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Supplementary information

Global cycling and climate effects of aeolian dust controlled by biological soil crusts

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Supplementary Material for

Global cycling and climate effects of aeolian dust controlled by biological soil crusts

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1. Supplementary Tables

Supplementary Table 1 | Threshold friction velocity of biocrusts and underlying reference soils, for (a) experimental studies analyzing TFV as function of biocrust coverage increase, (b) experimental studies comparing TFV of soils completely covered by biocrust (100% coverage) and reference soils, and (c) experimental studies analyzing TFV of soils completely covered by biocrust (100% coverage) but not the reference soils. In tables (A) and (B), the TFV increase shows the ratio of biocrust TFV divided by the bare soil TFV multiplied with 100. In addition, information on the biocrust type, dominant organism, cover, treatment (disturbance), soil texture, precipitation, study area, and the referenced literature is given. Data were obtained from previous peer-reviewed publications in scientific journals. * Restored biocrust community; + Saltation initiation

a)

Biocrust TFV (cm s-1)	Bare soil TFV (cm s-1)	TFV increase (%)	Biocrust type	Dominant organism	Cover (%)	Soil texture	Precipitation (mm)	Study area	Reference
2500	842	297	rugose	cyanobacteria and lichens	100	sand	79.5	Gurbangtunggut	3
1604	842	190	rugose	cyanobacteria and lichens	90	sand	79.5	Gurbangtunggut	1
1226	842	146	rugose	cyanobacteria and lichens	80	sand	79.5	Gurbangtunggut	1
1200	842	143	rugose	cyanobacteria and lichens	70	sand	79.5	Gurbangtunggut	1
1100	842	131	rugose	cyanobacteria and lichens	50	sand	79.5	Gurbangtunggut	1
1000	842	119	rugose	cyanobacteria and lichens	20	sand	79.5	Gurbangtunggut	1
1900+	592	321	smooth*	cyanobacteria	100	sand	180	Shapotou	2
1175+	592	198	smooth*	cyanobacteria	90	sand	180	Shapotou	2
970+	592	164	smooth*	cyanobacteria	80	sand	180	Shapotou	2
952+	592	161	smooth*	cyanobacteria	60	sand	180	Shapotou	2
872+	592	142	smooth*	cyanobacteria	20	sand	180	Shapotou	2

b)

Biocrust TFV (cm s-1)	Bare soil TFV (cm s-1)	TFV increase (%)	Biocrust type	Dominant organism	Treatment (disturbance)	Soil texture	Precipitation (mm)	Study area	Reference
1000	100	1000	rugose	cyanobacteria	undisturbed	----	161	Snake Valley	3
550	100	550	smooth	cyanobacteria	undisturbed	loamy sand	101	Mojave	4
425	120	354	smooth	cyanobacteria	undisturbed	sandy loam	101	Mojave	4
376	16	2350	pinnacled	lichen and bryophytes	undisturbed	sandy loam	250	Moab	5
323	30	1077	rolling	lichen and bryophytes	undisturbed	clayey loam	247	Jornada Experimental	6
300	150	200	smooth	cyanobacteria	undisturbed	loamy sand	101	Mojave	4
200	100	200	smooth	cyanobacteria	disturbed	loamy sand	101	Mojave	4
200	90	222	pinnacled	lichen and bryophytes	undisturbed	coarse loam	300-660	Capitol Reff National park	7
173	30	577	smooth	cyanobacteria	undisturbed	clayey loam	247	Jornada Experimental	6
150	100	150	smooth	cyanobacteria	disturbed	sand	101	Mojave	4
100-30	16	203	pinnacled	lichen and bryophytes	disturbed	sandy loam	250	Moab	5
87	16	544	rolling	cyanobacteria	undisturbed	sandy loam	250	Moab	5
75	30	250	smooth	cyanobacteria	undisturbed	sandy loam	247	Jornada Experimental	6
75	30	250	smooth	cyanobacteria	disturbed	clayey loam	247	Jornada Experimental	6
70	40	175	rugose	cyanobacteria	disturbed	----	161	Snake Valley	3
50	30	167	smooth	cyanobacteria	disturbed	sandy loam	247	Jornada Experimental	6

