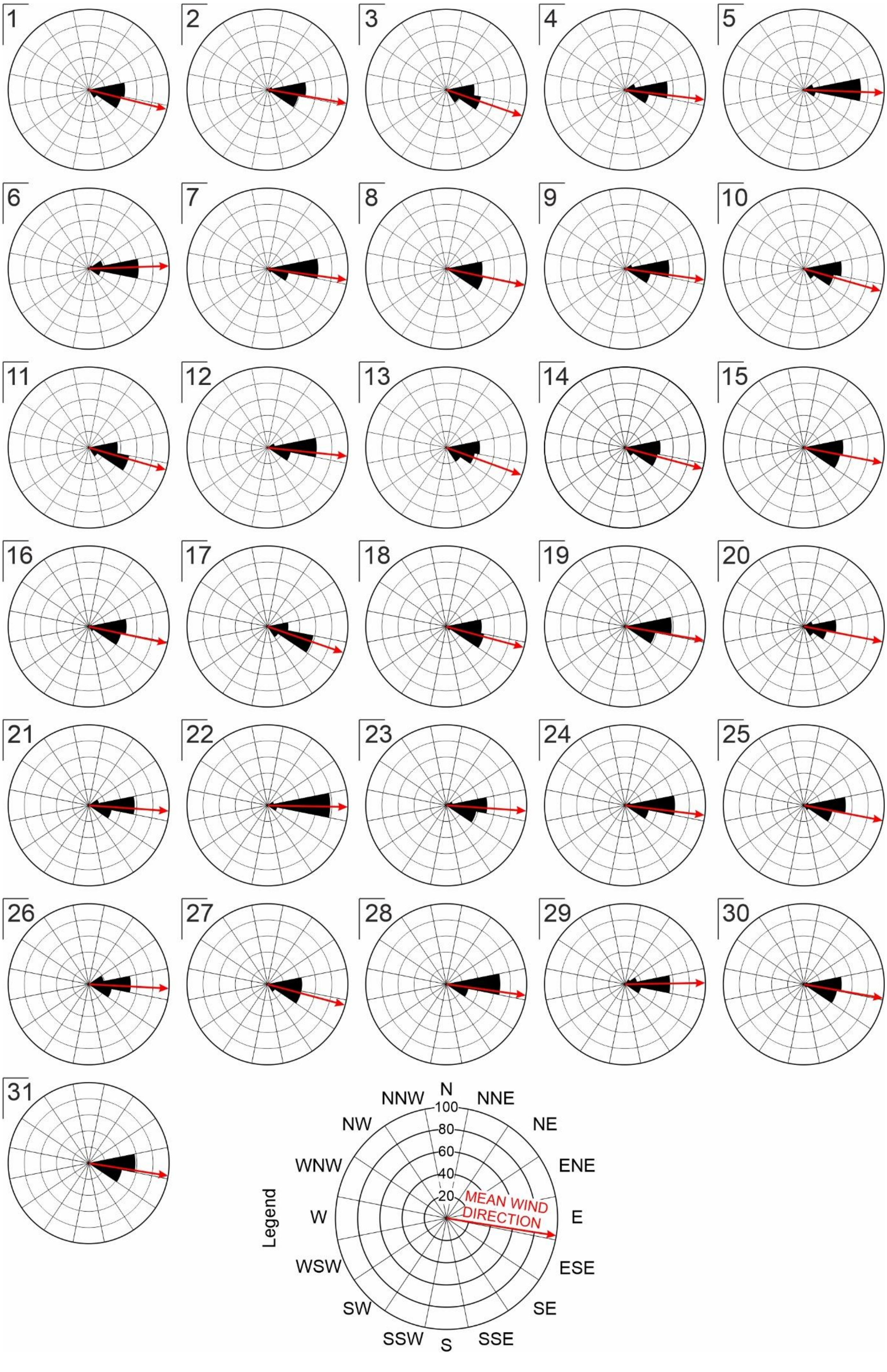
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Fig. 8. Rose diagrams showing the orientation of the dunes in the studied dune fields. All dune fields were formed by winds blowing from the W and WNW. For a list of sites, see Table 1.

6. Discussion

Our study of 31 sites in the central part of the ESB revealed a high diversity of dune field patterns. In the first part of the discussion (6.1), we compare them to patterns known from other deserts. In the latter part, we focus on the importance of regional (6.2) and local (6.3) factors on the observed variation in the morphology of the dune fields.

6.1. Comparison to patterns observed in other deserts

The pattern properties of the studied dune fields have been compared to those known from warm deserts (Fig. 9; Ewing et. al., 2006). As the pattern evolves over time, crest length and spacing between dunes increase, while defect density decreases. There is a linear relation between crest length and spacing (r^2 = 0.61), and also between spacing and defect density (r^2 = 0.57). The pattern properties from both studies reveal considerable similarities, even though Ewing et al.'s (2006) results were based on a smaller dataset. Studies conducted in cold-climate dune field in Victoria Valley (Antarctica, Bourke et al. 2009) and Alaska (Baughmann et al., 2018) have also reported that correlation between crest length, spacing, and defect density is valid for cold-climate areas, characterized by high variability of wind directions and niveo-aeolian processes (Seppälä, 2004).

