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Narrowing down dune establishment drivers on the beach

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S1 Establishment patterns

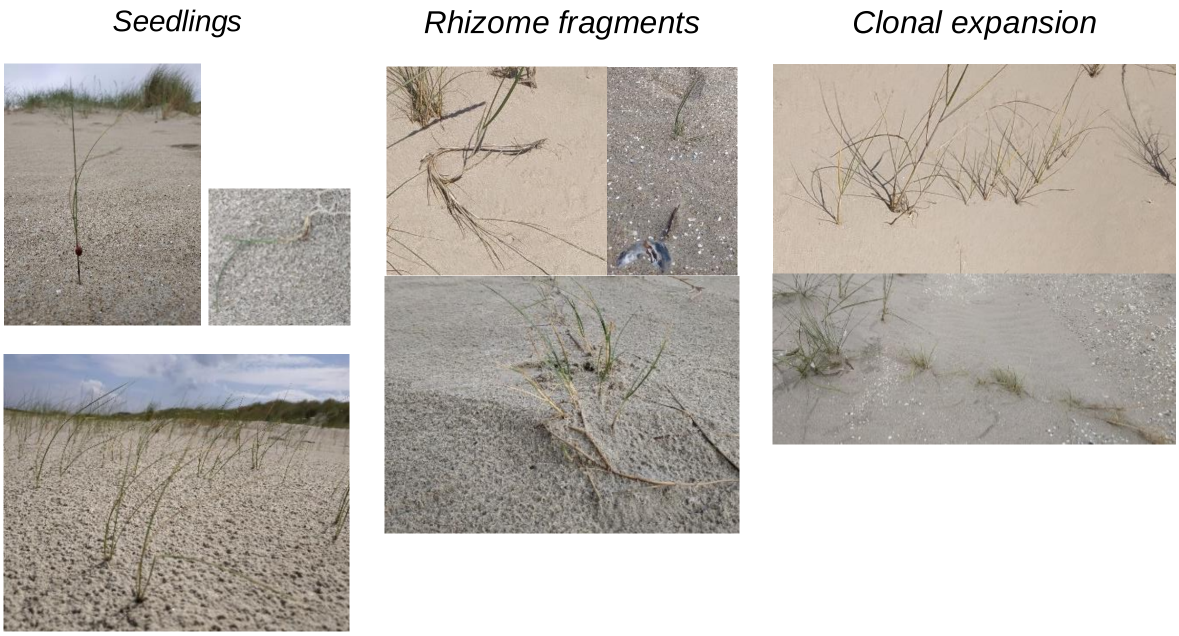

Figure S1. Establishment patterns used to identify seedling establishment.

