

SUPPLEMENTARY MATERIALS

Mosaic of biological soil crusts and vascular plants contributes to the spatial heterogeneity of key soil properties at different successional stages of restored inland sand dunes

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Table S1. The formulas used to calculate chlorophyll concentrations (according to Caesar et al. 2018).

Parameter	Formula
The total amount of chl <i>a</i> + <i>b</i> in a sample	$\text{Chl } a + b (\mu g) = [(A_{665} - A_{700}) \times 8.02 + (A_{648} - A_{700}) \times 20.2] \times DF \times S$
Chl <i>a</i> + <i>b</i> concentration on a surface area	$\text{Chl } a + b (mg \times m^{-2}) = \frac{\text{Chl } a+b (\mu g)}{AR \times 1000}$
Chl <i>a</i> + <i>b</i> concentration on dry weight	$\text{Chl } a + b (\mu g \times g^{-1}) = \frac{\text{Chl } a+b (\mu g)}{DW}$
Total chl <i>a</i> amount in a sample	$\text{Chl } a (\mu g) = [(A_{665} - A_{700}) \times 12.19] \times DF \times S$
Chl <i>a</i> concentration based on a surface area	$\text{Chl } a (mg \times m^{-2}) = \frac{\text{Chl } a (\mu g)}{AR \times 1000}$
Chl <i>a</i> concentration based on dry weight	$\text{Chl } a (\mu g \times g^{-1}) = \frac{\text{Chl } a (\mu g)}{DW}$

A_x = absorbance at certain wavelength, DF = dilution factor, S = amount of DMSO (ml), AR = area (m²), DW = dry weight (g).

Table S2. Results of one-way analysis of variance ($p < 0.05$) testing the significance of differences in photosynthetic pigment concentrations in BSC, cover and species richness of lichens, bryophytes, and vascular plants and light intensity in the study plots among vegetation succession stages.

Parameter	F	p	df
Chlorophyll <i>a</i> + <i>b</i> concentration ($\mu\text{g g}^{-1}$ DW)	5.97	0.009	21
Chlorophyll <i>a</i> + <i>b</i> concentration (mg m^{-2})	7.45	0.004	21
Chlorophyll <i>a</i> concentration ($\mu\text{g g}^{-1}$ DW)	6.26	0.007	21
Chlorophyll <i>a</i> concentration (mg m^{-2})	7.15	0.004	21
Chlorophyll <i>b</i> concentration ($\mu\text{g g}^{-1}$ DW)	5.51	0.012	21
Chlorophyll <i>b</i> concentration (mg m^{-2})	7.54	0.003	21
Chlorophyll <i>a/b</i> ratio	8.28	0.002	21
Vascular plants cover	7.35	0.004	21
Lichen cover	3.54	0.047	21
Bryophyte cover	0.410	0.669	21
Vascular plant species richness	11.42	<0.001	21
Lichen species richness	30.30	<0.001	21
Bryophyte species richness	2.13	0.144	21
Light intensity	71.21	<0.001	21

Table S3. PERMANOVA pairwise comparisons of lichen, bryophyte, and vascular plant species composition between soil condition classes. Lower diagonal – P values by permutation. Upper diagonal – average similarities between groups (%).

Succession stage	Initial	Middle	Late
Initial		38.184	24.761
Middle	0.002		36.233
Late	0.001	0.001	

Table S4. Results of two-way analysis of variance ($p < 0.05$) for the effect of succession stage and substrate type factors on physicochemical parameters of the substrate.