In our study, a correlation between dune height and spacing was observed only at a few sites, reaching a maximum r^2 of 0.55 (Tab. 1). In most sites r^2 does not exceed 0.3 evidencing a lack of correlation between these parameters. However, it should be noted that spacing measurement is difficult in the case of the dune fields we surveyed due to the high number of secondary ridges and arms of parabolic dunes. A correlation between dune height and spacing was found only in well-organized dune fields. Measurements of the height of dunes in the cross sections may also be flawed because it does not always pass through the highest part of a dune ridge.

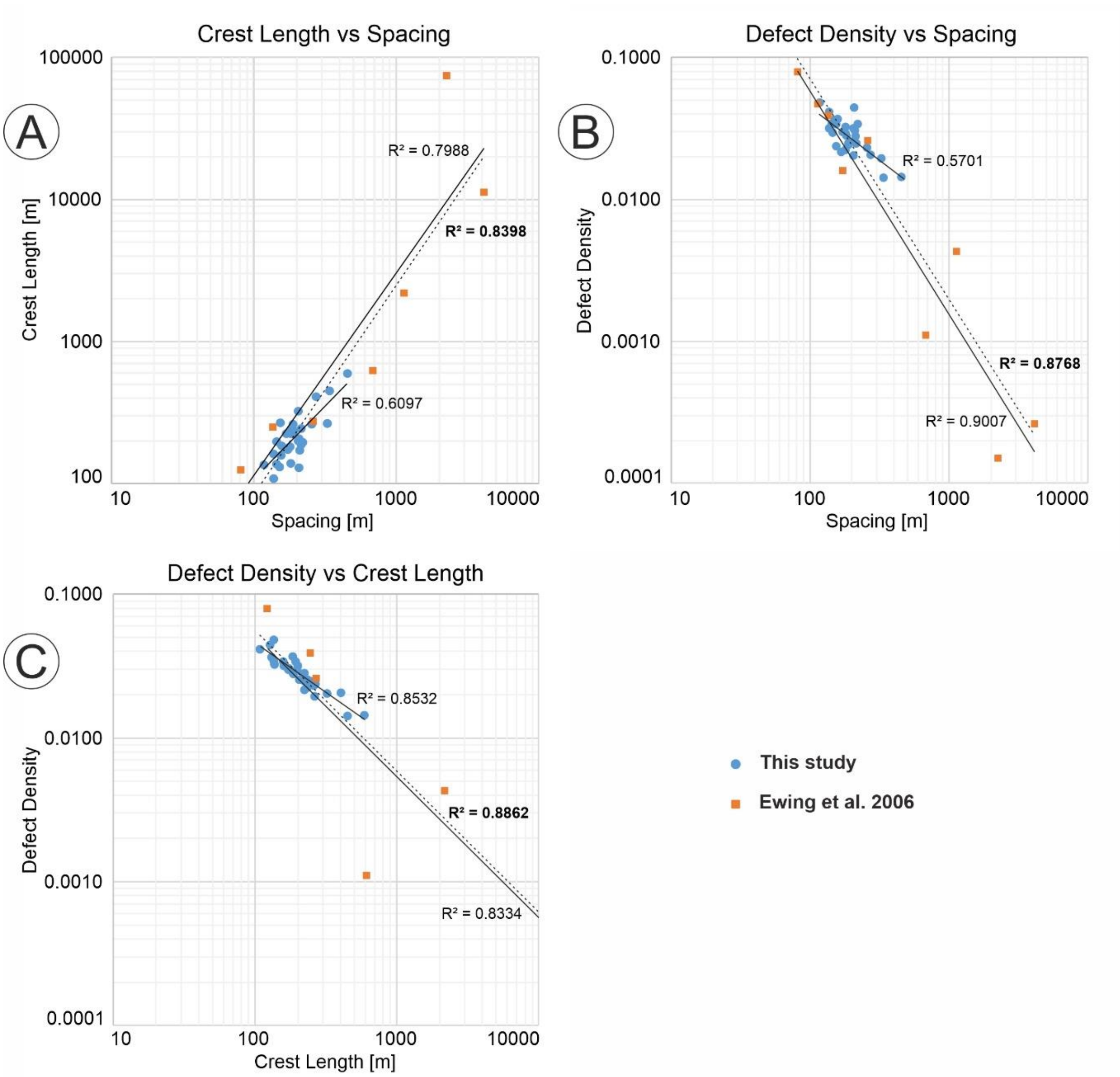

Fig. 9. Crest length (A), defect density (B), and dune height (C) plotted against spacing, D – Defect density plotted against crest length. Line is the best fit to the data.

Besides good correlations of data, the patterns of the studied dune fields within the central part of the ESB do not differ from those observed in warm dune fields. Relations between basic pattern characteristics are consistent with the self-organization paradigm, as are the trends observed in pattern evolution in a downwind direction. At the Wkra Forest site (No. 1, Fig. 1; Fig. 10), a development of the pattern with distance from the supply zone can clearly be observed. The dune field emerges as a chaotic surface covered by low initial dunes, progressively rising, merging, and organizing into parabolic dunes in the central part of the dune field. In most distant parts of the dune field, parabolic dunes start to form long-walled, sinuous transgressive ridges, characterized by long crestlines and an absence of defects. Spacing between dunes increases towards the leeward part of the dune field. The progradation and evolution of this pattern are similar to those observed at the White Sand Dune Field (Ewing and Kocurek, 2010a). However, a similar evolution of the dune field pattern is not visible in many of the studied sites possibly due to sand supply from a large and planar area. In that case, the progradation of the forms is not visible, as they are all equally distant from the source of the material (Ewing and Kocurek, 2010b).