50	30	167	Rolling	lichens and bryophytes	disturbed	clayey loam	247	Jornada Experimental	6
50-30	16	250	rolling	cyanobacteria	disturbed	sandy loam	250	Moab	5
46	16	288	smooth	cyanobacteria	undisturbed	sandy loam	250	Moab	5
30	16	188	smooth	cyanobacteria	disturbed	sandy loam	250	Moab	5
30	16	188	smooth	cyanobacteria	disturbed	sandy loam	250	Moab	5

c)

Biocrust TFV (cm s-1)	Biocrust type	Dominant organism	Treatment (disturbance)	Soil texture	Precipitation (mm)	Study area	Reference
1500	pinnacled	lichens and bryophytes	undisturbed	sandy loam	230	Arches National Park	8
1500	smooth	cyanobacteria and lichens	undisturbed	fine sandy loam	135	Mojave	8
1500	smooth	cyanobacteria and lichens	undisturbed	coarse sandy loam	135	Mojave	8
1500	smooth	cyanobacteria	undisturbed	loam	230	Colorado Plateau	8
1450	smooth	cyanobacteria	undisturbed	clayey loam	230	Colorado Plateau	8
1400	smooth	cyanobacteria	undisturbed	fine sandy loam	230	Colorado Plateau	8
1200	smooth	cyanobacteria and lichens	undisturbed	sandy loam	135	Mojave	8
1100	smooth	cyanobacteria and lichens	undisturbed	loamy sand	135	Mojave	8
1100	smooth	cyanobacteria and lichens	undisturbed	coarse loamy sand	135	Mojave	8
1000	smooth	cyanobacteria and lichens	undisturbed	sand	135	Mojave	8
500	smooth	cyanobacteria	disturbed	loam	230	Colorado Plateau	8
500	smooth	cyanobacteria and lichens	disturbed	fine sandy loam	135	Mojave	8
450	smooth	cyanobacteria	disturbed	clayey loam	230	Colorado Plateau	8
450	smooth	cyanobacteria	disturbed	coarse sandy loam	135	Mojave	8
450	smooth	cyanobacteria and lichens	disturbed	loamy sand	135	Mojave	8
400	smooth	cyanobacteria and lichens	disturbed	sandy loam	135	Mojave	8
400	smooth	cyanobacteria and lichens	disturbed	coarse loamy sand	135	Mojave	8

400	smooth	cyanobacteria	disturbed	fine sandy loam	230	Colorado Plateau	8
350	smooth	cyanobacteria and lichens	disturbed	sand	135	Mojave	8
78-56	smooth	lichens and bryophytes	disturbed	loam	----	Mallee Cliffs National Park	9
58-55	smooth	lichens and bryophytes	disturbed	sand	----	Tapio Station	9
68	smooth	lichens and bryophytes	undisturbed	loam	----	Mallee Cliffs National Park	9
54	smooth	lichens and bryophytes	undisturbed	sand	----	Tapio Station	9

Supplementary Table S2 | Global dust emission, sedimentation, and dry and wet deposition [in Tg a^{-1}]. Values obtained with ECHAM6-HAM2-BIOCRUST. Calculations were made for mean (mean TFV), maximum (Max TFV) and minimum (Min TFV) effects of biocrusts on TFV. Statistically significant differences between the different parameterization schemes of ECHAM6-HAM2-BIOCRUST (Min TFV, Mean TFV and Max TFV) and ECHAM6-HAM2-NO BIOCRUST according to the results of a one-way ANOVA and a Tukey's posthoc test are indicated by an asterisk (significance level: $p< 0.01$).

