Supplementary material of "Unearthing the soil-borne microbiome of land plants"

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Table S1. List of land plants sampled and their taxonomic categories. N = no; Y = yes.

Species	Division	Major_clade	Familly	Vascular_pla	Seed_pla	Flowering_pla	Eudico	Microsi
Calliergonella	Bryophyta	Bryophytes	Amblystegiace	N	N	N	N	MOSS
Sanionia	Bryophyta	Bryophytes	Amblystegiace	N	N	N	N	MOSS
Brachythecium	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Eurhynchium	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Eurhynchium	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Eurhynchium	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Homalothecium	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Kindbergia	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Myuroclada	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Pseudoscleropodi	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Rhynchostegium	Bryophyta	Bryophytes	Brachytheciac	N	N	N	N	MOSS
Bryum argenteum	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Bryum	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Bryum sp	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Ptychostomum	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Rosulabryum	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Rosulabryum	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Rosulabryum sp	Bryophyta	Bryophytes	Bryaceae	N	N	N	N	MOSS
Campylopus	Bryophyta	Bryophytes	Dicranaceae	N	N	N	N	MOSS
Campylopus	Bryophyta	Bryophytes	Dicranaceae	N	N	N	N	MOSS
Campylopus	Bryophyta	Bryophytes	Dicranaceae	N	N	N	N	MOSS
Leucobryum sp	Bryophyta	Bryophytes	Dicranaceae	N	N	N	N	MOSS
Ceratodon	Bryophyta	Bryophytes	Ditrichaceae	N	N	N	N	MOSS
Fissidens sp	Bryophyta	Bryophytes	Fissidentaceae	N	N	N	N	MOSS
Funaria	Bryophyta	Bryophytes	Funariaceae	N	N	N	N	MOSS
Funaria sp	Bryophyta	Bryophytes	Funariaceae	N	N	N	N	MOSS
Hylocomium sp	Bryophyta	Bryophytes	Hylocomiacea	N	N	N	N	MOSS
Hylocomium	Bryophyta	Bryophytes	Hylocomiacea	N	N	N	N	MOSS
Rhytidium	Bryophyta	Bryophytes	Hylocomiacea	N	N	N	N	MOSS
Homomallium sp	Bryophyta	Bryophytes	Hypnaceae	N	N	N	N	MOSS
Hypnum	Bryophyta	Bryophytes	Hypnaceae	N	N	N	N	MOSS
Pylaisiella	Bryophyta	Bryophytes	Hypnaceae	N	N	N	N	MOSS
Antitrichia	Bryophyta	Bryophytes	Leucodonthace	N	N	N	N	MOSS
Mnium hornum	Bryophyta	Bryophytes	Mniaceae	N	N	N	N	MOSS
Mnium sp	Bryophyta	Bryophytes	Mniaceae	N	N	N	N	MOSS
Moss	Bryophyta	Bryophytes	NA	N	N	N	N	MOSS
Octoblepharum	Bryophyta	Bryophytes	Octoblepharac	N	N	N	N	MOSS
Atrichum	Bryophyta	Bryophytes	Polytrichaceae	N	N	N	N	MOSS
Polytrichum	Bryophyta	Bryophytes	Polytrichaceae	N	N	N	N	MOSS
Polytrichum	Bryophyta	Bryophytes	Polytrichaceae	N	N	N	N	MOSS
Polytrichum sp	Bryophyta	Bryophytes	Polytrichaceae	N	N	N	N	MOSS
Aloina bifrons	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Barbula sp	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Barbula vinealis	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Crossidium	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Crossidium	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Desmatodon sp	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Didymodon sp	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Didymodon	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS

Syntrichia	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Tortula ruralis	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Tortula sp	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Trichostomum	Bryophyta	Bryophytes	Pottiaceae	N	N	N	N	MOSS
Ptychomitrium sp	Bryophyta	Bryophytes	Ptychomitriace	N	N	N	N	MOSS
Sphagnum sp	Bryophyta	Bryophytes	Sphagnaceae	N	N	N	N	MOSS
Stereophyllum sp	Bryophyta	Bryophytes	Stereophyllace	N	N	N	N	MOSS
Thuidium	Bryophyta	Bryophytes	Thuidiaceae	N	N	N	N	MOSS
Acer	Magnolioph	Rosids	Aceraceae	Y	Y	Y	Y	V.
Acer	Magnolioph	Rosids	Aceraceae	Y	Y	Y	Y	V.
Acer sp	Magnolioph	Rosids	Aceraceae	Y	Y	Y	Y	V.
Acer spicatum	Magnolioph	Rosids	Aceraceae	Y	Y	Y	Y	V.
Acer tegmentosu	Magnolioph	Rosids	Aceraceae	Y	Y	Y	Y	V.
Acer triflorum	Magnolioph	Rosids	Aceraceae	Y	Y	Y	Y	V.
Atriplex clivicola	Magnolioph	Caryophylla	Amaranthacea	Y	Y	Y	Y	V.
Atriplex halimus	Magnolioph	Caryophylla	Amaranthacea	Y	Y	Y	Y	V.
Atriplex	Magnolioph	Caryophylla	Amaranthacea	Y	Y	Y	Y	V.
Chenopodium	Magnolioph	Caryophylla	Amaranthacea	Y	Y	Y	Y	V.
Haloxylon	Magnolioph	Caryophylla	Amaranthacea	Y	Y	Y	Y	V.
Noaea mucronata	Magnolioph	Caryophylla	Amaranthacea	Y	Y	Y	Y	V.
Schinus latifolius	Magnolioph	Rosids	Anacardiaceae	Y	Y	Y	Y	V.
Elaeis guineensis	Magnolioph	Monocots	Arecaceae	Y	Y	Y	N	V.
Alnus glutinosa	Magnolioph	Rosids	Betulaceae	Y	Y	Y	Y	V.
Betula dahurica	Magnolioph	Rosids	Betulaceae	Y	Y	Y	Y	V.
Carpinus betulus	Magnolioph	Rosids	Betulaceae	Y	Y	Y	Y	V.
Rorippa sp	Magnolioph	Rosids	Brassicaceae	Y	Y	Y	Y	V.
Tillandsia	Magnolioph	Monocots	Bromeliaceae	Y	Y	Y	N	V.
Buxus	Magnolioph	CRPT+B	Buxaceae	Y	Y	Y	N	V.
Browningia	Magnolioph	Caryophylla	Cactaceae	Y	Y	Y	Y	V.
Celtis australis	Magnolioph	Rosids	Cannabaceae	Y	Y	Y	Y	V.
Cistus creticus	Magnolioph	Rosids	Cistaceae	Y	Y	Y	Y	V.
Cupressus	Pinophyta	Gymnosper	Cupressaceae	Y	Y	N	N	V.
Juniperus sp	Pinophyta	Gymnosper	Cupressaceae	Y	Y	N	N	V.
Ephedra	Gnetophyta	Gymnosper	Ephedraceae	Y	Y	N	N	V.
Empetrum sp	Magnolioph	Asterids	Ericaceae	Y	Y	Y	Y	V.
Acacia caven	Magnolioph	Rosids	Fabaceae	Y	Y	Y	Y	V.
Adenanthera	Magnolioph	Rosids	Fabaceae	Y	Y	Y	Y	V.
Cassia tora	Magnolioph	Rosids	Fabaceae	Y	Y	Y	Y	V.
Senegalia caffra	Magnolioph	Rosids	Fabaceae	Y	Y	Y	Y	V.
Fagus sylvatica	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus ilex	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus robur	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus sp	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus suber	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Quercus mongoli	Magnolioph	Rosids	Fagaceae	Y	Y	Y	Y	V.
Ginkgo biloba	Ginkgophyta	Gymnosper	Ginkgoaceae	Y	Y	N	N	V.
Stachys sp	Magnolioph	Asterids	Lamiaceae	Y	Y	Y	Y	V.
Tilia amurensis	Magnolioph	Rosids	Malvaceae	Y	Y	Y	Y	V.