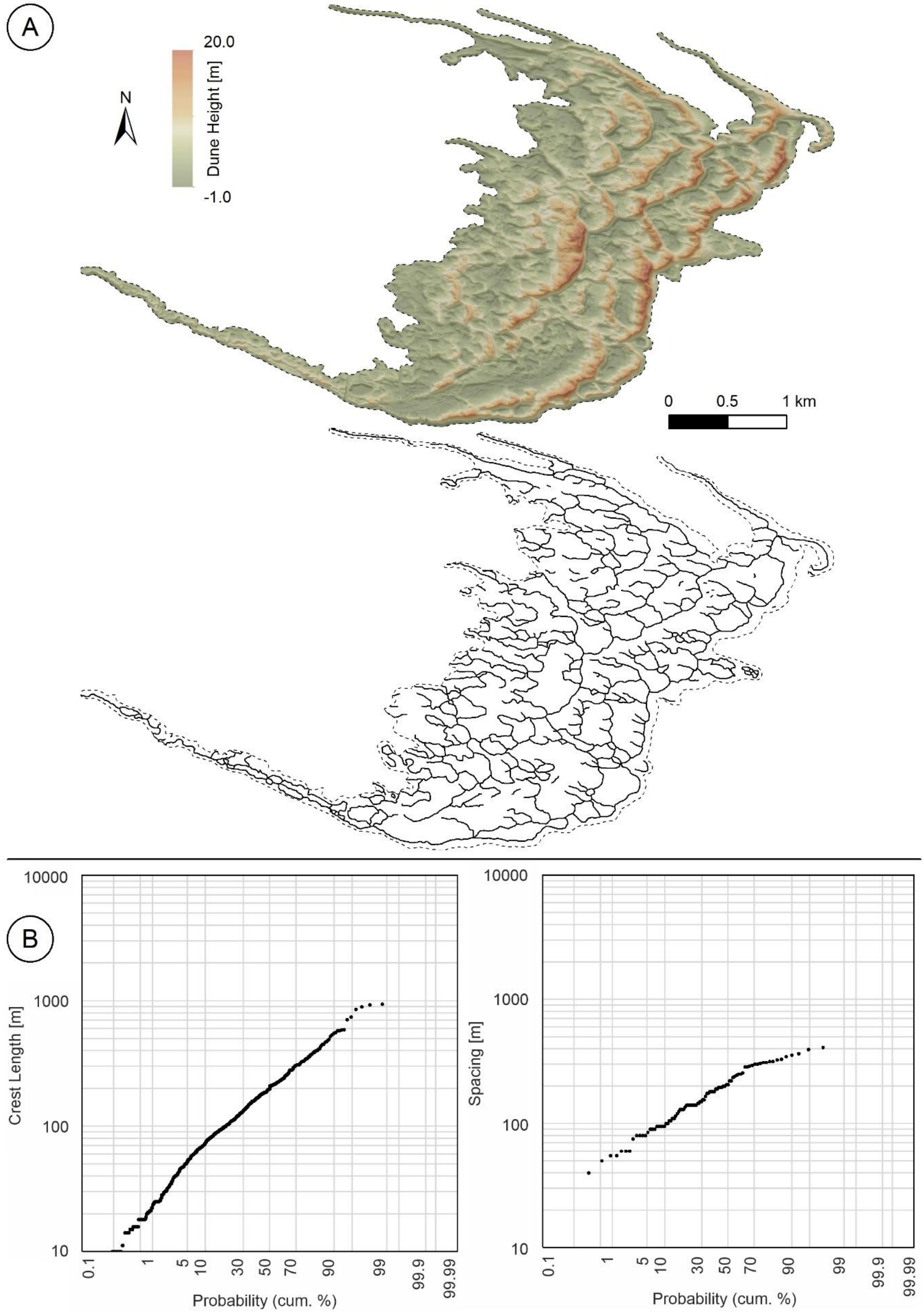

Fig. 10. A – the Wkra Forest site (No. 1, Figs. 1 and 5), B – Cumulative probability plots of crest length and dune spacing.

The preserved relations between the parameters of dune fields indicate that the factors characteristic for cold areas (high variability of wind directions, discontinuous sand supply, permafrost, niveo-eolian processes) did not directly affect the development of dune field patterns. This agrees with observations by Bourke et al. (2009) from Antarctica, where despite the presence of permafrost in the substrate, dunes migrate and form into a dune field in the same way as in other climate zones. This is caused by the isolation of the dunes from the basement by the deposited sand. However, this does not exclude the influence of the mentioned factors on the distribution of dune fields, their dimensions and spatial extent.