Parameter	Independent variables	F	p	df	Error df	R ²
pH (H ₂ O)	Succession stage	54.13	<0.001	2	63	0.65
	Substrate type	2.00	0.143	2		
	Succession stage $\times$ Substrate type	1.28	0.286	4		
Conductivity ($\mu\text{S cm}^{-1}$)	Succession stage	7.08	0.002	2	63	0.29
	Substrate type	4.51	0.015	2		
	Succession stage $\times$ Substrate type	0.71	0.585	4		
WHC (%)	Succession stage	5.15	0.008	2	63	0.56
	Substrate type	2.27	0.112	2		
	Succession stage $\times$ Substrate type	16.37	<0.001	4		
Specific gravity of soil solids (mg m^{-3})	Succession stage	5.81	0.005	2	63	0.54
	Substrate type	24.02	<0.001	2		
	Succession stage $\times$ Substrate type	3.62	0.010	4		
Total C (%)	Succession stage	37.79	<0.001	2	63	0.69
	Substrate type	26.73	<0.001	2		
	Succession stage $\times$ Substrate type	2.87	0.030	4		
Organic C (%)	Succession stage	41.05	<0.001	2	63	0.71
	Substrate type	29.84	<0.001	2		
	Succession stage $\times$ Substrate type	2.86	0.030	4		
Total N (%)	Succession stage	25.55	<0.001	2	63	0.78
	Substrate type	64.44	<0.001	2		
	Succession stage $\times$ Substrate type	10.76	<0.001	4		
N-NO ₃ (mg kg^{-1})	Succession stage	5.12	0.009	2	63	0.25
	Substrate type	0.94	0.395	2		
	Succession stage $\times$ Substrate type	2.29	0.070	4		
P-PO ₄ (mg kg^{-1})	Succession stage	22.09	<0.001	2	63	0.62
	Substrate type	26.66	<0.001	2		
	Succession stage $\times$ Substrate type	1.81	0.139	4		
N-NH ₄ (mg kg^{-1})	Succession stage	0.23	0.794	2	63	0.39
	Substrate type	13.35	<0.001	2		
	Succession stage $\times$ Substrate type	3.35	0.015	4		
Pog. (mg kg^{-1})	Succession stage	18.50	<0.001	2	63	0.51
	Substrate type	9.42	<0.001	2		
	Succession stage $\times$ Substrate type	2.16	0.084	4		
K _T (mg kg^{-1})	Succession stage	2.20	0.119	2	63	0.18
	Substrate type	2.47	0.093	2		
	Succession stage $\times$ Substrate type	1.01	0.411	4		
Ca _T (mg kg^{-1})	Succession stage	0.18	0.833	2	63	0.11
	Substrate type	0.86	0.427	2		
	Succession stage $\times$ Substrate type	1.43	0.235	4		

K_{EX} (mg kg ⁻¹)	Succession stage	14.75	<0.001	2	63	0.75
	Substrate type	71.37	<0.001	2		
	Succession stage × Substrate type	3.95	<0.001	4		
Ca_{EX} (mg kg ⁻¹)	Succession stage	33.30	<0.001	2	63	0.73
	Substrate type	46.54	<0.001	2		
	Succession stage × Substrate type	3.27	0.017	4		

Table S5. Distance-based linear model of lichen, bryophyte, and vascular species composition as well as BSC morphological groups against below-crust soil drivers determined in the study plots. The proportion of variance explained by soil variables in stepwise forward sequential tests following adjusted R^2 selection criterion.

Data set	Soil variable	R^2	SS (trace)	Pseudo-F	p	Prop.	Cumul.	Res df
Species composition (presence/absence)	WHC	0.226	10332	6.417	0.001	0.23	0.23	22
	pH (H ₂ O)	0.354	5874.5	4.175	0.001	0.13	0.35	21
	Organic C	0.421	3068.8	2.318	0.010	0.07	0.42	20
	Total K	0.483	2807.8	2.254	0.018	0.06	0.48	19
	Total N	0.537	2485.1	2.111	0.023	0.05	0.54	18
BSC morphological groups (frequencies)	pH (H ₂ O)	0.4363	7251.9	17.027	0.001	0.44	0.44	22
	WHC	0.5514	1914.1	5.391	0.005	0.12	0.55	21
	Total N	0.6033	862.7	2.617	0.040	0.05	0.60	20
	Conductivity	0.6510	792.7	2.597	0.049	0.05	0.65	19

Prop. – proportion of variance explained by each variable; Cumul. – cumulative proportion of variance explained by multiple variables; Res.df – residual degrees of freedom.

