

Supplementary Material

1 Extended Data Analysis Methods

To implement our structural equation models, we first formulated an *a priori* model that specifies how different measurements are expected to be interrelated (see Supplementary Figure 1). The model structure reflected the temporal order in which different data were measured. For example, biocrust properties were measured at the beginning of the experiment and thus presented a pre-existing factor that might lead to different outcomes; consequently, we accounted for a biocrust influence on all other variables. To improve interpretability of models, we constructed our models using cover data from the focal time point, and emergence data from the last available previous observation. For example, our models for June 2017 used emergence data obtained in May 2017. This practice makes us more confident in predicting directed effects of emergence on cover; had we used observations from the same moment in time it would have been plausible that cover also influenced emergence, or that both are simultaneously affected by an external variable such as a weather or herbivory event, complicating our interpretation. Finally, our management outcomes data were final and static, measured or calculated at the end of the 2-year experiment. Although these data are static, the effects of plant community properties could vary among time points in any given model because the plant community data varied among time points. We can interpret these effects as measuring how predictive a plant community property is of an outcome in a given moment. Our *a priori* model features the use of composite variables to pool the joint effects of biocrust total cover, biocrusts species richness, and proportional moss cover, measured just prior to seeding, on other variables. Each composite provides a single path coefficient for all biocrust effects on a given response. A composite is modeled as a latent variable influenced by its indicators rather than vice-versa, with a residual variance of 0. We created separate composite variables for the biocrust effects on exotic and native emergence, exotic and native cover, and management outcomes; this practice allows the weights of the individual biocrust properties to vary by response variable.

Second, we conducted diagnostics, checking model assumptions, emphasizing linearity. We also checked bivariate correlations between pairs of variables in our models to alert us to potential for multicollinearity and did not find high potential for that problem. Although SEM does make distribution assumptions, these can be relaxed by using bootstrap-based methods. We transformed data only when: 1. Departure from a normal distribution was extreme and easily detected visually, 2. The transformation visibly improved normality, and 3. The transformed data had an improved linear fit against other variables (e.g., fewer outliers, more heterogeneous variance, or higher R^2 , in descending order of importance). A cube root transformation was beneficial for fecundity and total biomass, while a square root transformation was beneficial for cover data.

Third, we tested fit of our *a priori* model in ambient rainfall and irrigated pots for each time point individually. In this process, we discovered some borderline and poor fits that were resolved by the addition of a path at some points in the irrigated dataset only: native emergence → exotic cover. Our sample size of 60 per model was slightly low for our model complexity; the problem most likely to occur due to low sample size would be low power in probability tests, in overall model fit tests, and tests of path coefficients. We buffered ourselves against this issue by adopting less sample-size sensitive tests and indicators of fit, including the Jöreskog-Sörbom GFI index (Jöreskog and Sörbom

1984), the Bollen-Stine bootstrap test of fit (Bollen and Stine 1992), and bootstrap tests of paths, alongside more traditional tools. Bootstrap goodness of fit tests proved to be sensitive to removal of key paths, and bootstrap tests of paths proved sensitive enough to distinguish most moderate ($r = 0.20 - 0.30$), and some minor effects (r as low as 0.17) from zero, giving us confidence that our methods were sufficiently powerful.

Fourth, we fit and parameterized the final models, including one of the four final management outcomes in each model. We repeated the same process for each additional management outcome, substituting only a new management outcome but keeping the rest of the model the same. The result was a series of 72 parameterized models (9 time points $\times$ 2 water availabilities $\times$ 4 management outcomes).