6.2. Impact of regional conditions

6.2.1. The role of permafrost in the development of dune fields

The regional increase of wind-abraded quartz grains observed in fluvial units from the Late Pleniglacial (Marine Isotope Stage 2) is correlated with the high intensity of aeolian processes (Woronko et al., 2015). However, these aeolian processes did not result in the formation of aeolian dunes and dune fields. The presence of continuous permafrost should be considered as the main factor limiting the amount of available sandy material (Kasse, 1997; Zieliński et al., 2015). OSL dating results from inland aeolian dunes from Eastern Germany and Poland suggest that dune-forming processes started when permafrost degraded at the beginning of the Lateglacial (ca. 15-14 ka; Hilgers, 2007; Kappler et al., 2019; Sokołowski et al., 2022). The presence of at least discontinuous permafrost was observed in fluvio-aeolian covers from the very end of the Late Pleniglacial and the beginning of the Lateglacial periods (Zieliński et al., 2014; Moska et al., 2020). Local factors (mainly morphology and ground-water circulation) preserved permafrost longer, presumably to the Older Dryas. This factor could locally reduce the amount of sandy sediments available for aeolian transport and deposition. In some areas, the permafrost may have aggraded again during the Younger Dryas (Petera-Zganiacz and Dzieduszyńska, 2017). However, there is not clear if it could prevent or reduce the aeolian deposition in such areas. It should be emphasized that the Younger Dryas was one of the most important periods for aeolian dune formation in the whole ESB, despite of rebuilt of permafrost in that period (Vandenberghe et al., 2013; Bertran et al., 2014; Kappler et al., 2019).

Decay of permafrost is correlated with considerable river incision particularly observed in IMVs as well as in extraglacial fluvial systems in the ESB (Vandenberghe et al., 1994; Starkel et al., 2015; Weckwerth, 2018). The formation of river terraces since the Bølling interstadial with thick sandy-gravelly deposits provided the opportunity for sand to be blown away due to the lowering of groundwater levels and drying of terraces (Weckwerth, 2010). This led to the formation of extensive dune fields known from the Vistula and Noteć valleys (e.g. the Gorzów Basin and the Toruń Basin), amongst other locations.

Our results support the thesis that river incision was the main factor driving the release of material. This is indicated by the uniform patterns (development in the leeward direction is not visible; Fig. 11) of most of the dune fields studied, which is characteristic for dune fields supplied with sand from a vast area (e.g., the entire terrace level or outwash plain; Ewing and Kocurek, 2010b). All dunes in the Toruń Basin 4 (Fig. 11A) are similar to each other and in the same stage of development. The lack of variation in the pattern within a dune field indicates that the dune field was supplied with sand from a vast high glaciofluvial terrace of the Vistula River.

There, the fluvioglacial terraces exceed 10 km in width and were probably entirely undergoing deflation. In smaller valleys and locations where river incision was slight, deflation was local and limited in the area. In general, the size of the dune field reflects well the nature of the material supply. Although the incision of rivers was the main process responsible for the formation of dune fields in the study area, it was asynchronous and dependent on local factors (Kozarski et al., 1988; Starkel et al., 2015; Zieliński, 2016; Gębica et al., 2022). The situation is not so clear within alluvial fans which often do not have well-developed terrace levels.