Table S6. Factors derived from vegetation and substrate properties of plots. Factor loadings are given in parentheses; only variables with factor loadings greater than 0.65 are provided. The percentage of explained variance for each factor is provided.

Factor no	Variables (factor loadings)	Variance explained (%)
Vegetation matrix		
Factor 1 VEG	chl <i>a</i> in BSC (0.83), chl <i>a+b</i> in BSC (0.83), vascular plant frequency (-0.75), pine age (0.70), green algal frequency (-0.63)	40.37
Factor 2 VEG	vascular plant cover (0.84), vascular plant species richness (0.83), litter frequency (0.63)	15.91
Factor 3 VEG	bryophyte frequency (-0.95), bryophyte cover (-0.94), lichen cover (0.67), fruticose lichen frequency (0.63)	13.20
Factor 4 VEG	lichen species richness (-0.84), cyanobacteria crust frequency (0.82), bare soil frequency (0.75), birch age (-0.74), light intensity (0.71)	6.37
Substrate matrix		
Factor 1 SUBST	total N (0.96), organic C (0.95), total C (0.94), Ca _{EX} (0.93), K _{EX} (0.91), total P (0.83), P-PO ₄ (0.82), total K (0.63)	47.66
Factor 2 SUBST	substrate conductivity (0.82), substrate pH (0.65), WHC (0.65)	14.41
Factor 3 SUBST	total Ca (0.77), specific gravity of soil solids (-0.75)	9.49
Factor 4 SUBST	N-NO ₃ (0.80)	7.39

Table S7. The results of canonical correlation analysis. Correlation coefficients (structure coefficients) between factors and canonical variables are presented; the coefficients higher than 0.50 are provided in bold. Factor numbers are explained in Table S6.

Vegetation set	Canonical 1 root 1	Canonical root 2	Canonical root 3	Canonical root 4
Factor 1 VEG	-0.56	-0.58	0.59	0.01
Factor 2 VEG	-0.21	0.72	0.51	-0.42
Factor 3 VEG	-0.33	0.38	0.04	0.86
Factor 4 VEG	0.73	-0.07	0.62	0.28
Canonical R	0.90	0.72	0.52	0.16
Chi ²	51.63	20.20	6.42	0.47
P value	<0.001	0.016	0.169	0.495
Redundancy of second set (%)	20.43	13.13	6.89	0.62
Total redundancy (%)	41.06%			
Soil set	Canonical 1 root 1	Canonical root 2	Canonical root 3	Canonical root 4
Factor 1 SUBST	-0.86	0.43	0.26	0.09
Factor 2 SUBST	0.50	0.69	0.51	-0.12
Factor 3 SUBST	-0.09	0.29	-0.49	-0.82
Factor 4 SUBST	0.11	0.50	-0.65	0.56



Fig. S1. Location of the Błędowska Desert (Southern Poland).