2 Supplementary Tables

Supplementary Table 1. Direct effects of overall biocrust condition (unsigned), individual biocrust attributes, and exotic and native emergence on cover of exotics, expressed as standardized path coefficients. Bootstrap probabilities are based on 5000 bootstrap samples and 95% confidence intervals. - = not estimated

Group	Mo.	Yr.	Biocrust cond.	Boot. <i>p</i> =	Tot. cover	Rich.	Prop. Moss	Ex. Emerge.	Boot. <i>p</i> =	Nat. Emerge.	Boot. <i>p</i> =	<i>R</i> ²
Amb.	Jun	2017	0.24	0.009	-0.03	-0.11	0.17	0.38	0.007	-	-	0.20
	Jul	2017	0.26	0.01	-0.19	-0.02	0.20	0.23	0.06	-	-	0.13
	Aug	2017	0.19	0.10	-0.13	-0.08	0.07	0.24	0.05	-	-	0.11
	Sep	2017	0.16	0.07	-0.07	-0.07	0.10	0.61	0.0004	-	-	0.41
	May	2018	0.16	0.23	-0.11	0.11	0.16	0.16	0.27	-	-	0.06
	Jun	2018	0.25	0.03	-0.12	-0.10	0.16	0.33	0.01	-	-	0.17
	Jul	2018	0.27	0.04	-0.10	-0.22	-0.01	0.43	0.0009	-	-	0.25
	Aug	2018	0.26	0.04	-0.11	-0.21	-0.04	0.42	0.001	-	-	0.25
	Sep	2018	0.26	0.03	-0.11	-0.22	-0.06	0.44	0.001	-	-	0.27
Irr.	Jun	2017	0.11	0.37	-0.05	0.11	0.10	0.39	0.005	-0.30	0.002	0.23
	Jul	2017	0.07	0.31	-0.04	-0.03	0.05	0.30	0.06	-0.38	0.003	0.15
	Aug	2017	0.06	0.49	-0.01	0.07	0.04	0.53	0.0004	-0.33	0.03	0.31
	Sep	2017	0.21	0.04	-0.12	0.23	0.12	0.59	0.0004	-0.29	0.007	0.46
	May	2018	0.31	0.004	-0.02	0.31	-0.01	0.21	0.18	-0.19	0.19	0.20
	Jun	2018	0.27	0.004	-0.22	0.22	0.03	0.35	0.009	-0.30	0.02	0.30
	Jul	2018	0.08	0.60	-0.05	0.09	0.04	0.42	0.002	0.03	0.75	0.20
	Aug	2018	0.06	0.67	-0.02	0.07	0.02	0.41	0.001	0.05	0.62	0.19

Sep	2018	0.08	0.61	-0.02	0.09	0.01	0.42	0.002	0.03	0.76	0.20
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Supplementary Table 2. Direct effects of overall biocrust condition (unsigned), individual biocrust attributes, and native emergence on cover of natives, expressed as standardized path coefficients. Bootstrap probabilities are based on 5000 bootstrap samples and 95% confidence intervals.

Group	Mo.	Yr.	Biocrust cond.	Boot. <i>p</i> =	Tot. cover	Rich.	Prop. Moss	Na. Emerge.	Boot. <i>p</i> =	<i>R</i> ²
Amb.	Jun	2017	0.22	0.06	0.01	0.13	-0.14	0.40	0.0004	0.24
	Jul	2017	0.17	0.25	0.04	0.08	-0.12	0.49	0.0008	0.32
	Aug	2017	0.25	0.10	0.04	0.01	-0.25	0.18	0.18	0.12
	Sep	2017	0.10	0.10	0.06	-0.11	-0.07	0.78	0.0004	0.60
	May	2018	0.08	0.33	0.07	-0.08	-0.03	0.64	0.0008	0.39
	Jun	2018	0.28	0.003	0.22	-0.01	-0.21	0.51	0.0004	0.40
	Jul	2018	0.17	0.04	0.13	-0.17	-0.07	0.48	0.0009	0.23
	Aug	2018	0.19	0.03	0.15	-0.18	-0.06	0.48	0.0005	0.22
	Sep	2018	0.18	0.03	0.14	-0.18	-0.05	0.49	0.0004	0.23
Irr.	Jun	2017	0.22	0.03	0.11	0.16	0.10	0.73	0.0004	0.45
	Jul	2017	0.21	0.01	-0.01	0.13	0.23	0.63	0.0004	0.35
	Aug	2017	0.18	0.04	0.03	0.07	0.18	0.61	0.0004	0.33
	Sep	2017	0.17	0.04	0.04	0.05	0.16	0.65	0.0004	0.38
	May	2018	0.23	0.10	-0.22	-0.03	0.01	0.26	0.12	0.16
	Jun	2018	0.12	0.39	0.08	0.08	0.00	0.32	0.03	0.10
	Jul	2018	0.26	0.05	-0.06	-0.01	0.26	0.34	0.01	0.15
	Aug	2018	0.21	0.12	-0.06	-0.03	0.19	0.17	0.31	0.06
	Sep	2018	0.24	0.06	-0.08	-0.01	0.24	0.24	0.14	0.10

