S1 Establishment patterns

Figure S1. Establishment patterns. Left: random seedling patterns. right: clonal expansion.

S2 Experimental design: doubly balanced sampling algorithm

To ensure a wide range in environmental conditions was covered in the experimental setup we derived auxiliary information from digital terrain models (DTM: (https://downloads.rijkswaterstaatdata.nl/ (last access: 22.11.2023)) for the block selection. From the DTMs we derived three covariates that we considered to potentially correlate with dune-grass establishment: the height above sea level of 2021, the topographical wetness index (i.e. TWI, DTM 2021) and the average yearly change in beach bed level (from 2016 to 2021). The latter was calculated with:

(1)
$$DTM_{\Delta height} = \frac{1}{5}\left[(DTM_{2017} - DTM_{2016}) + (DTM_{2018} - DTM_{2017}) + (DTM_{2019} - DTM_{2018}) + (DTM_{2020} - DTM_{2019}) + (DTM_{2021} - DTM_{2020})\right]$$

We used the k-means clustering algorithm with 5 clusters to identify areas with similar TWI, bed level change and heights (Figure S2).

For each cluster per area, we allocated 15 blocks with the doubly balanced sampling algorithm with equal inclusion probabilities. The algorithm allocates a random sample by spreading it in geographical space, thereby minimizing spatial autocorrelation (Grafström and Tillé 2013).

We used the DTM derived covariates as auxiliary information for balancing the design, which can potentially improve the estimate of the variable of interest (Grafström and Tillé 2013). The center coordinates of the raster pixels (x and y) were used as spreading variables.

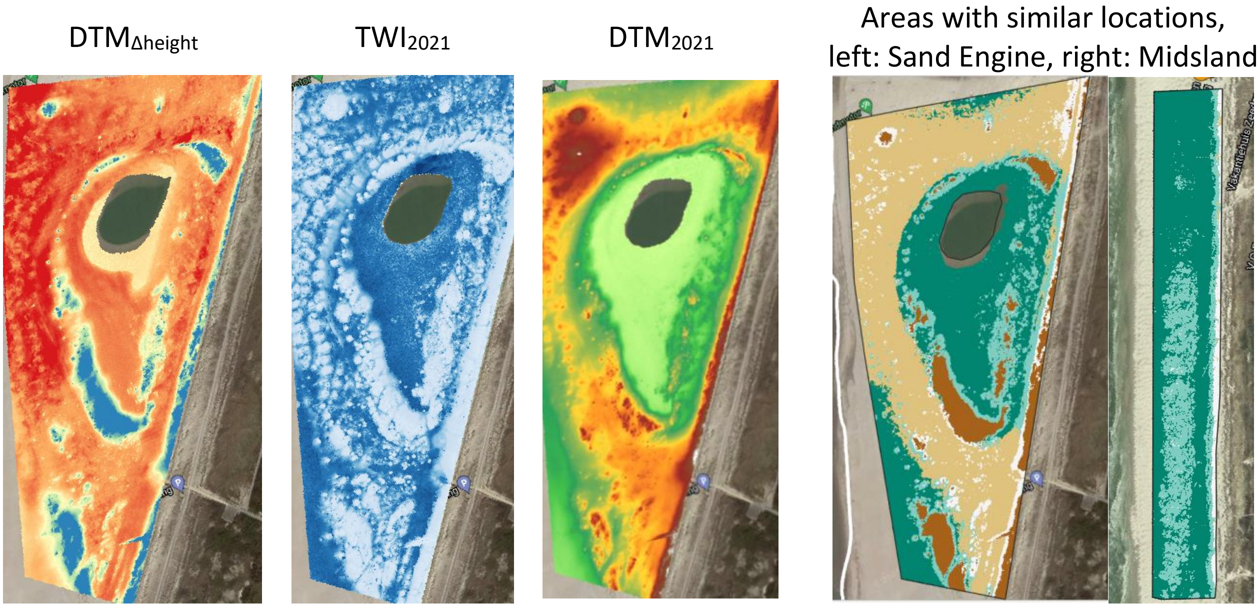

Figure S2. Deriving areas with similar environmental conditions.

S3 Model error distributions and tests

The model error distributions and structure were adjusted based on criteria of normality of residuals, homogeneity of variances and absence of zero inflation. We selected for the model that complied with most or all of these assumptions. Furthermore, we tested concurvity on the worst estimate at a level of 0.5.
For the shoot presence/absence model we used a negative binomial distribution with a logit link. For the establishment success model we used a zero- inflated poisson distribution with a log link and an offset term correcting for the number of introduced plant material in March. In both cases we included possible biotic effects as fixed effects (treatment) and additive effects by varying the smoother over the treatment. Additionally, a tensor interaction between soil moisture and bed level change was included. For the dune formation model we modelled the dune occurrence probability in winter 2023 with a negative binomial distribution with a logit link.
The effect of salinity was tested on smaller dataset, since the WET-2 sensor is only able to record salinity once a soil moisture content of 15 % has been exceeded. This resulted in additional models with a simplified model structure for each of the response variables.