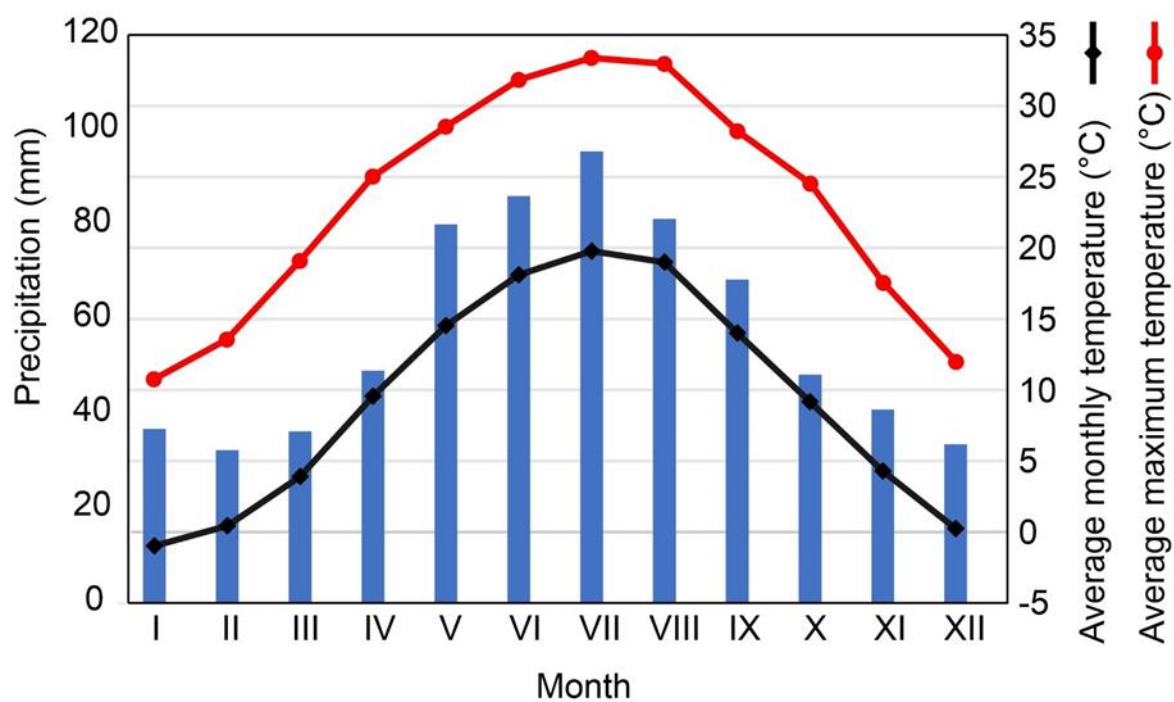


Fig. S2. The climatic diagram for average monthly temperature (black line), average maximum temperature (red line) and precipitation (blue bars) for meteorological station in the study area (IMGW station code: 250190390) calculated for the years 1986-2022.