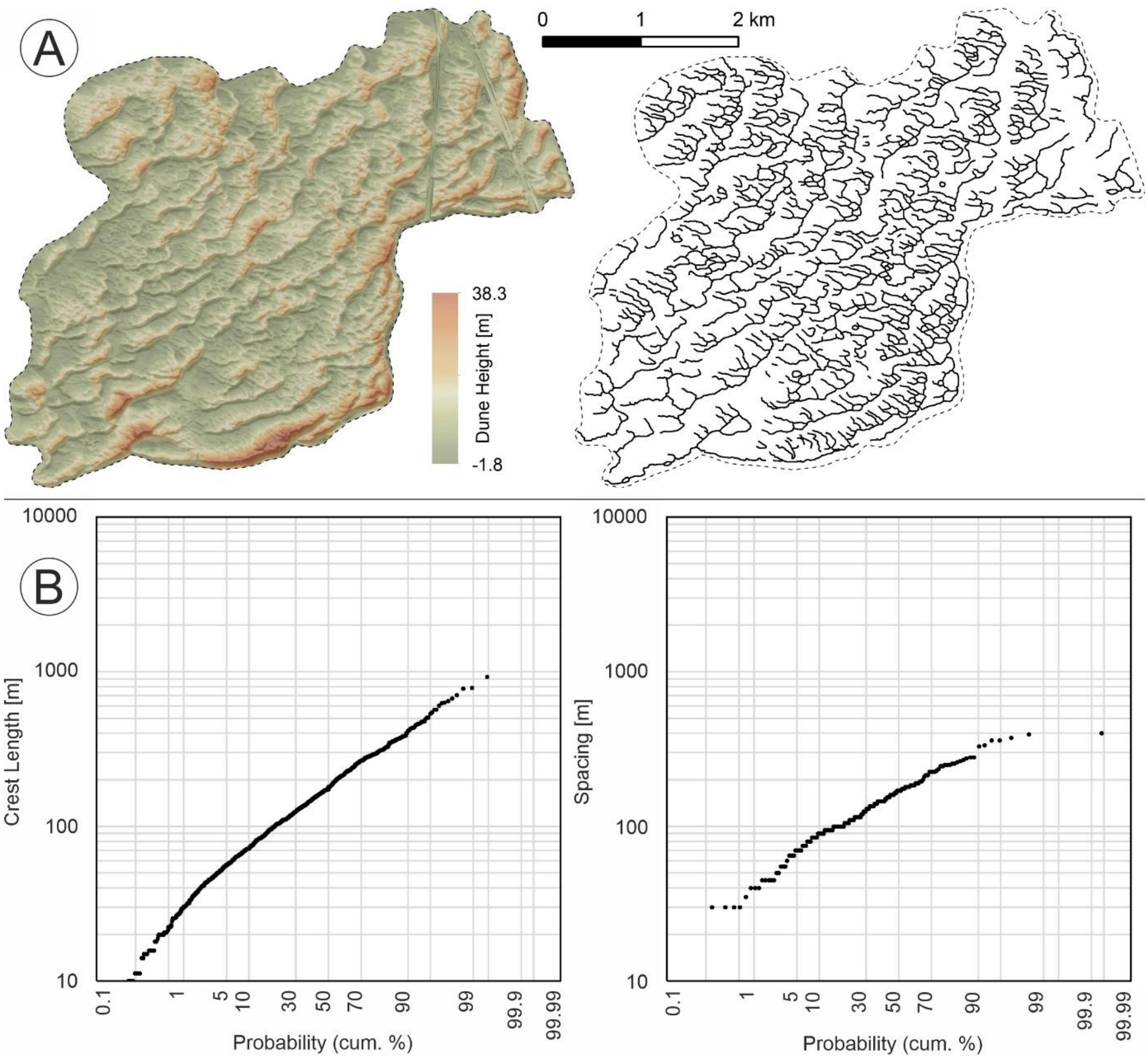

Fig. 11. Site Toruń Basin 4 (No. 13, Figs. 1 and 5). B – Cumulative probability plots of crest length and dune spacing.

The irregular spatial distribution of morphological groups, and therefore the constructional time of specific dune fields, proves this. The glaciated zone, where dune fields are similar to each other and dominated by fields with poorly developed patterns, had to undergo shorter aeolian processes than fields in the unglaciated zone. This assumption is in accordance with the results from glaciated zone, which reveal that the main dune-forming phase took place in the Younger Dryas and the Early Holocene (Nowaczyk, 2000; Andrzejewski and Weckwerth, 2010; Jankowski, 2012). High variability of dune fields organization in the unglaciated zone suggests the generally longer time of their formation and considerable importance of local conditions.

6.2.2. Impact of climate oscillations and changing atmospheric circulation

The existing model of the development of Lateglacial dunes in Poland assumes three main dune-forming phases, correlated with the climate coolings of the Oldest, Older and Younger Dryas (Nowaczyk, 1986, 2000; Manikowska, 1991, 1995). In the western part of the ESB one main dune-forming phase is distinguished (the end of the Pleniglacial and continued into the Bølling and Older Dryas) and the reworking of previously existing dunes during the Younger Dryas (Kasse, 2002). Recent findings suggest that the chronology of dune formation may have been more complex and multi-phase (Moska et al., 2022b). It should be noted that recent results of ^{14}C and OSL datings of dune-forming sediments, as well as palaeosol horizons, come from relatively small individual dunes located mostly in the unglaciated zone and only a limited number of key sites located north of the LGM limit (Moska et al., 2020, 2022a, 2022b; Sokołowski et al., 2022). This means that these ^{14}C and OSL ages may not be representative for the largest dune fields within the central part of ESB. Multi-phase dune formation is also postulated from other parts of the ESB (Kasse, 2002; Kasse and Aalsberberg, 2019; Bertran et al., 2020; Kaiser et al., 2020). Results from Central Sweden (Bernhardson and Alexanderson, 2017, 2018) and the Czech Republic (Holuša et al., 2022) point to two independent wind directions forming two separated aeolian dune systems. The main evidence is the varying orientation of the individual dunes that are part of separated patterns. Unfortunately, these data are not supported by ^{14}C and OSL results or sedimentological analysis. The wind directions responsible for dune formation in the central part of the ESB have been debated for many years (Böse, 1991; Zeeberg, 1998). The findings have been analysed and summarized by Zieliński (2016), who postulated that the main dune-forming phase took place during the Older Dryas, with a predominance of NW to W wind direction. During the Younger Dryas aeolian dunes underwent reconstruction by SW-WSW oriented wind.

Our results do not indicate that possibility, as the investigated dune fields consist of simple patterns made up of single dune populations (Fig. 7) oriented in the same direction (E to ESE, Fig. 8). This direction is consistent with the orientation of the top dune-building aeolian units in Poland, which have been dated to the Younger Dryas (Nowaczyk, 1986, 2000; Moska et al., 2022a; Sokołowski et al., 2022). This may indicate that during this period the dune fields in the entire study area underwent final formation, becoming homogeneous in terms of orientation and number of dune populations. At the same time, temporal variation in the development of dune fields cannot be ruled out, as other parameters of the pattern (crest lengths, spacing, defect density) vary between sites indicating a different time of construction of individual dune fields. This implies that the initiation of aeolian activity was asynchronous, in contrast to synchronous stabilization. This observation further strengthens the argument about the crucial influence of local river incision in the development of aeolian processes demonstrated in Section 6.2.1.