S4 Establishment success model

Full model equation: Shoot number ~ s(Moisture) + s(Bed Level Change) + s(Study area, bs = "re") + s(BlockGroup, bs = "re") + offset(log(Plant Material)) + Treatment + ti(Moisture, Bed Level Change) + s(Moisture, by = Treatment) + s(Bed Level Change, by = Treatment)

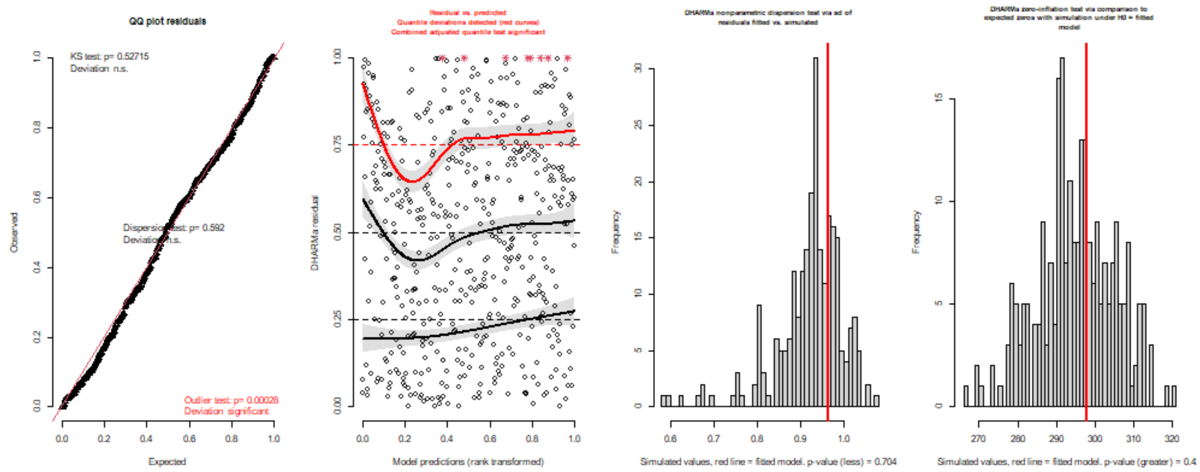

Figure S3. Establishment success checks for normality, zero inflation and overall heterogeneity.

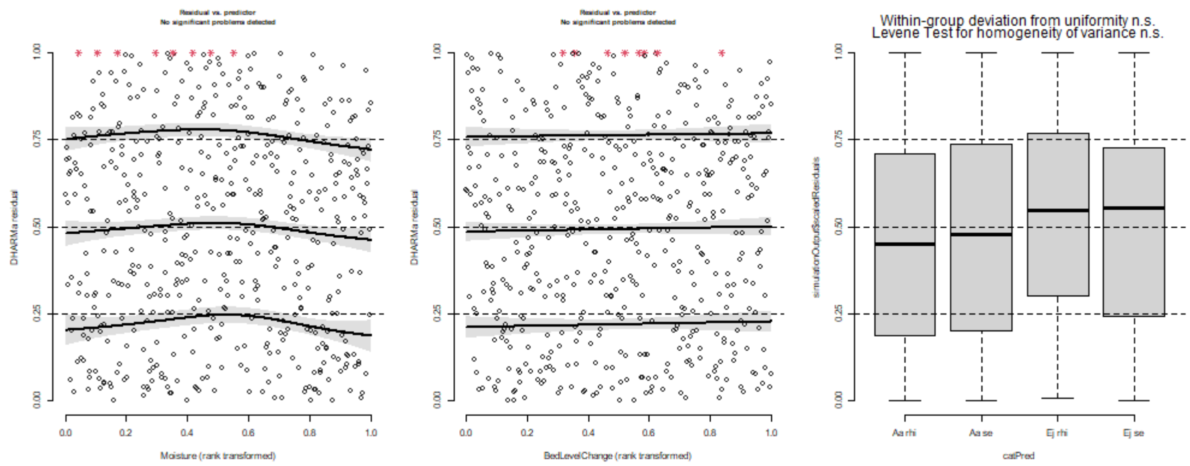

Figure S4: Checks for heterogeneity.

Table S1. Concurvity test under the 0.5 criteria (in blue) and worst model estimate.

	para	s(Moist)	s(BLC)	ti(Moist,BLC)	s(Moist) x Aa rhi	s(Moist) x Aa se	s(Moist) x Ej rhi	s(Moist) x Ej se	s(BLC) x Aa rhi	s(BLC) x Aa se	s(BLC) x Ej rhi	s(BLC) x Ej se
para	1	0	0	0.12	0.01	0	0.01	0.17	0.05	0.01	0.15	0.25
s(Moist)	0	1	0.09	0.75	0.34	0.38	0.52	0.32	0.05	0.04	0.05	0.03
s(BLC)	0	0.09	1	0.96	0.03	0.05	0.05	0.03	0.38	0.98	0.64	0.43
ti(Moist,BLC)	0.12	0.75	0.96	1	0.22	0.28	0.27	0.18	0.47	0.8	0.38	0.25
s(Moist) x Aa rhi	0.01	0.34	0.03	0.22	1	0	0	0	0.18	0	0	0
s(Moist) x Aa se	0	0.38	0.05	0.28	0	1	0	0	0	0.17	0	0
s(Moist) x Ej rhi	0.01	0.52	0.05	0.27	0	0	1	0	0	0	0.19	0
s(Moist) x Ej se	0.17	0.32	0.03	0.18	0	0	0	1	0	0	0	0.69
s(BLC) x Aa rhi	0.05	0.05	0.38	0.47	0.18	0	0	0	1	0	0	0
s(BLC) x Aa se	0.01	0.04	0.98	0.8	0	0.17	0	0	0	1	0	0
s(BLC) x Ej rhi	0.15	0.05	0.64	0.38	0	0	0.19	0	0	0	1	0
s(BLC) x Ej se	0.25	0.03	0.43	0.25	0	0	0	0.69	0	0	0	1

Table *S2*. Model statistics summary establishment success model.