Supplementary Table 3. Direct effects of overall biocrust condition (unsigned), individual biocrust attributes, and emergence and cover of exotics and natives on nativeness, expressed as standardized path coefficients. Bootstrap probabilities are based on 5000 bootstrap samples and 95% confidence intervals.

Group	Mo.	Yr.	Biocrust cond.	Boot. $p =$	Tot. cover	Rich.	Prop. moss	Ex. Emerge.	Boot. $p =$	Ex. Cover	Boot. $p =$	Na. Emerge	Boot. $p =$	Na. Cover	Boot. $p =$	R^2
Amb.	Jun	2017	0.33	0.005	0.33	0.00	-0.01	0.17	0.32	-0.39	0.006	-0.12	0.35	0.25	0.02	0.3
	Jul	2017	0.23	0.007	0.21	0.06	0.00	0.02	0.88	-0.43	0.004	-0.3	0.02	0.44	0.01	0.45
	Aug	2017	0.21	0.003	0.19	0.04	0.03	0.07	0.59	-0.66	0.0004	-0.19	0.04	0.47	0.0004	0.59
	Sep	2017	0.20	0.01	0.16	0.08	0.04	-0.11	0.22	-0.57	0.0004	-0.15	0.34	0.52	0.0009	0.62
	May	2018	0.28	0.004	0.20	0.15	-0.03	-0.37	0.002	-0.21	0.01	-0.08	0.67	0.44	0.006	0.45
	Jun	2018	0.18	0.03	0.14	0.07	0.05	-0.34	0.02	-0.18	0.27	-0.01	0.95	0.43	0.005	0.42
	Jul	2018	0.17	0.18	0.16	0.01	-0.05	-0.12	0.28	-0.56	0.0004	0.05	0.69	0.33	0.005	0.56
	Aug	2018	0.18	0.05	0.17	0.01	-0.08	-0.12	0.30	-0.55	0.0005	0.08	0.56	0.28	0.01	0.55
	Sep	2018	0.18	0.05	0.17	0.01	0.01	-0.11	0.35	-0.58	0.0004	0.08	0.52	0.28	0.01	0.57
Irr.	Jun	2017	0.18	0.05	0.03	-0.20	-0.09	-0.25	0.10	-0.37	0.006	-0.21	0.24	0.32	0.007	0.39
	Jul	2017	0.22	0.04	0.04	-0.21	-0.20	-0.44	0.002	-0.31	0.002	-0.13	0.39	0.37	0.002	0.5
	Aug	2017	0.18	0.08	0.03	-0.19	-0.14	-0.23	0.10	-0.46	0.0004	-0.07	0.72	0.26	0.03	0.5
	Sep	2017	0.14	0.28	0.02	-0.15	-0.09	-0.27	0.06	-0.35	0.02	-0.02	1.00	0.24	0.05	0.43
	May	2018	0.16	0.12	0.16	-0.11	-0.10	-0.37	0.0009	-0.30	0.02	0.09	0.38	0.32	0.03	0.49
	Jun	2018	0.12	0.14	-0.07	-0.06	-0.07	-0.21	0.12	-0.67	0.0004	0.02	0.93	0.05	0.45	0.62
	Jul	2018	0.14	0.06	0.06	-0.15	-0.11	-0.19	0.06	-0.66	0.0004	0.21	0.01	0.12	0.19	0.69
	Aug	2018	0.14	0.06	0.08	-0.15	-0.10	-0.18	0.06	-0.64	0.0004	0.25	0.01	0.10	0.32	0.67
	Sep	2018	0.14	0.08	0.07	-0.15	-0.10	-0.19	0.07	-0.63	0.0004	0.24	0.02	0.05	0.68	0.63