S2 Experimental design

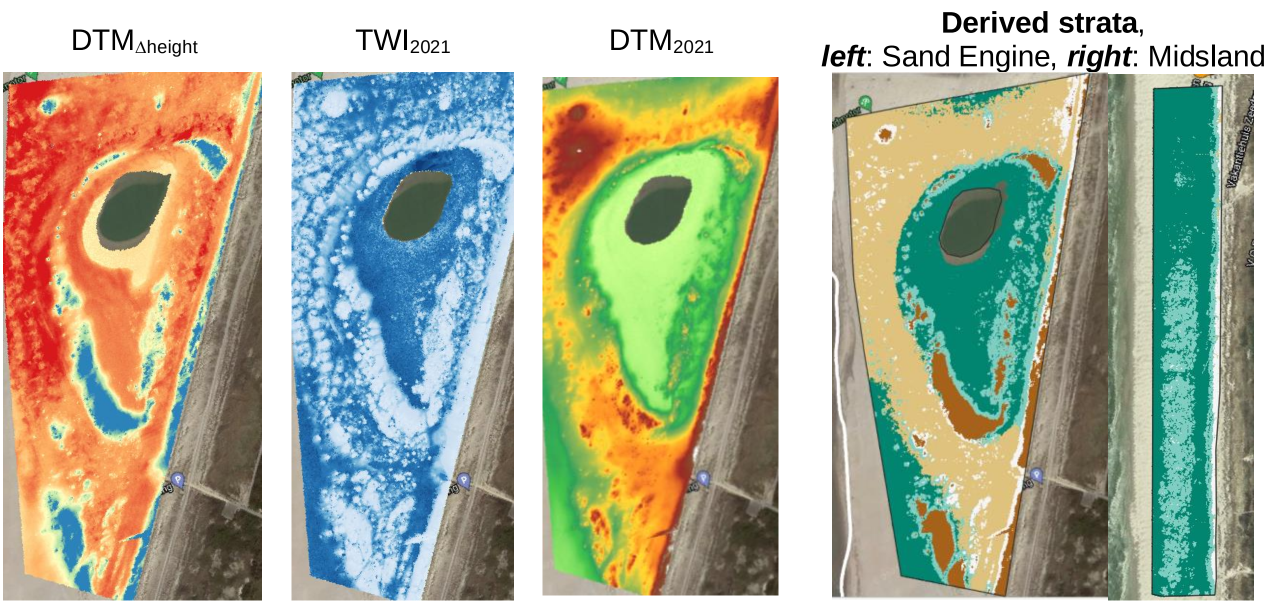

Figure S2. Covariates and derived strata (i.e., areas with similar environmental conditions). The example for derivation at the sand engine is shown. Final Strata for the Sand Engine and Midsland can be seen on the right.

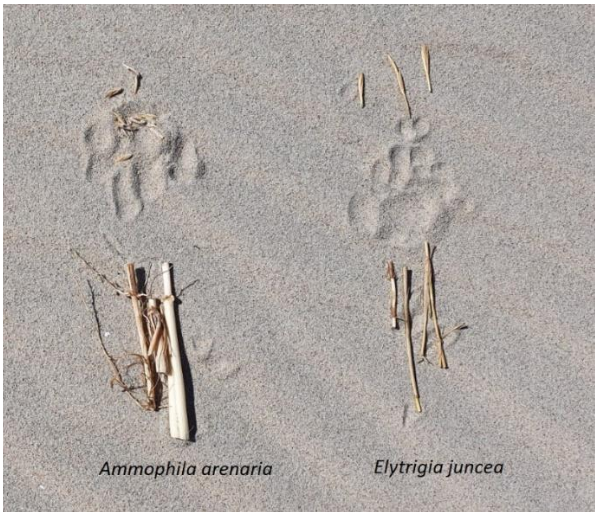

Figure S3*.* Introduced seeds (top) and rhizome pieces (bottom) per species.

Figure S4*.* Pictures of the different treatments and emerged shoots taken at the Sand Engine on August 2022. From top to bottom: Block 22 (showing no establishment), Block 37, Block 65 and Block 66 (the latter with substantial establishment). The yellow markers were placed at the measured corners and removed after each measurement round.

S3 Gam structure: Establishment success models

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

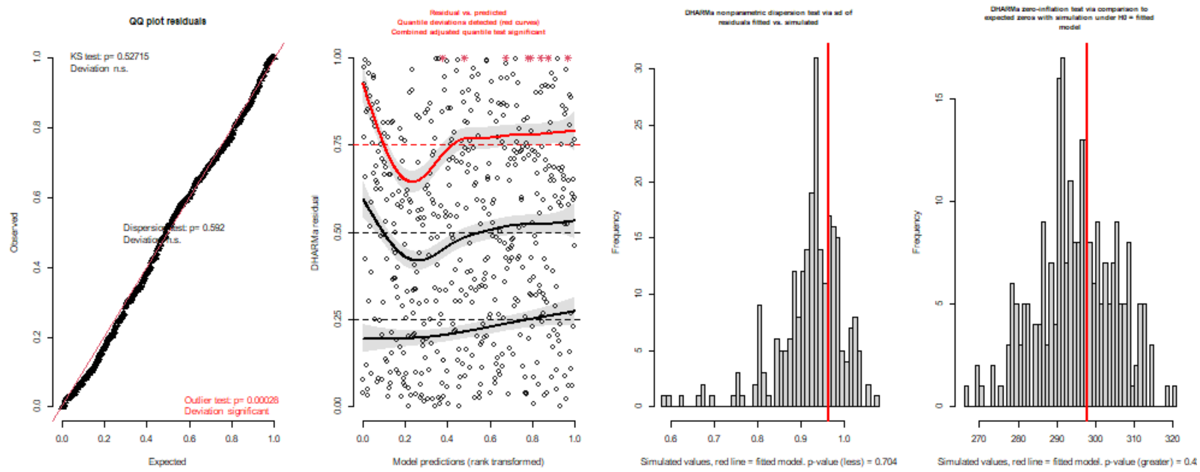

Figure S5. Establishment success checks for normality, zero inflation and overall heterogeneity.