Approximate significance of parametric coefficients	Estimate	Std Error	t-value	p-value	
Intercept	-3.91	0.30	-13.01	0.00	***
Seeds Aa	-3.00	0.24	-12.61	0.00	***
Rhizomes Ej	0.15	0.23	0.65	0.51	
Seeds Ej	-0.00	0.09	-0.01	0.99	
Approximate significance of smooth terms	**edf**	**Ref.df**	**Chisq-value**	**p-value**	
Moisture	0.60	9.00	5.36	0.19	
Change in Bed Level	6.13	9.00	1,370.03	0.00	***
s(Study area)	0.90	3.00	1,307.17	0.22	
s(BlockGroup)	108.43	126.00	2,244.01	0.00	***
Moisture x Change in Bed Level	13.70	16.00	20,123.41	0.00	***
Moisture x Rhizomes Aa	7.62	9.00	1,137.77	0.00	***
Moisture x Seeds Aa	4.42	9.00	305.31	0.00	***
Moisture x Rhizomes Ej	0.00	9.00	0.00	0.50	
Moisture x Seeds Ej	7.62	9.00	3,372.35	0.00	***
Change in Bed Level x Rhizomes Aa	0.00	9.00	0.00	0.15	
Change in Bed Level x Seeds Aa	4.43	9.00	240.29	0.00	***
Change in Bed Level x Rhizomes Ej	6.13	9.00	965.18	0.00	***
Change in Bed Level x Seeds Ej	0.71	9.00	16.95	0.11	

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Adjusted R-squared: NA, Deviance explained 0.903

-REML : 1344.151, Scale est: 1.000, N: 508

Salinity model equation: Shoot number~ s(Moisture) + s(Bed Level Change) + s(Salinity) + s(Study area, bs = "re") + s(BlockGroup, bs = "re") + offset(log(Plant material)) + Treatment + ti(Moisture, Salinity) + ti(Bed Level Change, Moisture)

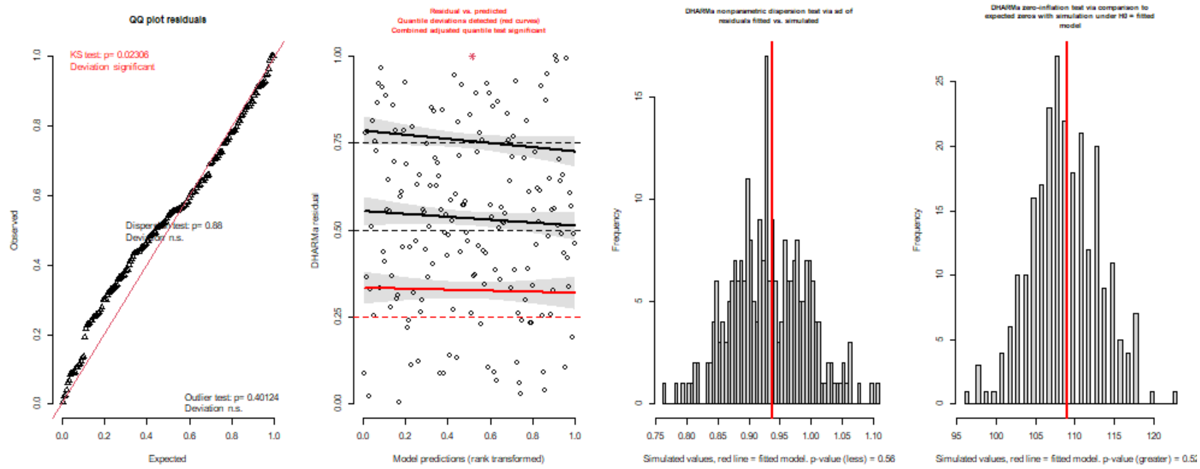

Figure S5. Shoot number salinity for normality, zero inflation and overall heterogeneity.

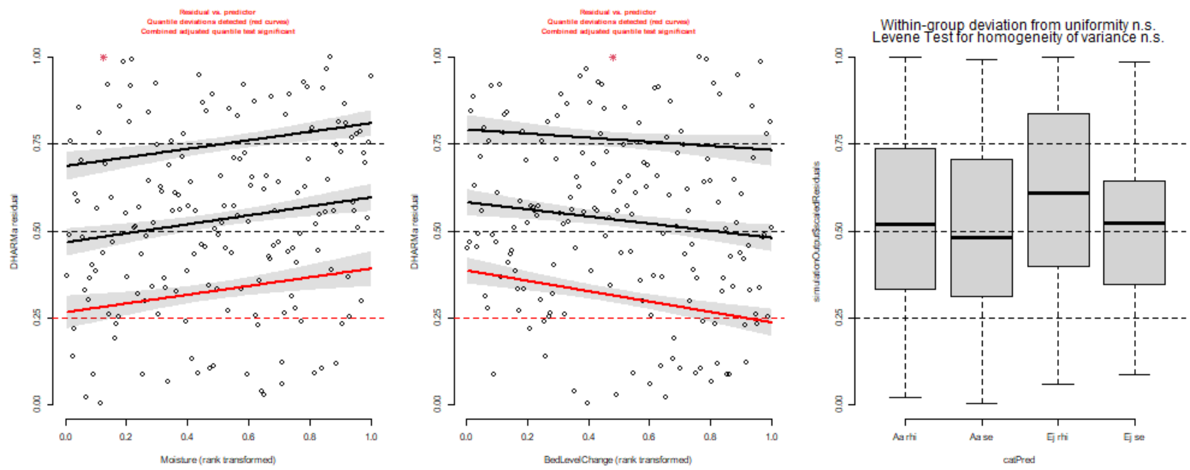

Figure S6 : Checks for heterogeneity.