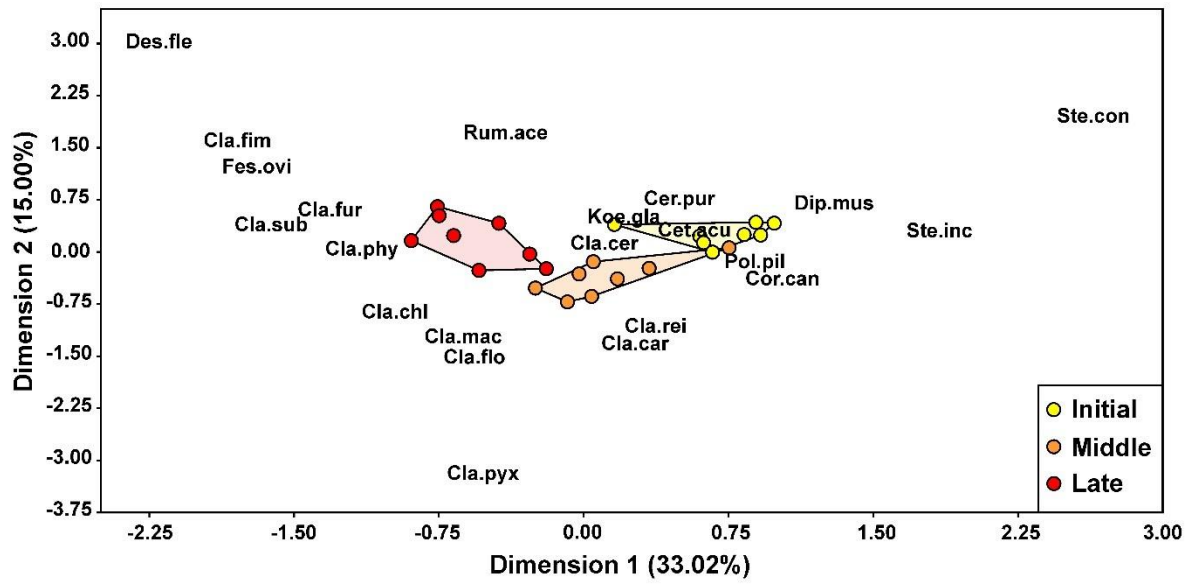


Fig. S3. Correspondence analysis (CA) scatter plot of analysed study plots representing three succession stages and particular species along the first two axes. Abbreviations of species are as follows: Lichens: Cla.fim – *Cladonia fimbriata*; Cla.fur – *Cladonia furcata*; Cla.sub – *Cladonia subulata*; Cla.phy – *Cladonia phyllophora*; Cla.chl – *Cladonia chlorophaea*; Cla.mac – *Cladonia macilenta*; Cla.flo – *Cladonia floerkeana*; Cla.pyx – *Cladonia pyxidata*; Cla.cer – *Cladonia cervicornis*; Cla.rei – *Cladonia rei*; Cla.car – *Cladonia cariosa*; Cet.acu – *Cetraria aculeata*; Dip.mus – *Diploschistes muscorum*; Ste.inc – *Stereocaulon incrustatum*; Ste.com – *Stereocaulon condensatum*; Vascular plants: Des.fle – *Deschampsia flexuosa*; Fes.ovi – *Festuca ovina s. stricto*; Rum.ace – *Rumex acetosella*; Koe.gla – *Koeleria glauca*; Cor.can – *Corynephorus canescens*. Bryophytes: Pol.pil – *Polytrichum piliferum*; Cer.pur – *Ceratodon purpureus*.