The inconsistency between the number of dune-forming phases in the Polish part of the ESB and the patterns recorded in the dune fields is puzzling, because dune fields tend to overlap and develop complex patterns, rather than completely reconstruct (Kocurek and Ewing, 2005). Three possibilities might be considered at this point. The first possible solution is that the studied dune fields were never stabilized, and as a result, complex patterns were not formed. While this would seemingly contradict sedimentological studies, it should be considered that such studies were conducted in sites located in isolated dunes or at the margins of the largest dune fields, but not within the dune fields (Sokołowski et al., 2022). Stabilization and subsequent reactivation may have occurred on individual dunes, while at the same time not taking place in the largest dune fields, the sizes of which significantly slowed down the process of plant colonization. Seppälä (1995) pointed out that in cold areas the short growing season significantly lengthens the colonization time of dune areas by lichens and shrubs. In subarctic Canada, this process takes 150 to 200 years (Filion and Payette, 1989). Given that the periods of dune stabilization in the Bølling and Allerød were relatively short (300-600 years), colonization of the largest dune fields may have been limited only to their margins. The second explanation is that the predominant wind directions were limited during the Lateglacial to the SW-NW sector (Zieliński, 2016). In that case, the reactivation of aeolian processes (interrupted by vegetation cover) did not have to transform the orientation of dunes.

At a few sites, deflection points on spacing plots suggest that they are built by two generations of dunes (Fig. 7B; Kampinos site). However, spacing measurements are affected by dense secondary ridges and tailing arms common in dune fields developed from parabolic dunes. Their widespread presence at the study sites potentially leads to misinterpretation of the dune field pattern. Trailing ridges can be mistaken as components of another pattern oriented in a different direction. They can also affect measurements of dune orientation, leading to an incorrect determination of the direction of dune field migration. Our results obtained from 31 dune fields suggest the predominance of simple patterns. Therefore, results reported by Bernhardson and Alexanderson (2017, 2018) may be caused by a misinterpretation of the arms of the parabolic dunes. The third possibility to consider is the influence of several local factors, among others, on sand availability. In sand-limited areas, redistribution of previously deposited sand accumulations may predominate. This factor depends on the rate of river incision and the built-up of thick sandy river terraces. It is visible in the Toruń Basin, where the Vistula River incision reached at least 30-40 m during the Late Pleniglacial – Lateglacial (Weckwerth, 2010).

6.3. Impact of local factors

6.3.1. Sand supply

The dune fields we studied are located in different positions in relation to morphology (IMV-s, outwash plains, extraglacial river valleys, piedmont alluvial fans, loess plateaus, intra-mountain river valleys). This conditions the basement lithology and the availability of sandy material.

Dune fields located in IMVs exhibit the largest surface and height of specific dunes (Fig. 6C, Tab. 1). This is a result of the large areas of sandy accumulation terraces and the high availability of dried material in a relatively short period (Andrzejewski and Weckwerth, 2010; Weckwerth, 2010). Comparison of river valleys of the N-S axis (for instance the middle Vistula River valley; site no. 24, Fig. 1) and the W-E axis (Toruń-Eberswalde IMV; e.g. sites no. 10-13; Fig. 1.) reveals the importance of this factor in dune field development. The W-E orientation of river valleys enhanced sand accumulation due to stable material supply. This orientation of the valleys in relation to the direction of dune field migration prevented the dune fields from encountering larger rivers and, as a result, the redeposition of sandy material. A similar dependence was also observed by Sitzia et al. (2017) in the western part of the ESB (southern France), where clusters of dunes are located only in valleys oriented in accordance with the wind direction prevailing during the Younger Dryas. Dunes in the valleys of N-S orientation migrated out of the source area (river terraces), were no longer fed, and lost sand as they migrated.

Dune fields fed from alluvial fans are significantly lower and smaller than those developed in IMVs (Fig.6C, Tab. 1). In addition, dune fields on alluvial fans are rare, in contrast to the IMVs largely covered by dunes. A similar lower supply of sand on the outwash plains was caused mainly by more limited Lateglacial incision and terrace formation. Terraces in such areas were only formed during the melting of dead ice blocks in the early Holocene (Błaszkiewicz et al., 2004, 2015), when climatic conditions were no longer favourable for intense aeolian activity.

6.3.2. Vegetation

Although the method used does not allow for the precise identification of the plant communities affecting the studied dune fields, the type of dunes and their morphology can indirectly indicate the degree of their transformation by vegetation (e.g. Nield and Baas, 2008; Reitz et al., 2010; Yan and Baas, 2017). The studied dune fields are composed mostly of transverse and parabolic dunes that are in different stages of this transformation by vegetation. Smaller and lower dunes are often fully transformed into V and U-shaped parabolic dunes, while the largest and highest transverse dunes are only affected in the vicinity of crestline terminations (Fig. 12).