Tilia cordata	Magnolioph	Rosids	Malvaceae	Y	Y	Y	Y	V.
Tilia europaea	Magnolioph	Rosids	Malvaceae	Y	Y	Y	Y	V.
Marantochloa	Magnolioph	Monocots	Marantaceae	Y	Y	Y	N	V.
Ficus	Magnolioph	Rosids	Moraceae	Y	Y	Y	Y	V.
Musa sp	Magnolioph	Monocots	Musaceae	Y	Y	Y	N	V.
Angophora	Magnolioph	Rosids	Myrtaceae	Y	Y	Y	Y	V.
Eucalyptus	Magnolioph	Rosids	Myrtaceae	Y	Y	Y	Y	V.
Eucalyptus	Magnolioph	Rosids	Myrtaceae	Y	Y	Y	Y	V.
Eucalyptus	Magnolioph	Rosids	Myrtaceae	Y	Y	Y	Y	V.
Eucalyptus sp	Magnolioph	Rosids	Myrtaceae	Y	Y	Y	Y	V.
Fraxinus	Magnolioph	Asterids	Oleaceae	Y	Y	Y	Y	V.
Fraxinus sp	Magnolioph	Asterids	Oleaceae	Y	Y	Y	Y	V.
Ligustrum	Magnolioph	Asterids	Oleaceae	Y	Y	Y	Y	V.
Olea europaea	Magnolioph	Asterids	Oleaceae	Y	Y	Y	Y	V.
Abies religiosa	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Larix gmelinii	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Picea abies	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Picea mariana	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Picea	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus elliottii	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus halepensis	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus palustris	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus pinaster	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus pinea	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus ponderosa	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus sp	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Pinus thunbergii	Pinophyta	Gymnosper	Pinaceae	Y	Y	N	N	V.
Brachiaria	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Cynodon	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Cynodon sp	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Echinolaena	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Eragrostis sp	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Festuca sp	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Merostachys sp	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Pennisetum	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Poa fendleriana	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Poa sp	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Stenotaphrum	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Triodia	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Zoysia japonica	Magnolioph	Monocots	Poaceae	Y	Y	Y	N	V.
Sorbus aucuparia	Magnolioph	Rosids	Rosaceae	Y	Y	Y	Y	V.
Citrus sp	Magnolioph	Rosids	Rutaceae	Y	Y	Y	Y	V.
Populus sp	Magnolioph	COM	Salicaceae	Y	Y	Y	N	V.
Buddleja cordata	Magnolioph	Asterids	Scrophulariace	Y	Y	Y	Y	V.
Tamarix sp	Magnolioph	Caryophylla	Tamaricaceae	Y	Y	Y	Y	V.
Ulmus pumila	Magnolioph	Rosids	Ulmaceae	Y	Y	Y	Y	V.
Ulmus sp	Magnolioph	Rosids	Ulmaceae	Y	Y	Y	Y	V.

Table S2. List of locations, sampling date, ecosystem type, and management. [See attached TableS2.csv file].

Table S3. Sequences associated with indicator bacterial phylotypes. [See attached TableS3.csv file].

Table S4. Sequences associated with indicator protistan phylotypes. [See attached TableS4.csv file].

Table S5. Sequences associated with indicator fungal phylotypes. [See attached TableS5.csv file].

Table S6. Primer sequences used in real time PCR.