Supplementary Table 4. Direct effects of overall biocrust condition (unsigned), individual biocrust attributes, and emergence and cover of exotics and natives on cumulative native richness, expressed as standardized path coefficients. Bootstrap probabilities are based on 5000 bootstrap samples and 95% confidence intervals.

Group	Mo.	Yr.	Biocrust cond.	Boot. $p =$	Tot. cover	Rich.	Prop. moss	Ex. Emerge.	Boot. $p =$	Ex. Cover	Boot. $p =$	Na. Emerge	Boot. $p =$	Na. Cover	Boot. $p =$	R^2
Amb.	Jun	2017	0.07	0.38	0.02	-0.08	-0.03	0.01	0.99	-0.17	0.22	0.63	0.0004	-0.04	0.81	0.4
	Jul	2017	0.13	0.21	0.07	-0.09	0.05	0.02	0.93	-0.02	0.85	0.41	0.007	0.2	0.24	0.26
	Aug	2017	0.13	0.26	0.06	-0.05	0.08	-0.03	0.65	-0.02	0.86	0.44	0.002	0.17	0.28	0.23
	Sep	2017	0.06	0.49	0.02	-0.03	0.04	-0.13	0.34	-0.06	0.76	0.47	0.008	-0.06	0.73	0.15
	May	2018	0.01	0.88	0.00	0.00	0.01	-0.15	0.23	0.04	0.71	0.22	0.15	0.17	0.29	0.11
	Jun	2018	0.02	0.77	0.00	-0.01	0.01	-0.12	0.39	-0.05	0.91	0.32	0.02	0	0.95	0.09
	Jul	2018	0.01	0.84	0.00	0.00	0.01	-0.13	0.35	0	0.96	0.29	0.02	0.05	0.77	0.09
	Aug	2018	0.02	0.81	0.02	0.01	0.01	-0.16	0.24	0.05	0.72	0.32	0.02	0.01	0.98	0.09
	Sep	2018	0.02	0.83	0.01	0.00	0.01	-0.15	0.28	0.03	0.84	0.31	0.02	0.02	0.94	0.09
Irr.	Jun	2017	0.34	0.01	-0.22	0.23	-0.08	-0.01	0.94	0.02	0.88	0.39	0.02	-0.05	0.72	0.3
	Jul	2017	0.37	0.01	-0.27	0.26	-0.06	0	0.98	-0.04	0.7	0.4	0.009	-0.05	0.69	0.32
	Aug	2017	0.35	0.01	-0.23	0.21	-0.12	-0.03	0.81	0.12	0.46	0.33	0.02	0.06	0.77	0.32
	Sep	2017	0.27	0.04	-0.16	0.21	-0.06	0.2	0.23	0.06	0.83	0.35	0.02	0.05	0.85	0.36
	May	2018	0.29	0.04	-0.22	0.22	-0.02	0.19	0.2	0.01	0.91	0.37	0.01	-0.06	0.53	0.34
	Jun	2018	0.27	0.04	-0.20	0.21	-0.01	0.2	0.19	0.03	0.84	0.33	0.02	0.1	0.46	0.35
	Jul	2018	0.31	0.01	-0.21	0.25	-0.03	0.3	0.02	-0.24	0.04	0.33	0.007	0.09	0.46	0.4
	Aug	2018	0.29	0.02	-0.20	0.24	-0.02	0.3	0.02	-0.21	0.08	0.35	0.006	0.07	0.6	0.39
	Sep	2018	0.30	0.02	-0.20	0.24	-0.03	0.3	0.03	-0.2	0.09	0.34	0.008	0.08	0.51	0.39