Table S3. Concurvity test under the 0.5 criteria (in blue) and worst model estimate.

	para	s(Moist)	s(BLC)	s(Salinity)	ti(Moist,Salinity)	ti(Moist,BLC)
para	1	0	0	0	0.57	0.16
s(Moist)	0	1	0.31	0.5	0.98	0.74
s(BLC)	0	0.31	1	0.2	0.49	0.93
s(Salinity)	0	0.5	0.2	1	1	0.38
ti(Moist,Salinity)	0.57	0.98	0.49	1	1	0.75
ti(Moist,BLC)	0.16	0.74	0.93	0.38	0.75	1

Table S4. Model statistics summary salinity model (establishment success).

Approximate significance of parametric coefficients	**Estimate**	**Std Error**	**t-value**	**p-value**	
Intercept	-3.98	0.61	-6.47	0.00	***
Seeds Aa	-2.59	0.12	-22.21	0.00	***
Rhizomes Ej	0.02	0.16	0.10	0.92	
Seeds Ej	-0.16	0.14	-1.19	0.23	
Approximate significance of smooth terms	**edf**	**Ref.df**	**Chisq-value**	**p-value**	
Moisture	7.43	9.00	447.82	-0.00	***
Change in Bed Level	0.00	9.00	0.00	0.72	
Salinity	6.42	9.00	534.88	0.00	***
s(Study area)	0.00	3.00	0.00	0.48	
s(BlockGroup)	35.78	47.00	523.30	0.00	***
Salinity x Moisture	5.89	16.00	333.65	0.03	*
Moisture x Change in Bed Level	6.32	16.00	12,410.13	0.00	***

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Adjusted R-squared: NA, Deviance explained 0. 962

-REML : 402.433, Scale est: 1.000, N: 173

S5 Presence/Absence model:

Full model equation: Plant presence/absence~ s(*Min* Moisture) + s(*Max* Bed Level Change) + s(Study area, bs = "re") + s(BlockGroup, bs = "re") + Treatment + ti(*Min* Moisture, *Max* Bed Level Change) + s(*Min* Moisture, by = Treatment) + s(*Max* Bed Level Change, by = Treatment)

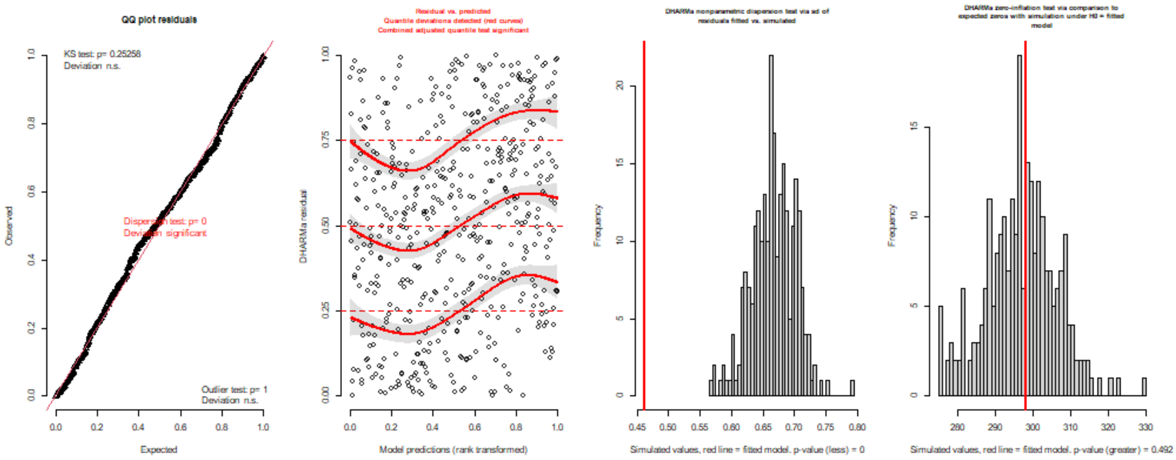

Figure S7 Presence absence of shoot number checks for normality, zero inflation and overall heterogeneity.

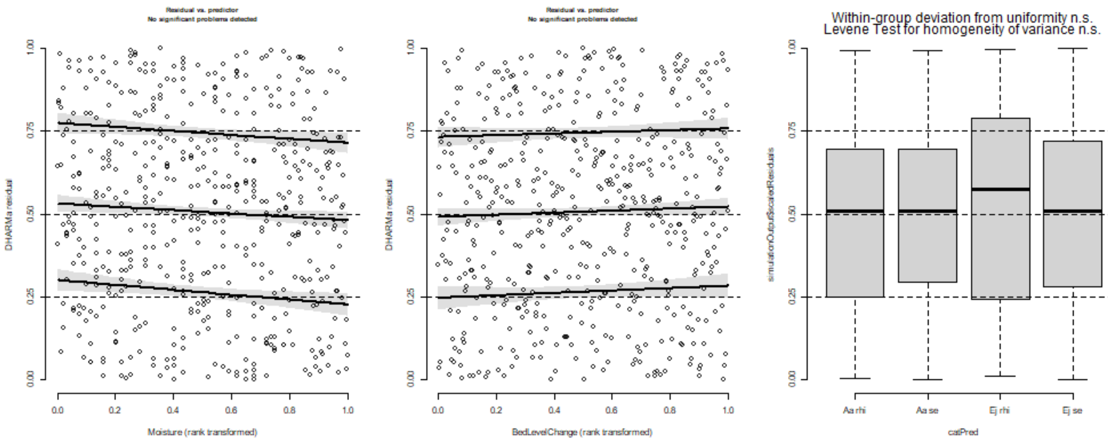

Figure S8 Presence absence of shoot number checks for heterogeneity of individual predictors.