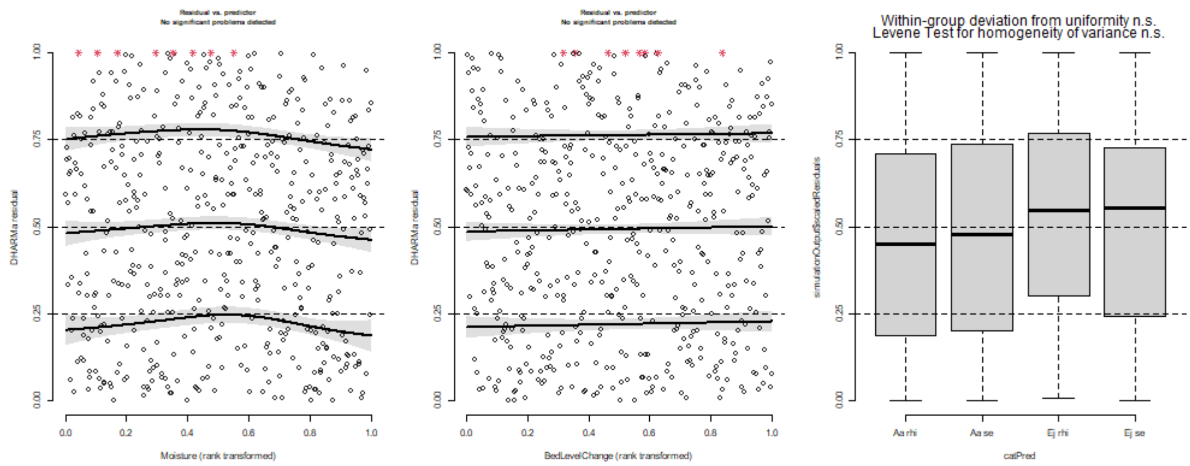

Figure S6. Checks for heterogeneity.

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(Block)	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(Block, bs = "re") + offset(log(Plant material)) + Treatment + ti(Moisture, Salinity) + ti(Bed Level Change, Moisture)

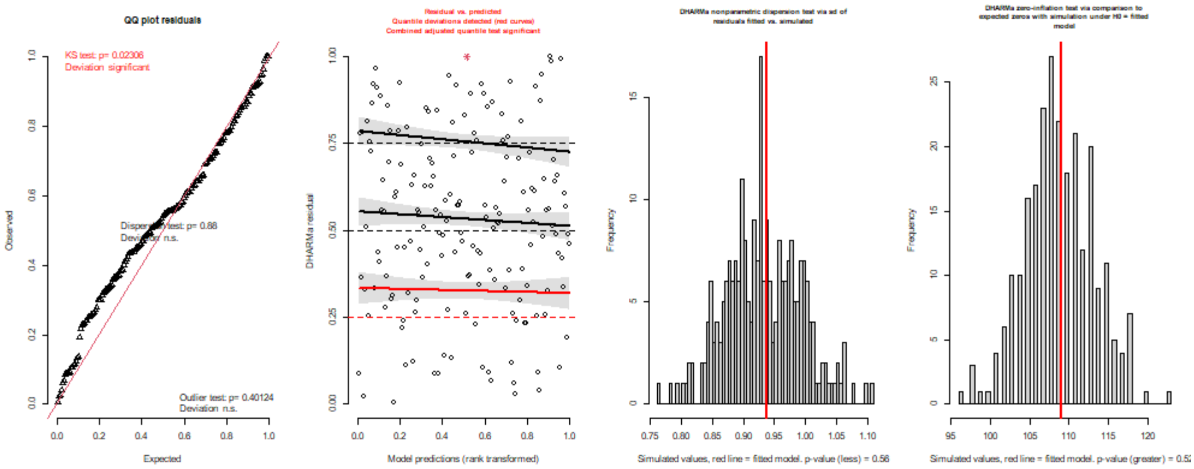

Figure S7. Shoot number salinity for normality, zero inflation and overall heterogeneity.