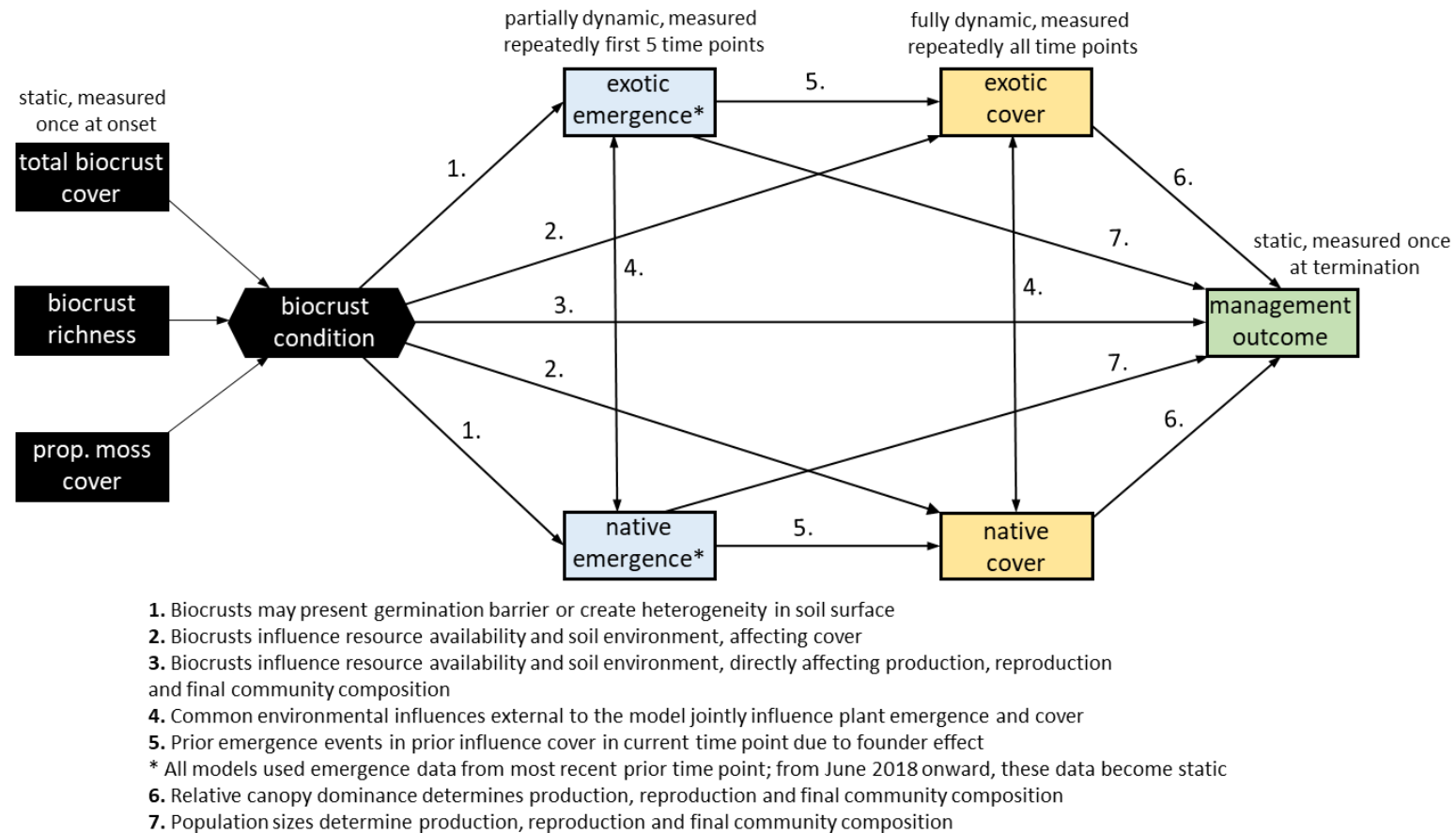
Supplementary Table 5. Direct effects of overall biocrust condition (unsigned), individual biocrust attributes, and emergence and cover of exotics and natives on exotic fecundity, expressed as standardized path coefficients. Bootstrap probabilities are based on 5000 bootstrap samples and 95% confidence intervals.