Table S5 Concurvity test under the 0.5 criteria (in blue) and worst model estimate.

	para	s(Moist)	s(BLC)	ti(Moist,BLC)	s(Moist) x Aa rhi	s(Moist) x Aa se	s(Moist) x Ej rhi	s(Moist) x Ej se	s(BLC) x Aa rhi	s(BLC) x Aa se	s(BLC) x Ej rhi	s(BLC) x Ej se
para	1	0	0	0.1	0.2	0.25	0.03	0.24	0.14	0.01	0.01	0.24
s(Moist)	0	1	0.14	0.98	0.76	0.37	0.63	0.33	0.09	0.06	0.07	0.05
s(BLC)	0	0.14	1	0.78	0.05	0.06	0.06	0.06	0.37	0.89	0.49	0.9
ti(Moist,BLC)	0.1	0.98	0.78	1	0.86	0.23	0.81	0.5	0.19	0.52	0.59	0.58
s(Moist) x Aa rhi	0.2	0.76	0.05	0.86	1	0	0	0	0.48	0	0	0
s(Moist) x Aa se	0.25	0.37	0.06	0.23	0	1	0	0	0	0.23	0	0
s(Moist) x Ej rhi	0.03	0.63	0.06	0.81	0	0	1	0	0	0	0.24	0
s(Moist) x Ej se	0.24	0.33	0.06	0.5	0	0	0	1	0	0	0	0.92
s(BLC) x Aa rhi	0.14	0.09	0.37	0.19	0.48	0	0	0	1	0	0	0
s(BLC) x Aa se	0.01	0.06	0.89	0.52	0	0.23	0	0	0	1	0	0
s(BLC) x Ej rhi	0.01	0.07	0.49	0.59	0	0	0.24	0	0	0	1	0
s(BLC) x Ej se	0.24	0.05	0.9	0.58	0	0	0	0.92	0	0	0	1

Table S6 Model statistics summary shoot presence absence model.

Approximate significance of parametric coefficients	**Estimate**	**Std Error**	**t-value**	**p-value**	
Intercept	-1.37	0.34	-3.98	0.00	***
Seeds Aa	0.76	0.32	2.41	0.02	*
Rhizomes Ej	0.27	0.32	0.84	0.40	
Seeds Ej	1.58	0.32	4.89	0.00	***
Approximate significance of smooth terms	**edf**	**Ref.df**	**Chisq-value**	**p-value**	
Moisture	0.00	9.00	0.00	0.54	
Change in Bed Level	4.57	9.00	85.68	0.00	***
s(Study area)	0.98	3.00	3.97	0.26	
s(BlockGroup)	72.80	126.00	135.28	0.00	***
Moisture x Change in Bed Level	0.46	16.00	0.71	0.26	
Moisture x Rhizomes Aa	0.00	9.00	0.00	0.88	
Moisture x Seeds Aa	0.23	9.00	0.30	0.29	
Moisture x Rhizomes Ej	0.00	9.00	0.00	0.79	
Moisture x Seeds Ej	0.00	9.00	0.00	0.57	
Change in Bed Level x Rhizomes Aa	0.00	9.00	0.00	0.44	
Change in Bed Level x Seeds Aa	0.00	9.00	0.00	0.85	
Change in Bed Level x Rhizomes Ej	0.00	9.00	0.00	0.63	
Change in Bed Level x Seeds Ej	0.00	9.00	0.00	0.46	

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Adjusted R-squared: 0.450, Deviance explained 0.458

-REML : 286.728, Scale est: 1.000, N: 508

Salinity model equation: Plant presence/absence ~ s(*Min* Moisture) + s(*Max* Bed Level Change) + s(*Max* Salinity) + s(Study area, bs = "re") + s(BlockGroup, bs = "re") + Treatment + ti(*Min* Moisture, *Max* Salinity) + ti(*Max* Bed Level Change, Moisture)