Target Gene	Primer name	Primer sequence (5'–3')	Reference
nifH	nifH-F	AAAGGYGGWATCGGYAARTCCACCAC	Rösch et al., 2002
	nifH-R	TTGTTSGCSGCRTACATSGCCATCAT	
chiA	chif2	GACGGCATCGACATCGATTGG	Xiao et al., 2005
	Chir	CSGTCCAGCCGCGSCCRTA	
amoA	Arch-amoAF	STAATGGTCTGGCTTAGACG	Francis et al., 2005
	Arch-amoAR	GCGGCCATCCATCTGTATGT	
nosZ	nosZ-F	CGY TGT TCM TCG ACA GCC AG	Throback et al., 2004
	nosZ-R	CGSACCTTSTTGCCSTYGCG	
phoC	phoc-A-F1	CGGCTCCTATCCGTCCGG	Fraser et al., 2017
	phoc-A-R1	CAACATCGCTTTGCCAGTG	

phoD	ALPS-F730	CAGTGGGACGACCACGAGGT	Sakurai et al., 2008
	ALPS-R1101	GAGGCCGATCGGCATGTCG	
cbbL	K2F	ACCACCAAGCCGAAGCTCGGG-	Wu et al., 2015
	V2r	GCCTTCGAGCTTGCCGACCGC	
GH18	GH18F	ATHGGNGGNTGGGGGNGAY	Hannula and van Veen, 2016.
	GH18R	GAYNTNGAYTGGGARTAY	
ClassII peroxidases	F	GGIGGIGCIGAYGGITC	Hannula and van Veen, 2016.
	R	GGIGTIGARTCGAABGG	
pmoA	pmo189f	GGNGACTGGGACTTCTGG	Bourne and Murrell, 2001
	pmo650r	ACGTCCTTACCGAAGGT	
apsA	apsAF	TGGCAGATMATGATYMACGG	Friedrich, 2002
	apsAR	GGGCCGTAACCGTCCTTGAA	

Table S7. List of bacterial species that are indicative of land plant-associated microbiomes. [See attached TableS7.csv file].

Table S8. List of protistan species that are indicative of land plant-associated microbiomes. [See attached TableS8.csv file].

Table S9. List of bacterial species that are indicative of vascular plant-associated microbiomes. [See attached TableS9.csv file].

Table S10. List of protistan species that are indicative of vascular plant-associated microbiomes. [See attached TableS13.csv file].

Table S11. List of fungal species that are indicative of vascular plant-associated microbiomes. [See attached TableS14.csv file].

Table S12. List of bacterial species that are indicative of soil moss-associated microbiomes. [See attached TableS12.csv file].

Table S13. List of protistan species that are indicative of soil moss microbiomes. [See attached TableS13.csv file].

Table S14. List of fungal species that are indicative of soil moss microbiomes. [See attached TableS11.csv file].

Table S15. Results of linear mixed models evaluating the effect of soil microhabitat on the relative abundance of microbial groups at different taxonomic levels. Post-hoc contrasts are based on Tukey tests. [See attached TableS15.csv file].

Table S16. Detection of thresholds in the relationship between the standardized abundance of the uniquely associated moss and plant microbiomes and environmental variables. [See attached TableS16.csv file].

Figure S1. Schematic representation of sampling design. At each location, we established a 30 m × 30 m plot comprising three, equally spaced 30 m vegetation transects. Soil samples, depicted as yellow circle, were collected within three microsites: (1) underneath the most common perennial vegetation type at each location (generally tree, shrub, or grass), (2) underneath mosses and (3) in bare soil, defined as patches devoid of vegetation and not colonised by plant roots. Within each plot, only one species was sampled. Five composite soil cores were collected from each microsite, bulked and divided into two sub-samples; one that was immediately frozen (-20ºC) for molecular analyses and the other air-dried for chemical analyses.