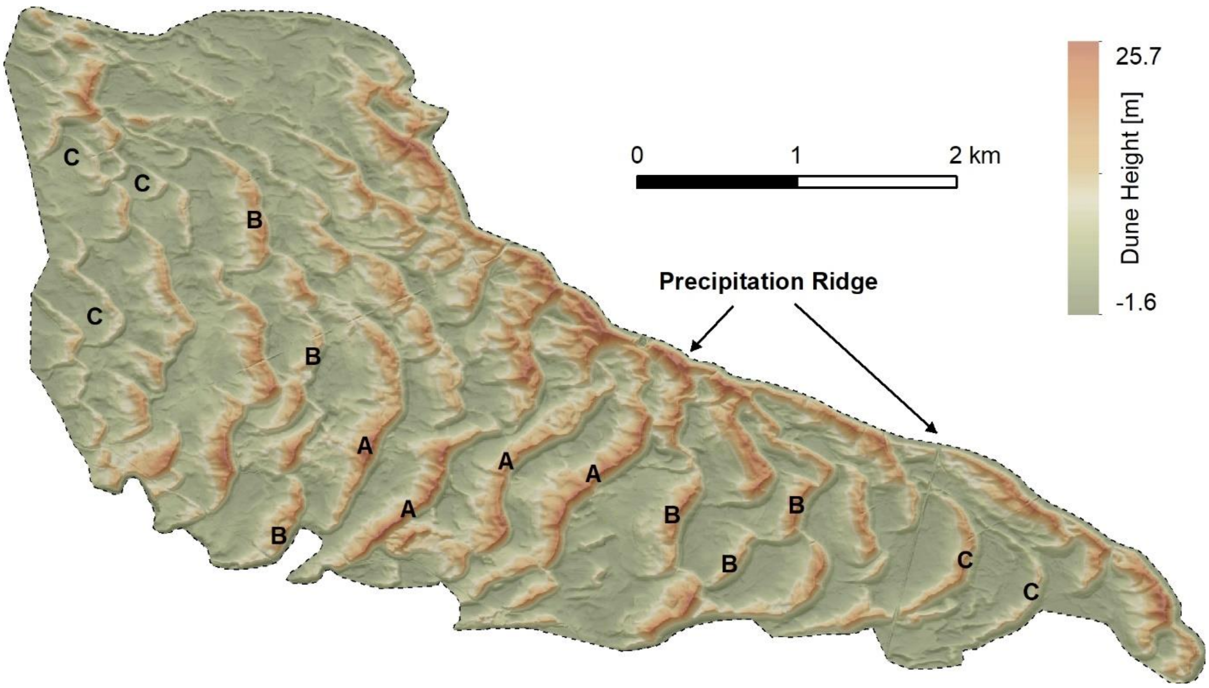

Fig. 12. Site Sandomierz Forest 1 (No. 25, Figs. 1 and 5). In the central part, the dune field consists of transverse dunes (A), which towards the edges of the dune field are gradually transformed into parabolic dunes. In cases of large dunes, the transformation only affected the terminations of the ridges, initiating the formation of trailing arms (B). In the outermost parts of the dune field, low dunes have been

completely transformed into parabolic dunes (C). The varying levels of transformation indicate a different stage of colonization of the dunes by vegetation. The long precipitation ridge which forms the NE edge of the dune field is evidence of movement of the dune field towards an area that is decelerating the dune migration rate, potentially because of denser vegetation (e.g. Cooper, 1958; Hesp, 2011)

The degree of transformation appears to depend mainly on the size of the dune, which determines the ground-water level, crucial for pioneer species (Landsberg, 1956; Tsoar, 2008). In the case of a low precipitation rate during the Lateglacial (250-350 mm; Koster, 1988) dune height was possibly the main factor limiting soil moisture. The transformation of dunes from transverse to parabolic relates to changes in the vegetation occurring from the Younger Dryas (11.7-12.9 ka BP) to the Preboreal (10.3-9.0 ka BP), when tundra habitats dominated by dwarf birch, juniper and other shrubs gradually transformed into boreal pine-birch forests (Latałowa, 2003a). Intriguingly, some fields composed of transverse dunes do not show signs of significant transformation by vegetation. This may be due to the fast expansion of vegetation, causing rapid dune stabilization (Bernhardson and Alexanderson, 2017). These dunes have not been mobilized in later periods, so their original shape has been preserved. The dune fields of Alaska (Noghabara, Kobuk Valley; Baughmann et al., 2018) and Canada (Athabasca Dunes, Carson and MacLean, 1986) are often only partially active and are accompanied by fully vegetated and stabilized dunes of other types. In this case, the different types of dunes document different environmental conditions that prevailed in the past. Partial reactivation of dune fields is likely to explain the proximity of sites with different stages of dune field pattern development (Kotlina Gorzowska (No. 2-4, Fig. 5A) and Puszcza Sandomierska (No.

25-27, Fig. 5A). Other factors responsible for the reactivation and transformation of dunes may have involved human activity, particularly intense in river valleys (Twardy, 2016; Lungershausen et al., 2018; Kappler et al., 2019).

6.3.3. Groundwater level

The incision of rivers, as mentioned in section 6.2.1, led to a lowering of groundwater levels in river valleys. However, this did not proceed in the same way at all sites, being influenced by the characteristics of the valley, the degree of incision, as well as the number and height of river terraces. The studied dune fields within IMVs are located mostly on the Lateglacial river terraces, which were drained first.

The variation in groundwater levels between the river terraces is particularly evident at the Kampinos site (No. 19, Fig. 1; Fig. 13), composed mainly of parabolic dunes. In contrast to the other sites, distances between individual dunes are large (spacing = 324 m) whereas crests lengths (= 265 m) are similar to other sites located in the IMVs (Tab. 1). It is crucial in this case that this dune field is located on a high terrace (6–8 m above the river) separated from both the north and south by the lower terraces (4–6 m above the river; Nowak and Skompski, 1990). Furthermore, the dune field steps towards the SE into a lower fluvial terrace, which comprises a 10 km long precipitation ridge in the southernmost part of the Kampinos dune field (Fig. 13B). The specific setting may have resulted in a variable groundwater table, documented by the widespread occurrence of residual dune ridges in the area, i.e., successions of low ridges left by the migration of dunes on a substrate affected by fluctuations of the groundwater table (Fig. 13C), which are characteristic for wet aeolian systems (Lindhorst and Reimann, 2021). Residual dune ridges are rare in other studied dune fields and suggest specific local depositional conditions determining the distinctiveness of the Kampinos site.