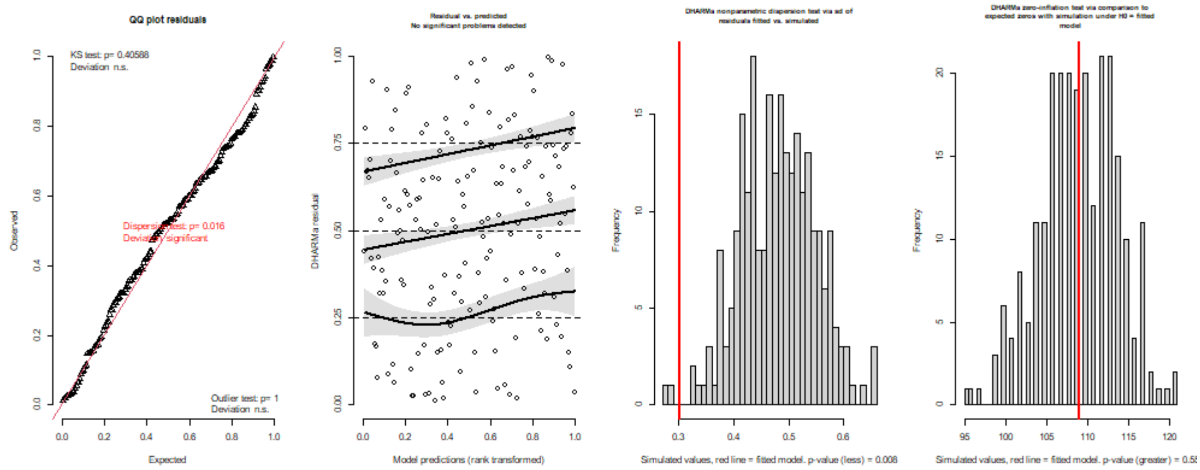

Figure S9 Shoot presence/absence checks for normality, zero inflation and overall heterogeneity.

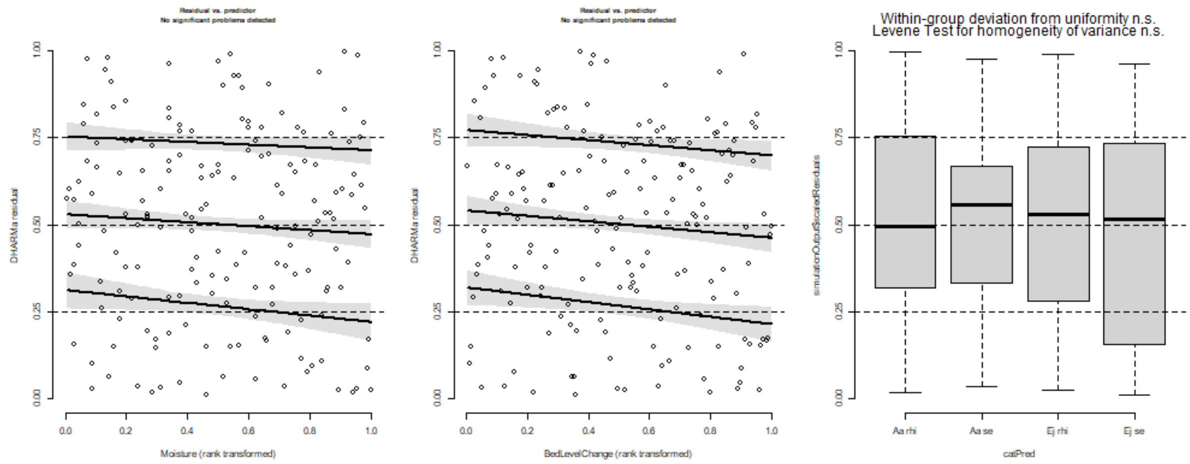

Figure S10 : Checks for heterogeneity.

Table S7 Concurvity test under the 0.5 criteria (in blue) and worst model estimate.

	para	s(Moist)	s(BLC)	s(Salinity)	ti(Moist,Salinity)	ti(Moist,BLC)
para	1	0	0	0	0.31	0.19
s(Moist)	0	1	0.24	0.26	0.93	0.99
s(BLC)	0	0.24	1	0.21	0.31	0.91
s(Salinity)	0	0.26	0.21	1	0.99	0.33
ti(Moist,Salinity)	0.31	0.93	0.31	0.99	1	0.97
ti(Moist,BLC)	0.19	0.99	0.91	0.33	0.97	1

Table S8 Model statistics summary shoot presence absence salinity model.

Approximate significance of parametric coefficients	**Estimate**	**Std Error**	**t-value**	**p-value**	
Intercept	-4.90	0.74	-6.67	0.00	***
Seeds Aa	-3.29	0.67	-4.93	0.00	***
Rhizomes Ej	0.21	0.66	0.32	0.75	
Seeds Ej	-0.20	0.66	-0.31	0.76	
Approximate significance of smooth terms	**edf**	**Ref.df**	**Chisq-value**	**p-value**	
Moisture	0.00	9.00	0.00	0.63	
Change in Bed Level	0.00	9.00	0.00	0.79	
Salinity	0.00	9.00	0.00	0.66	
s(Study area)	0.59	3.00	3.09	0.55	
s(BlockGroup)	34.24	47.00	69.05	0.01	**
Salinity x Moisture	1.41	16.00	7.84	0.23	
Moisture x Change in Bed Level	0.12	16.00	0.13	0.45	

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Adjusted R-squared: 0.612, Deviance explained 0.711

-REML : 88.714, Scale est: 1.000, N: 173

S6 Dune formation model:

Equation: Dune presence/absence ~ s(Moisture) + s(Bed Level Change) + s(BlockGroup, bs = "re") + s(Shoot number) + s(Study area, bs = "re") + ti(Moisture, Bed Level Change) + ti(Moisture, Shoot number) + ti(Bed Level Change, Shoot number) + ti(Bed Level Change, Shoot number, Moisture)