	Emission	Sedimentation	Dry deposition	Wet deposition
Biocrust (Min TFV)	1534*	636*	779*	145*
Biocrust (Mean TFV)	1191*	506*	105*	592*
Biocrust (Max TFV)	1198*	516*	105*	589*

Supplementary Table S3 | Comparison of regional estimates of dust emission fluxes [Tg a^{-1}] obtained with ECHAM6-HAM2-BIOCRUST (explicitly accounting for the effect of biocrusts on threshold friction velocity) and reference values obtained by AeroCom simulations and by 30-year simulations with ECHAM6-HAM2.1[2].

	N-Africa	S-Africa	Middle East	Asia	N-America	Australia	S-America	Total
ECHAM6-HAM2-BIOCRUST ***(max TFV – min TFV)***	782 (815- 858)	1.26 (0.7 - 12)	157 (152 - 183)	36 (32 - 96)	35 (21 - 51)	96 (79 - 221)	8.3 (6.2 - 14.8)	1191 (1534 - 1198)
AeroCom median **(range)**	792 (204-2888)	11.8 (2.9 - 55.4)	128 (25.6-531)	137 (27-727)	2 (1.7-286)	30.7 (9.0 -129)	9.8 (0.2-186)	1123 (514–4313)
ECHAM-HAM2.1	588.21	9.50	151.38	81.00	35.66	181.88	11.5	931

Supplementary Table S4 | Impact of biocrusts on dust emission, sedimentation, and dry and wet deposition by continents and global values [Tg a^{-1}]. Calculations are based on mean (mean TFV), maximum (Max TFV) and minimum (Min TFV) effects of biocrusts on TFV.

	Continent	Asia	N-America	Europe	Africa	S-America	Oceania	Total
Biocrust (Min TFV)	Emission	-97.68	-2.93	-0.94	-168.76	-8.02	-63.03	-341.36
	Sedimentation	-31.61	-0.8	-1.25	-53.69	-1.33	-13.36	-102.04
	Dry deposition	-6.05	-0.55	-0.54	-9.47	-1.66	-7.25	-25.52
	Wet deposition	-46.2	-3.54	-5.23	-27.66	-2.97	-5.1	-90.7
Biocrust (Mean TFV)	Emission	-208.17	-19.71	-5.33	-243.45	-14.6	-185.44	-676.7
	Sedimentation	-64.2	-3.92	-4.32	-85.65	-2.61	-39.76	-200.46
	Dry deposition	-13.62	-3.85	-2.13	-15.72	-3.12	-23.06	-61.5
	Wet deposition	-96.15	-10.89	-16.8	-34.64	-6.77	-17.64	-182.89
Biocrust (Max TFV)	Emission	-217.55	-32.21	-6.26	-195.84	-16.58	-199.27	-667.71
	Sedimentation	-66.83	-6.31	-4.44	-75.69	-2.28	-42.07	-197.62
	Dry deposition	-14.38	-6.07	-2.12	-12.79	-2.67	-24.4	-62.43
	Wet deposition	-102.86	-14.9	-16.52	-35.5	-4.62	-19.37	-193.77

Supplementary Table S5 | Impact of biocrusts on dust sedimentation, and dry and wet deposition on oceans and global water body values [Tg a^{-1}]. Calculations are based on mean (mean TFV), maximum (Max TFV) and minimum (Min TFV) effects of biocrusts on TFV.

	Oceans and water bodies	Arctic	Antartic	N-Atlantic	N-Pacific	S-Pacific	Indian	S-Atlantic	Others	Total
Biocrust (Min TFV)	Sedimentation	-0.08	-0.02	-12.97	-0.87	-0.98	-6.05	-1.85	-14.03	-36.85
	Dry deposition	-0.04	-0.57	-25.02	-4.37	-5.2	-9.91	-7.98	-34.17	-87.26
	Wet deposition	-0.01	-0.01	-0.8	-0.17	-0.17	-0.55	-0.34	-2.18	-4.23
Biocrust (Mean TFV)	Sedimentation	-0.07	-0.07	-21.02	-1.9	-3.17	-13.25	-3.99	-25.54	-69.01
	Dry deposition	-0.27	-1.49	-36.5	-10.15	-17.69	-28.07	-14.68	-72.5	-181.35
	Wet deposition	-0.01	-0.02	-1.64	-0.41	-0.58	-1.31	-0.66	-3.73	-8.36
Biocrust (Max TFV)	Sedimentation	-0.03	-0.07	-11.8	-2.04	-3.28	-15.18	-4.1	-25.84	-62.34
	Dry deposition	-0.24	-1.64	-25.11	-10.53	-18.43	-30.97	-14.07	-72.1	-173.09
	Wet deposition	-0.01	-0.02	-0.72	-0.43	-0.61	-1.5	-0.77	-3.75	-7.81