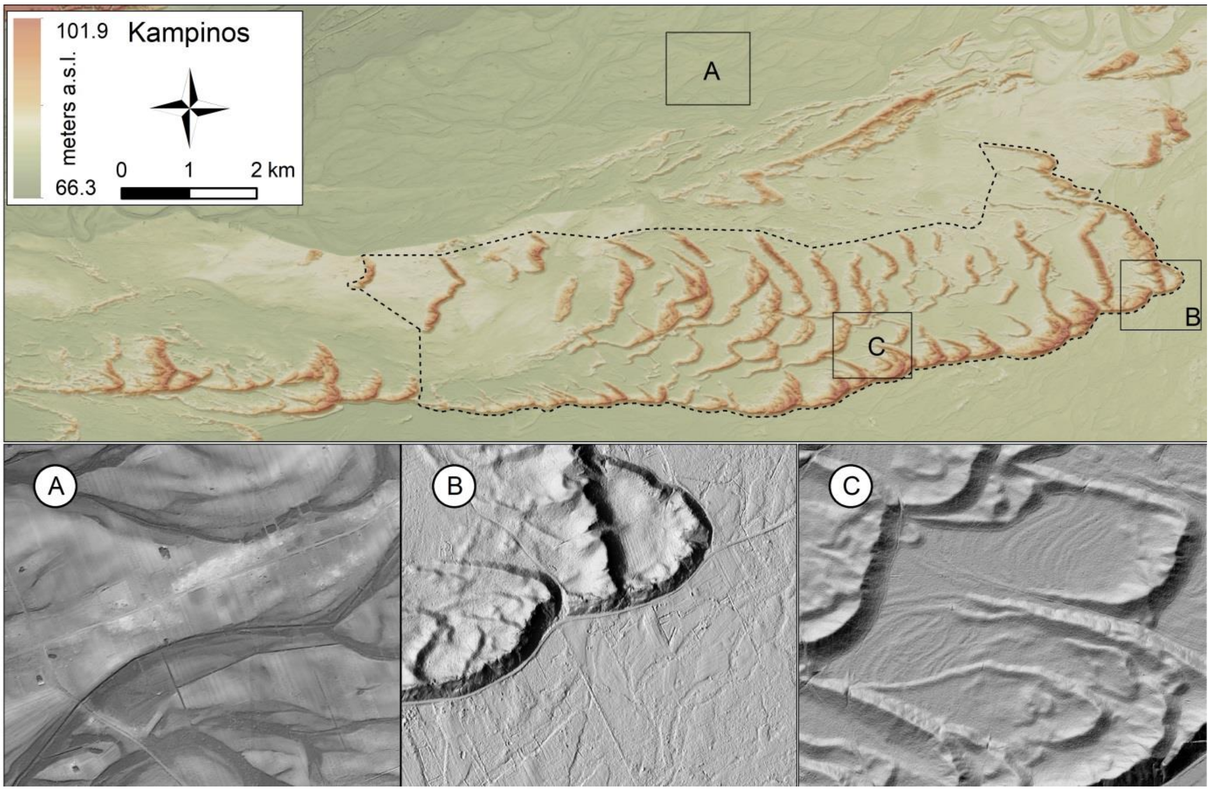

Fig. 13. Site Kampinos (No. 19, Fig. 1). A – braided river channels located on a terrace 4-6 meters above the river. B – Precipitation ridge developed at the contact of a dune field with a lower terrace level as indicated by braided river channels. C – residual dune ridges that formed as dunes were migrating over a substrate affected by fluctuations of the groundwater table (Lindhorst and Reinmann, 2021). The dashed line marks the area subjected to pattern analysis.

The groundwater level may have been less important in areas built of permeable sediments, such as glaciofluvial terraces and alluvial fans. There, residual dune ridges have not been found, and the development of dune fields has not been disturbed by the high moisture of the basement.

7. Conclusions

This article presents an overview of the geomorphological features and pattern properties of 31 cold-climate dune fields in the central part of the ESB. Their variability reflects a differentiation of aeolian processes shaping the landscape within the ESB during the Lateglacial and early Holocene. Several conclusions can be drawn:

(1) Cold-climate dune fields undergo the same pattern self-organization as dune fields located in other climatic zones. The temporal relation between crest length, spacing, and defect density is preserved in all dune fields, regardless of the specific local conditions.

(2) The studied dune fields exhibit simple patterns consisting of a single population of dunes oriented towards E-ESE. The results indicate the shaping of large dune fields during the entire Lateglacial and their simultaneous stabilization. Alternatively, the dune-forming wind did not change direction in subsequent phases of aeolian activity.

(3) Dune fields located within the central part of the ESB represent a wide range of patterns interpreted as different stages of maturity. The degree of organization depends on the local setting, which also determines the possible timeframe of sand release and further dune field development.

(4) All dune fields consist of transverse dunes transformed to varying degrees into parabolic dunes. This is indicative of a large supply of material during dune formation and further evolution into parabolic dunes driven by vegetation development.

(5) The organization of dune fields is weakly related to the LGM ice sheet extent, the morphological setting, and shape of the dune field basement.

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