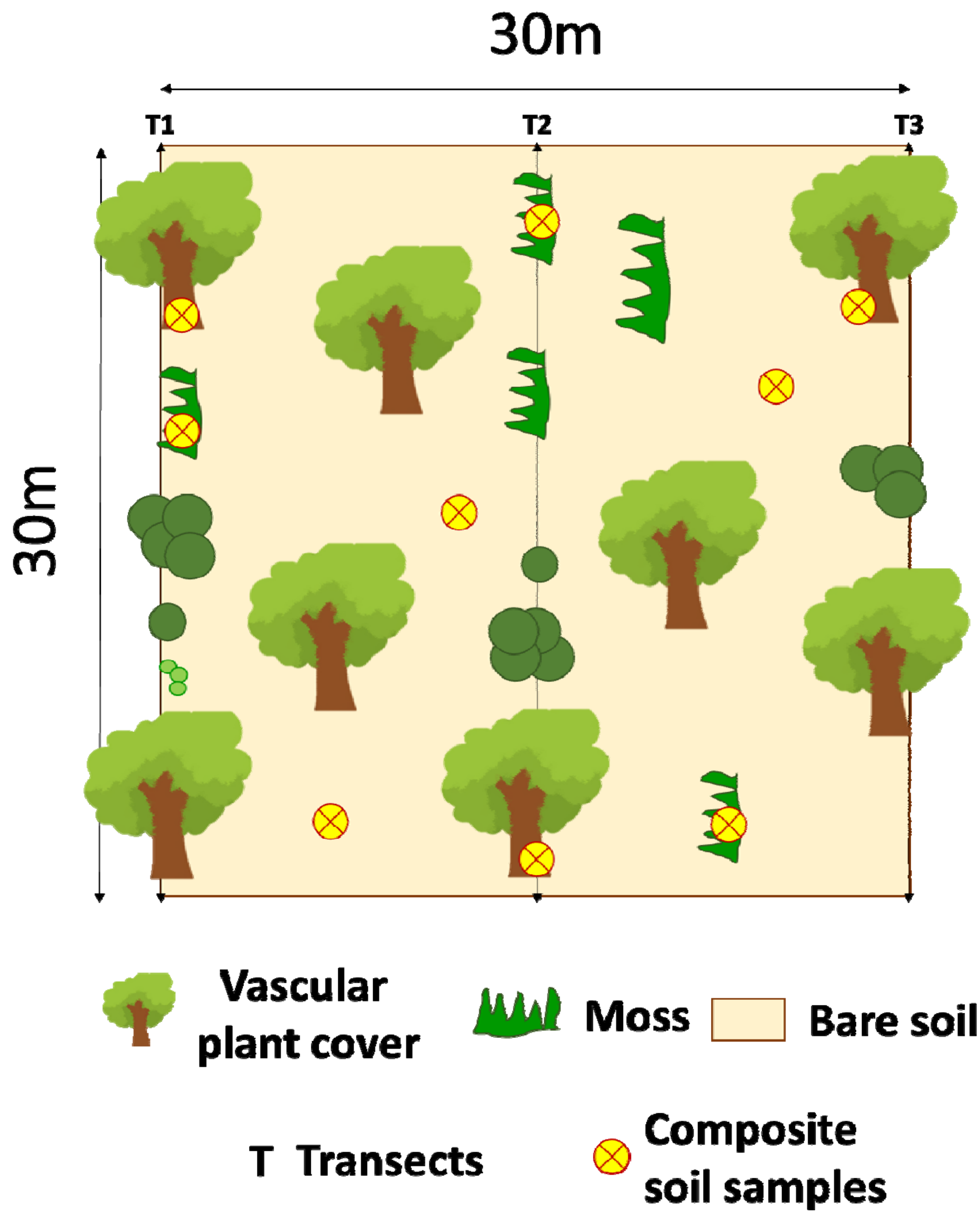


Figure S2. Map of locations and schematic representation of experimental design.