Supplementary Table S6 | Impact of biocrusts on dust burden, Aerosol Optical Depth (AOD) and net (Net RB), short wave (Shortwave RB), and long wave aerosol effect on the radiative balance (Longwave RB) at the top of the atmosphere. Calculations were made for mean (Mean TFV), maximum (Max TFV) and minimum (Min TFV) effects of biocrusts on TFV. Statistically significant differences between the different parameterization schemes of ECHAM6-HAM2-BIOCRUST (Min TFV, Mean TFV and Max TFV) and ECHAM6-HAM2-NO BIOCRUST according to the results of a one-way ANOVA and a Tukey's posthoc test are indicated by an asterisk (significance level: $p < 0.01$).

	Dust burden [Tg]	AOD	Net RB [W m^{-2}]	Shortwave RB [W m^{-2}]	Longwave RB [W m^{-2}]
Biocrust (Min TFV)	-4.8*	-0.022*	+0.02*	+0.04*	-0.02*
Biocrust (Mean TFV)	-8.6*	-0.022*	+0.48*	+0.58*	-0.10*
Biocrust (Max TFV)	-8.2*	-0.007*	+0.48*	+0.58*	-0.10*

Supplementary Table S7 | Comparison of future as compared to current estimates of global mean annual dust emission, sedimentation, and dry and wet deposition fluxes [Tg a^{-1}] obtained with ECHAM6-HAM2-BIOCRUST (explicitly accounting for the effect of biocrusts on threshold friction velocity). Future estimates are given for the representative concentration pathways RCP 2.6, 4.5, and 8.5. Calculations are based on mean (Mean TFV), maximum (Max TFV), and minimum (Min TFV) effects of biocrusts on TFV.

		RCP2.6	RCP4.5	RCP8.5	Current
Biocrust (Min TFV)	Emission	1595	1556	1635	1534
	Sedimentation	647	640	661	636
	Dry deposition	135	125	142	145
	Wet deposition	833	813	854	779
Biocrust (Mean TFV)	Emission	1242	1210	1376	1191
	Sedimentation	522	525	579	506
	Dry deposition	100	93	91	105
	Wet deposition	645	619	711	592
Biocrust (Max TFV)	Emission	1231	1199	1330	1198
	Sedimentation	524	531	565	516
	Dry deposition	96	90	107	105
	Wet deposition	636	614	679	589

Supplemetary S8 | Comparison of future as compared to current estimates of continental and marine total dust deposition fluxes [Tg a^{-1}] obtained with ECHAM6-BIOCRUST (explicitly accounting for the effect of biocrusts on threshold friction velocity). Future estimates are given for the representative concentration pathways RCP 2.6, 4.5, and 8.5. Calculations were made for the sum of sedimentation, dry deposition and wet deposition over the continents and oceans and are based on mean (Mean TFV), maximum (Max TFV) and minimum (Min TFV) effects of biocrusts on TFV.

		RCP2.6	RCP4.5	RCP8.5	Current
Biocrust (Min TFV)	Continental dust deposition	969	948	999	938
	Marine dust deposition	646	630	658	615
Biocrust (Mean TFV)	Continental dust deposition	769	747	850	702
	Marine dust deposition	498	490	531	485
Biocrust (Max TFV)	Continental dust deposition	760	746	816	712
	Marine dust deposition	496	489	535	500

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