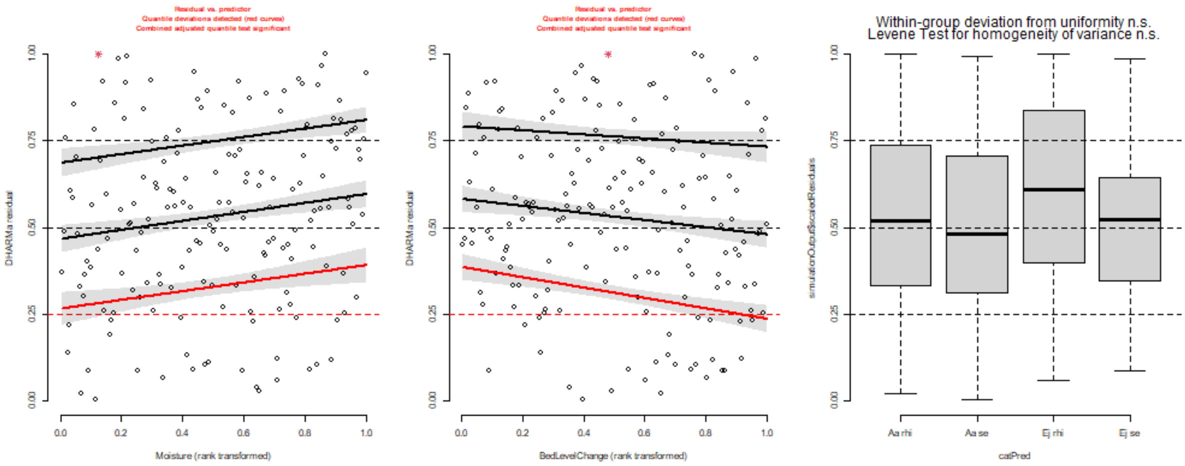

Figure S8. Checks for heterogeneity.

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(Block)	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

S4 Gam structure: Dune initiation model

Equation: Dune presence/absence ~ s(Moisture) + s(Bed Level Change) + s(Block, 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)

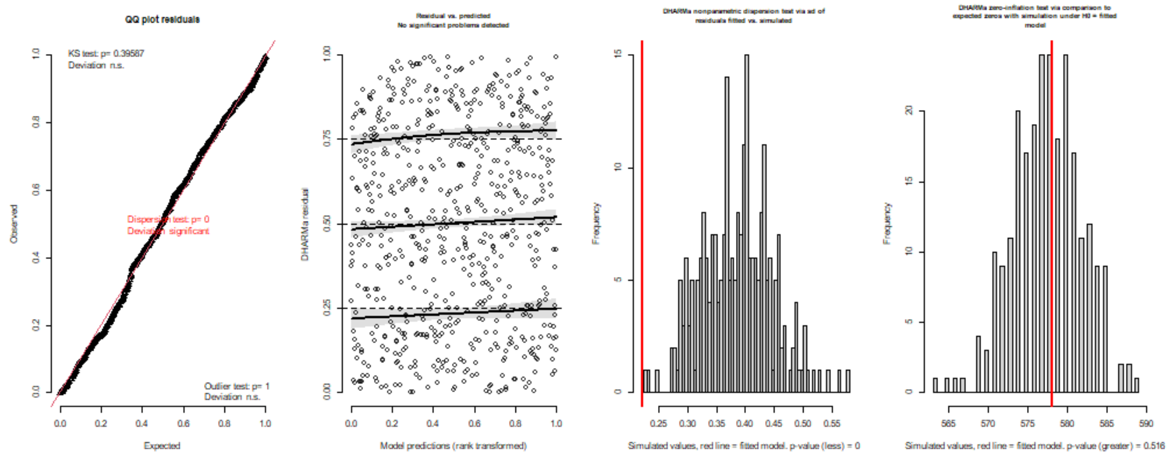

Figure S9. Dune formation checks for normality, zero inflation and overall heterogeneity.