Group	Mo.	Yr.	Biocrust cond.	Boot. $p =$	Tot. cover	Rich.	Prop. moss	Ex. Emerge.	Boot. $p =$	Ex. Cover	Boot. $p =$	Na. Emerge	Boot. $p =$	Na. Cover	Boot. $p =$	R^2
Amb.	Jun	2017	0.14	0.32	0.00	0.15	0.05	0.05	0.78	0.6	0.0004	0.09	0.57	0.01	0.65	0.38
	Jul	2017	0.09	0.46	0.00	0.08	0.07	0.19	0.21	0.26	0.10	-0.06	0.65	0.07	0.59	0.13
	Aug	2017	0.13	0.29	-0.08	0.11	0.13	-0.01	0.87	0.23	0.13	-0.07	0.61	0.18	0.16	0.11
	Sep	2017	0.17	0.19	-0.08	0.08	0.19	-0.14	0.33	0.21	0.22	0.03	0.93	0.32	0.11	0.14
	May	2018	0.15	0.09	-0.02	-0.06	0.11	-0.11	0.26	0.58	0.0004	0.32	0.02	0.12	0.50	0.46
	Jun	2018	0.18	0.20	-0.08	0.01	0.18	-0.01	0.83	0.07	0.56	0.30	0.04	0.03	0.81	0.11
	Jul	2018	0.18	0.17	-0.08	0.04	0.19	0.00	0.78	0.08	0.43	0.26	0.08	0.10	0.46	0.11
	Aug	2018	0.18	0.18	-0.08	0.05	0.19	-0.01	0.77	0.1	0.34	0.25	0.10	0.12	0.36	0.12
	Sep	2018	0.18	0.18	-0.08	0.05	0.19	-0.01	0.72	0.1	0.35	0.25	0.09	0.11	0.37	0.12
Irr.	Jun	2017	0.21	0.05	-0.06	0.19	-0.04	0.19	0.23	0.33	0.02	0.15	0.47	-0.35	0.01	0.37
	Jul	2017	0.20	0.12	-0.10	0.21	0.04	0.29	0.06	0.06	0.69	0.02	0.94	-0.34	0.02	0.27
	Aug	2017	0.27	0.05	-0.14	0.24	-0.04	0.00	0.79	0.19	0.15	0.08	0.72	-0.29	0.05	0.22
	Sep	2017	0.28	0.06	-0.15	0.19	-0.09	0.00	0.86	0.14	0.34	-0.06	0.67	-0.19	0.16	0.19
	May	2018	0.23	0.07	-0.16	0.07	-0.11	0.00	0.89	0.44	0.003	-0.14	0.23	-0.02	0.93	0.31
	Jun	2018	0.20	0.10	-0.07	0.10	-0.12	-0.04	0.61	0.43	0.03	-0.14	0.27	0.14	0.44	0.26
	Jul	2018	0.25	0.05	-0.17	0.18	-0.05	0.01	0.92	0.22	0.24	-0.14	0.25	-0.27	0.04	0.28
	Aug	2018	0.28	0.03	-0.18	0.19	-0.07	-0.01	0.83	0.21	0.29	-0.20	0.10	-0.24	0.05	0.27
	Sep	2018	0.27	0.03	-0.19	0.19	-0.05	-0.02	0.75	0.24	0.21	-0.17	0.16	-0.26	0.03	0.29

Supplementary Table 6. Direct effects of overall biocrust condition (unsigned), individual biocrust attributes, and emergence and cover of exotics and natives on total biomass, expressed as standardized path coefficients. Bootstrap probabilities are based on 5000 bootstrap samples and 95% confidence intervals.