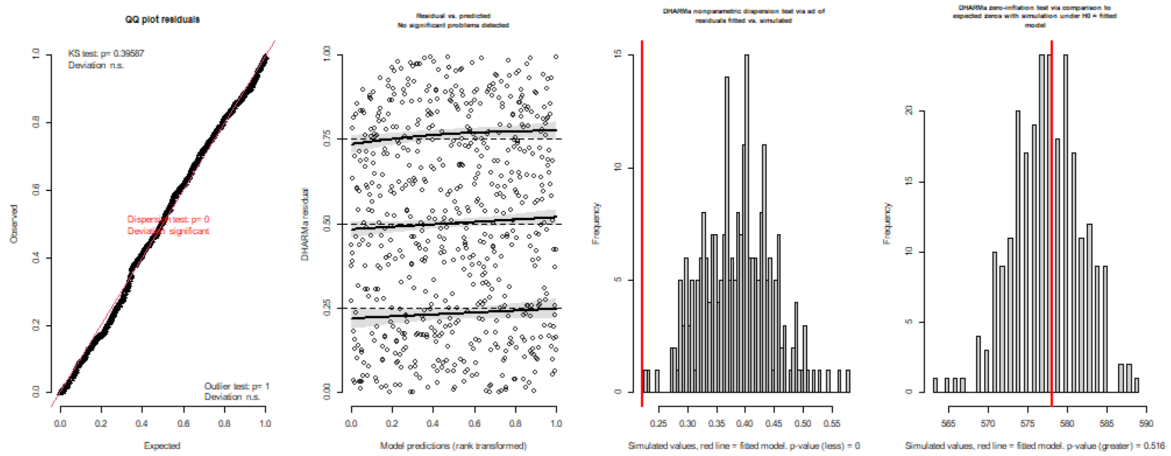

Figure S11. Dune formation checks for normality, zero inflation and overall heterogeneity.

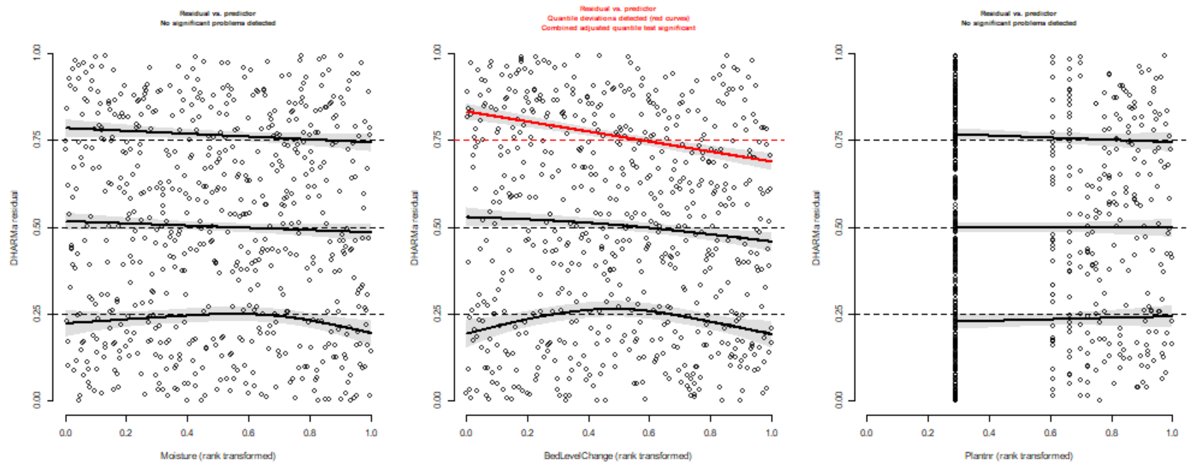

Figure S12: Checks for heterogeneity.

Table S9 Concurvity test under the 0.5 criteria (in blue) and worst model estimate.

	para	**s(Moist)**	**s(BLC)**	**s(Shoot nr)**	**ti(Moist,BLC)**	**ti(Moist,Shoot nr)**	**ti(BLC,Shoot nr)**	**ti(BLC,Shoot nr,Moist)**
para	1	0	0	0	0.1	0.04	0.2	0.19
s(Moist)	0	1	0.09	0.06	0.72	0.54	0.13	0.41
s(BLC)	0	0.09	1	0.06	0.94	0.08	0.99	0.94
s(Shoot nr)	0	0.06	0.06	1	0.13	1	1	1
ti(Moist,BLC)	0.1	0.72	0.94	0.13	1	0.26	0.93	1
ti(Moist,Shoot nr)	0.04	0.54	0.08	1	0.26	1	0.99	1
ti(BLC,Shoot nr)	0.2	0.13	0.99	1	0.93	0.99	1	1
ti(BLC,Shoot nr,Moist)	0.19	0.41	0.94	1	1	1	1	1

Table S10 Model statistics summary dune formation model.

Approximate significance of parametric coefficients	**Estimate**	**Std Error**	**t-value**	**p-value**	
Intercept	-4.24	0.98	-4.31	0.00	***
Approximate significance of smooth terms	**edf**	**Ref.df**	**Chisq-value**	**p-value**	
Moisture	1.71	9.00	30.61	0.06	.
Change in Bed Level	0.00	9.00	0.00	0.87	
s(BlockGroup)	29.80	126.00	42.68	0.01	*
s(Shoot number)	3.29	9.00	77.81	0.00	***
s(Study area)	2.29	3.00	13.75	0.06	.
Moisture x Bed level change	1.47	16.00	3.53	0.28	
Moisture x Shoot number	0.00	16.00	0.00	0.95	
Shoot number x Bed level change	1.62	10.00	17.46	0.00	**
Bed level change x Shoot number x Moisture	1.39	55.00	2.61	0.17	

Signif. codes: 0 <= '***' < 0.001 < '**' < 0.01 < '*' < 0.05

Adjusted R-squared: 0.762, Deviance explained 0.761

-REML : 96.093, Scale est: 1.000, N: 635

S7 Establishment dynamics during summer and winter

During the summer period shoot numbers increased on average on Terschelling, though the initial increase after the experimental setup was relatively small compared to the Sand Engine and coincided with a period of little precipitation (36 mm / month) and the highest average burial rate recorded (1.6 cm/month), though soil moisture measured in May 2022 was relatively high (12%) (Figure S13).