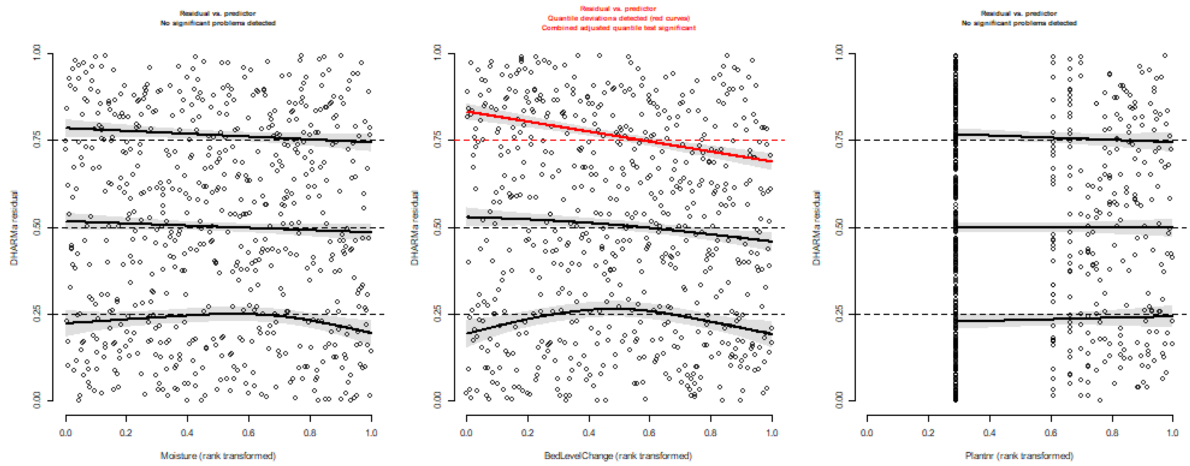

Figure S10. Checks for heterogeneity.

Table S5. 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 S6 Model statistics summary dune initiation 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(Block)	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

S5 Sensitivity analysis

Since not all plots were visited at the last monitoring moment a sensitivity analysis was performed to assess the potential impact of excluding blocks on the output of the main establishment success model. 23 blocks (i.e., 15% of plots) had been excluded based on the criteria that no plant emergence had been recorded at any monitoring moment.

We used two strategies:

1. ***Adding conditional plot data at random:*** We first created a subset from the original dataset which should represent conditions of excluded blocks. Therefore, we selected plots without any shoot emergence at any monitoring moment and plots where shoot emergence occurred at the last monitoring moment only (to account for spontaneous shoot emergence in the last monitoring moment). From this subset we sampled the equivalent of 23 blocks at random with replacement and added them to the original data set.

2. ***Removing conditional plot data at random:*** We randomly removed 15% of plots using the same criteria as mentioned above (no shoot emergence, shoot emergence in monitoring moment 4 only).

The random sampling was repeated a 100 times per strategy and at each iteration we fitted the gam model. We then assessed changes in predictions, p-values and smoother estimates.

The exclusion of blocks likely led to an increase in the average establishment success by 0.1% - 0.12 %. The establishment success per treatment likely increased by 0.11 % (Ammophila seeds) – 2.9 % (Ammophila rhizomes) (see Table S7).

Table *S7*. Average establishment success and standard deviation of the prediction as predicted from gam models.

Strategy	Average Establishment success	Average establishment success per treatment			
		Aa se	Aa rhi	Ej se	Ej rhi
Added plot data (+15% plots)	0.62% ± 0.005%	0.60% ± 0.02%	9.7% ± 0.4%	10.2% ± 0.3%	5.9% ± 0.4%
Removed plot data (-15% plots)	0.85% ± 0.009%	0.84% ± 0.03%	14.5% ± 0.78%	12.3 % ± 0.28%	7.6% ± 0.63%
Original model	0.72%	0.71%	11.6%	11.2%	6.3%

The predicted relationship between establishment success, soil moisture and bed level change mostly staid the same (Figure S11). Moreover, under the significance criteria of $p < 0.05$, the same conclusions about the significance of the predictors would have been reached (Table S8).

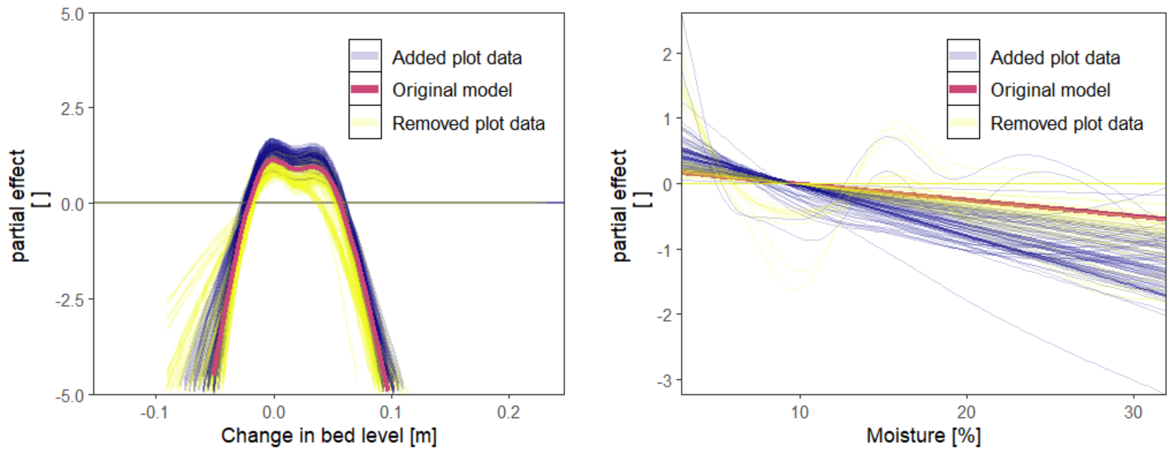

Figure S11. Results of the sensitivity analysis. The originally fitted model (see S3 Gam structure) is plotted as a reference in dark red. *Note:* Unlike in the main manuscript these figures do not include confidence intervals. In the original model the negative effect of soil moisture on establishment was found to be insignificant (see Table S8).