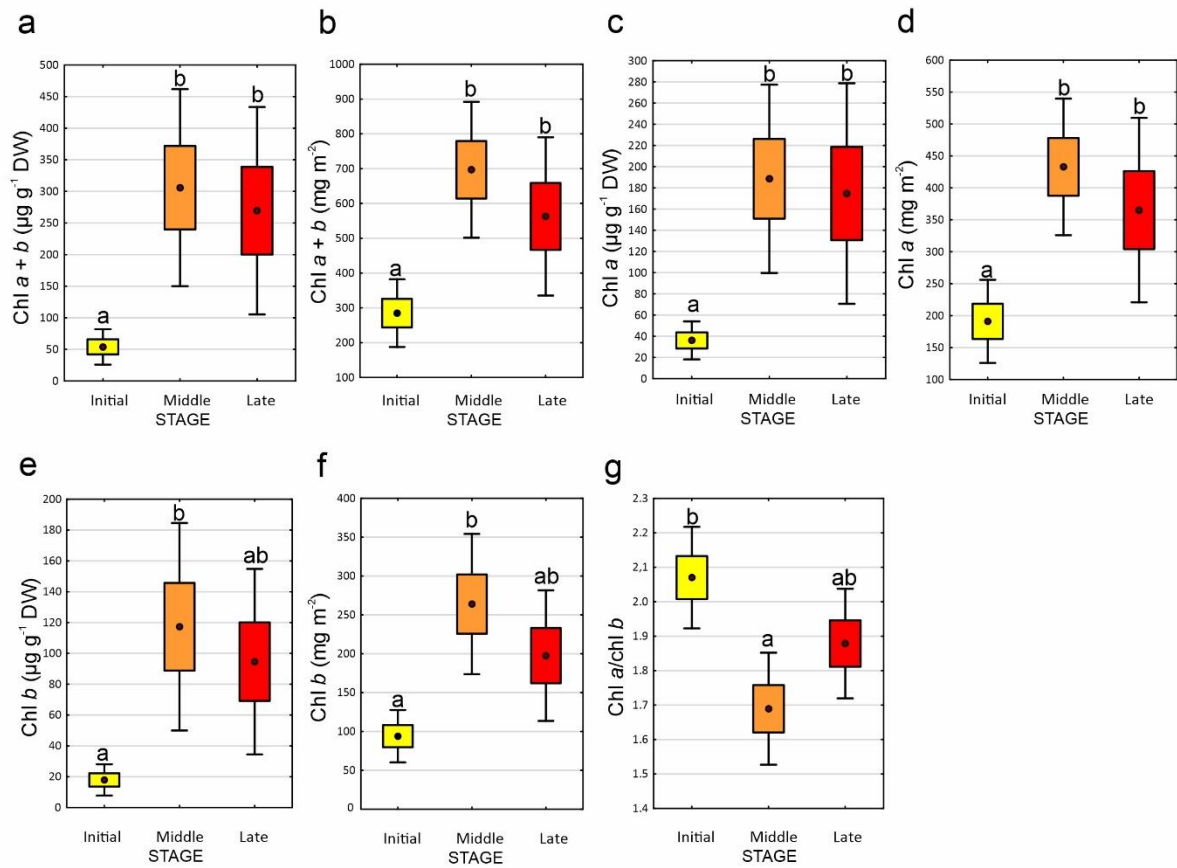


Fig. S4. Parameters related to chlorophyll concentrations in BSCs collected from different succession stages (dot = mean, box = SE, whisker = 95% confidence interval): **a** Chlorophyll $a + b$ concentration ($\mu\text{g g}^{-1}$ DW), **b** Chlorophyll $a + b$ concentration (mg m^{-2}), **c** Chlorophyll a concentration ($\mu\text{g g}^{-1}$ DW), **d** Chlorophyll a concentration (mg m^{-2}), **e** Chlorophyll b concentration ($\mu\text{g g}^{-1}$ DW), **f** Chlorophyll b concentration (mg m^{-2}), **g** Chlorophyll a/b ratio. The various letters above the whiskers indicate statistically significant differences ($p < 0.05$).

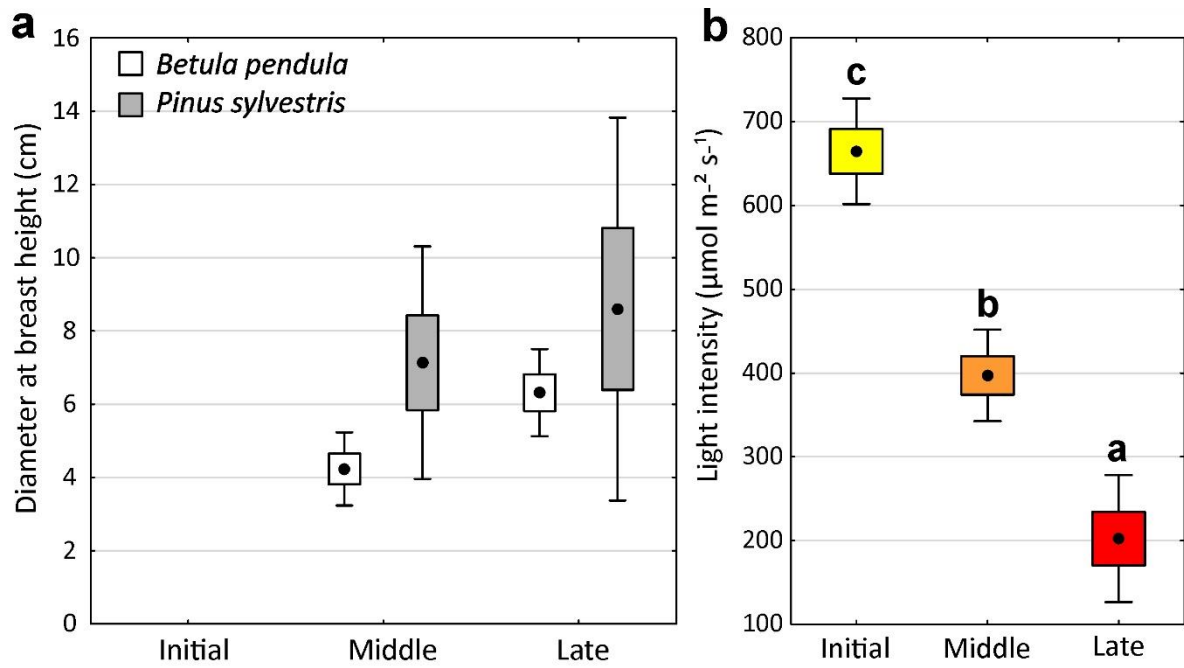


Fig. S5. Diameter at breast height of tree species present at a distance of up to 2 meters from the plot (a) and light intensity measured 150 cm above the plot (b) for plots representing different succession stages (dot = mean, box = SE, whisker = 95% confidence interval). The various letters above the whiskers indicate statistically significant differences ($p < 0.05$).