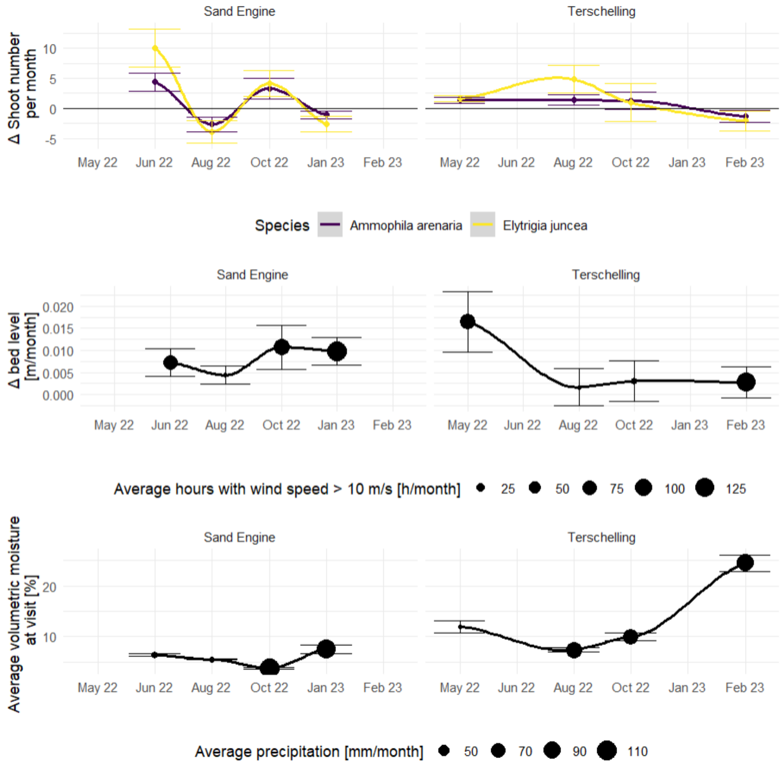

Figure S13. Establishment dynamics over summer and winter. In the lower two panels the size of the points represent the magnitude of measured climatic variables that can potentially explain the observed field conditions. Error bars are confidence interval.

Shoot numbers on the Sand Engine mostly increased during the summer period, except from June to August 2022 where a notable reduction in shoot numbers occurred. It coincided with the second lowest precipitation amount recorded (36 mm/month), with relatively low measured moisture (5.51 %). However, this period also had little burial.

During winter there was an average reduction in shoot numbers at both study areas which coincided with an increase in recorded climatic conditions and environmental conditions, most notably in volumetric moisture.

S8 Shoot presence/absence

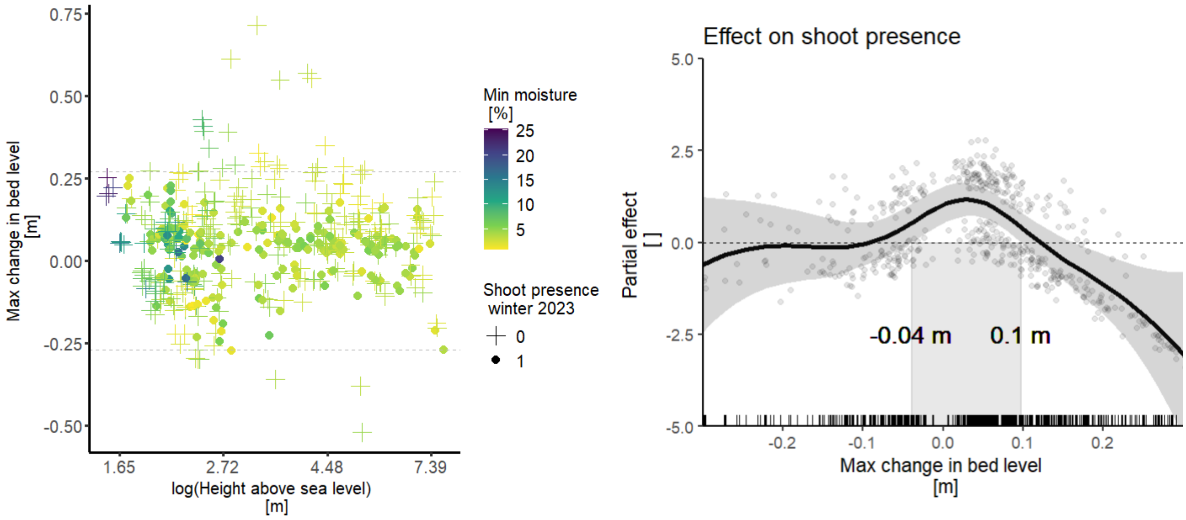

Figure S14. The effect of abiotic conditions on shoot presence at the onset of winter 2023. (a) Environmental conditions (minimum moisture and maximum average change in bed level) and shoot presence onset of winter 2023, across beach height gradients. (b) modelled effect of maximum bed level change on shoot presence.

Supplementary References

Grafström, A., and Y. Tillé. 2013. Doubly balanced spatial sampling with spreading and restitution of auxiliary totals. Environmetrics 24:120–131.