Table *S8*. p-values of the original model and average p-values and standard deviation per sampling strategy.

Model term	**Original model**	**Added plot data** (+15% plots)	**Removed plot data** (-15% plots)
Intercept	0.00	0.00 ±0.00	0.00 ±0.00
Seeds Aa	0.00	0.00 ±0.00	0.00 ±0.00
Rhizomes Ej	0.51	0.54 ±0.21	0.62 ±0.24
Seeds Ej	0.99	0.73 ±0.22	0.60 ±0.26
Moisture	0.19	0.07 ±0.14	0.46 ±0.40
Change in Bed Level	0.00	0.02 ±0.10	0.02 ±0.14
s(Study area)	0.22	0.22 ±0.04	0.14 ±0.05
s(Block)	0.00	0.00 ±0.00	0.00 ±0.00
Moisture x Change in Bed Level	0.00	0.00 ±0.00	0.00 ±0.00
Moisture x Rhizomes Aa	0.00	0.00 ±0.00	0.00 ±0.00
Moisture x Seeds Aa	0.00	0.01 ±0.04	0.00 ±0.00
Moisture x Rhizomes Ej	0.50	0.50 ±0.19	0.62 ±0.32
Moisture x Seeds Ej	0.00	0.00 ±0.00	0.00 ±0.00
Change in Bed Level x Rhizomes Aa	0.15	0.11 ±0.13	0.13 ±0.21
Change in Bed Level x Seeds Aa	0.00	0.00 ±0.00	0.01 ±0.05
Change in Bed Level x Rhizomes Ej	0.00	0.00 ±0.00	0.00 ±0.00
Change in Bed Level x Seeds Ej	0.11	0.07 ±0.08	0.10 ±0.15

S6 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 S12).

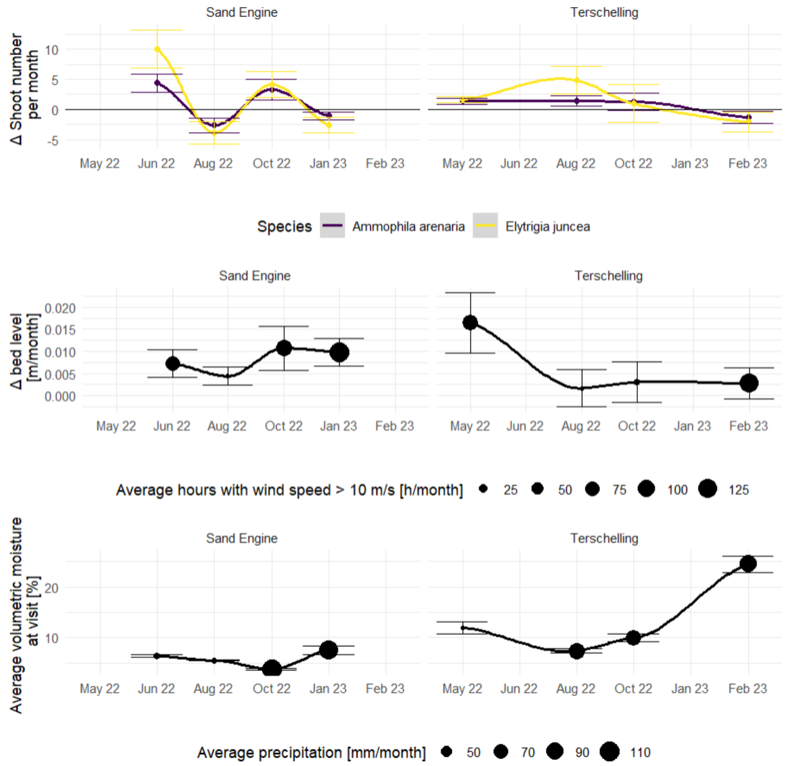

Figure S12. Establishment dynamics over summer and winter. In the lower two panels the size of the points represent the magnitude of measured climatic variables that can potentially explain the observed field conditions. Error bars are confidence interval.

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.