Group	Mo.	Yr.	Biocrust cond.	Boot. $p =$	Tot. cover	Rich.	Prop. moss	Ex. Emerge.	Boot. $p =$	Ex. Cover	Boot. $p =$	Na. Emerge	Boot. $p =$	Na. Cover	Boot. $p =$	R^2
Amb.	Jun	2017	0.20	0.04	-0.12	-0.05	-0.14	-0.16	0.16	0.64	0.0004	0.12	0.25	0.05	0.73	0.41
	Jul	2017	0.16	0.06	-0.03	-0.12	-0.14	-0.08	0.41	0.63	0.0004	0.02	0.85	0.16	0.18	0.42
	Aug	2017	0.10	0.23	-0.05	-0.07	-0.07	-0.06	0.52	0.69	0.0004	0.10	0.36	0.04	0.61	0.50
	Sep	2017	0.11	0.17	-0.07	-0.05	-0.05	-0.32	0.03	0.80	0.0004	-0.07	0.79	0.35	0.06	0.53
	May	2018	0.24	0.04	-0.07	-0.22	-0.04	0.09	0.52	0.39	0.0005	0.25	0.19	0.06	0.72	0.31
	Jun	2018	0.18	0.12	-0.08	-0.14	-0.03	0.03	0.82	0.38	0.008	0.22	0.17	0.10	0.60	0.28
	Jul	2018	0.08	0.45	-0.07	-0.02	0.02	-0.04	0.73	0.57	0.0004	0.14	0.19	0.17	0.24	0.43
	Aug	2018	0.07	0.51	-0.06	-0.01	0.04	-0.06	0.60	0.63	0.0004	0.13	0.20	0.19	0.11	0.47
	Sep	2018	0.08	0.55	-0.07	0.00	0.05	-0.07	0.51	0.63	0.0004	0.12	0.21	0.20	0.09	0.47
Irr.	Jun	2017	0.18	0.06	-0.10	0.14	-0.04	0.01	0.91	0.23	0.10	-0.07	0.83	-0.11	0.52	0.13
	Jul	2017	0.14	0.12	-0.06	0.11	-0.04	0.09	0.52	0.39	0.004	-0.15	0.50	0.05	0.79	0.23
	Aug	2017	0.07	0.38	-0.02	0.08	0.02	0.01	0.89	0.59	0.0005	-0.07	0.70	0.01	0.94	0.39
	Sep	2017	0.11	0.35	-0.02	-0.04	-0.11	-0.19	0.25	0.71	0.0004	-0.19	0.19	0.12	0.49	0.42
	May	2018	0.10	0.36	-0.10	0.01	0.00	0.12	0.35	0.40	0.006	-0.15	0.23	-0.09	0.56	0.28
	Jun	2018	0.06	0.51	0.06	-0.02	-0.02	-0.01	0.96	0.66	0.0004	-0.09	0.50	0.12	0.32	0.40
	Jul	2018	0.09	0.24	-0.06	0.09	0.01	0.04	0.81	0.46	0.0004	-0.22	0.11	-0.12	0.43	0.34
	Aug	2018	0.11	0.17	-0.07	0.09	-0.01	0.02	0.89	0.48	0.0004	-0.27	0.03	-0.03	0.81	0.33
	Sep	2018	0.11	0.21	-0.07	0.10	0.00	0.04	0.82	0.45	0.0005	-0.26	0.05	-0.02	0.84	0.30

2.1 Supplementary Figures



Supplementary Figure 1. *A priori* structural equation model depicting hypothesized interrelationships of variables in our data and a catalog of mechanisms. Rectangles represent single variables which were measured. The hexagon represents composite variables, pooling the effects of three measured biocrust attributes on response variables.