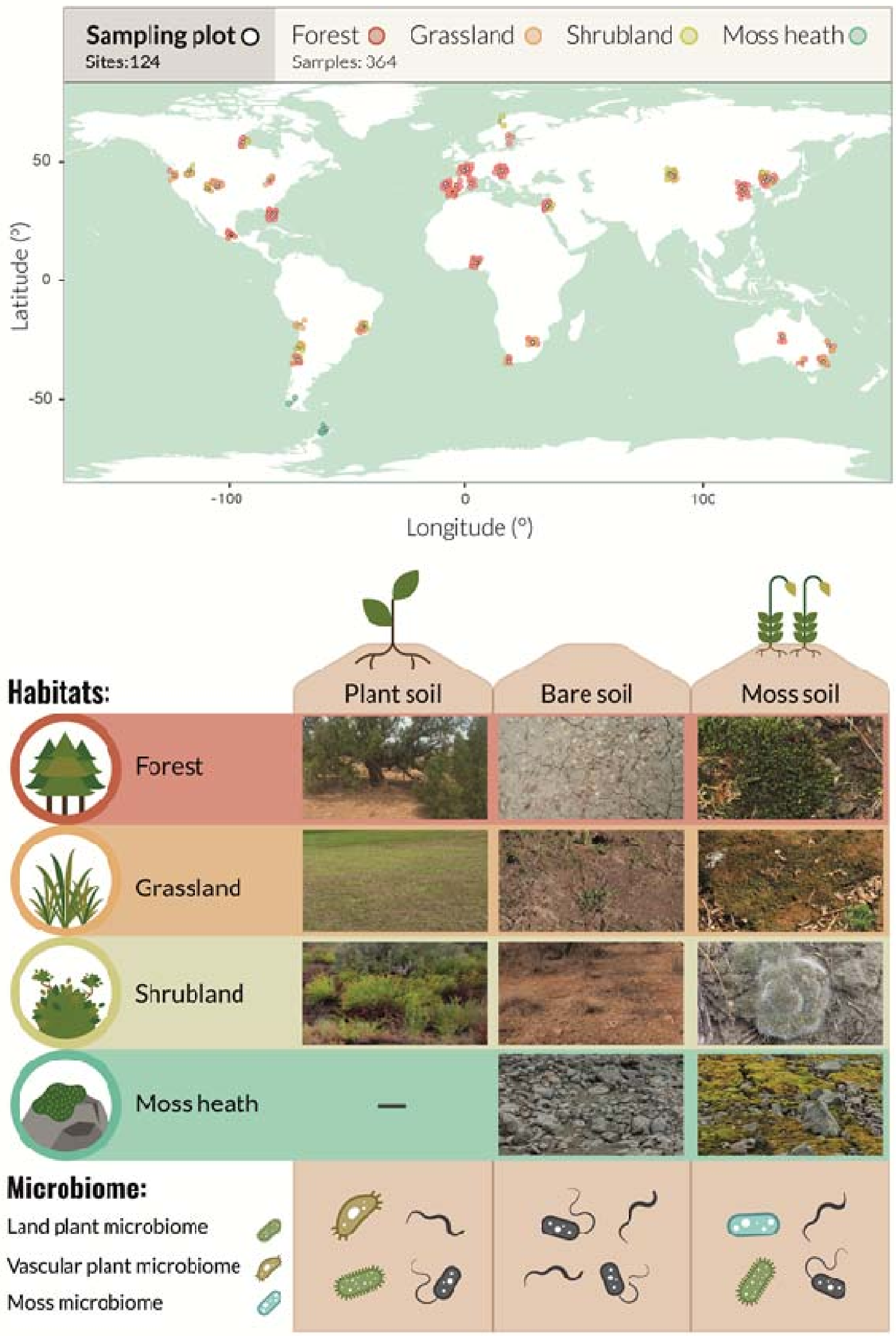


Figure S3. Standardised relative abundance of microbial taxa forming part of the soil-borne microbiome of vascular plants depending on functional traits (i.e., mycorrhizal type, and nitrogen fixing capacity), taxonomy (family), and land management (natural vs. urban environments). All contrasts showed no significant differences ($P > 0.05$; see main text for exact values). AM = arbuscular mycorrhizal species. EM = ectomycorrhizal species. Ericoid = ericoid mycorrhizal species. NM = non-mycorrhizal species. N = no. Y = yes. Magnoliophyta refers to flowering plants (angiosperms). Conifers (Pinophyta) are shown as representative of gymnosperms.

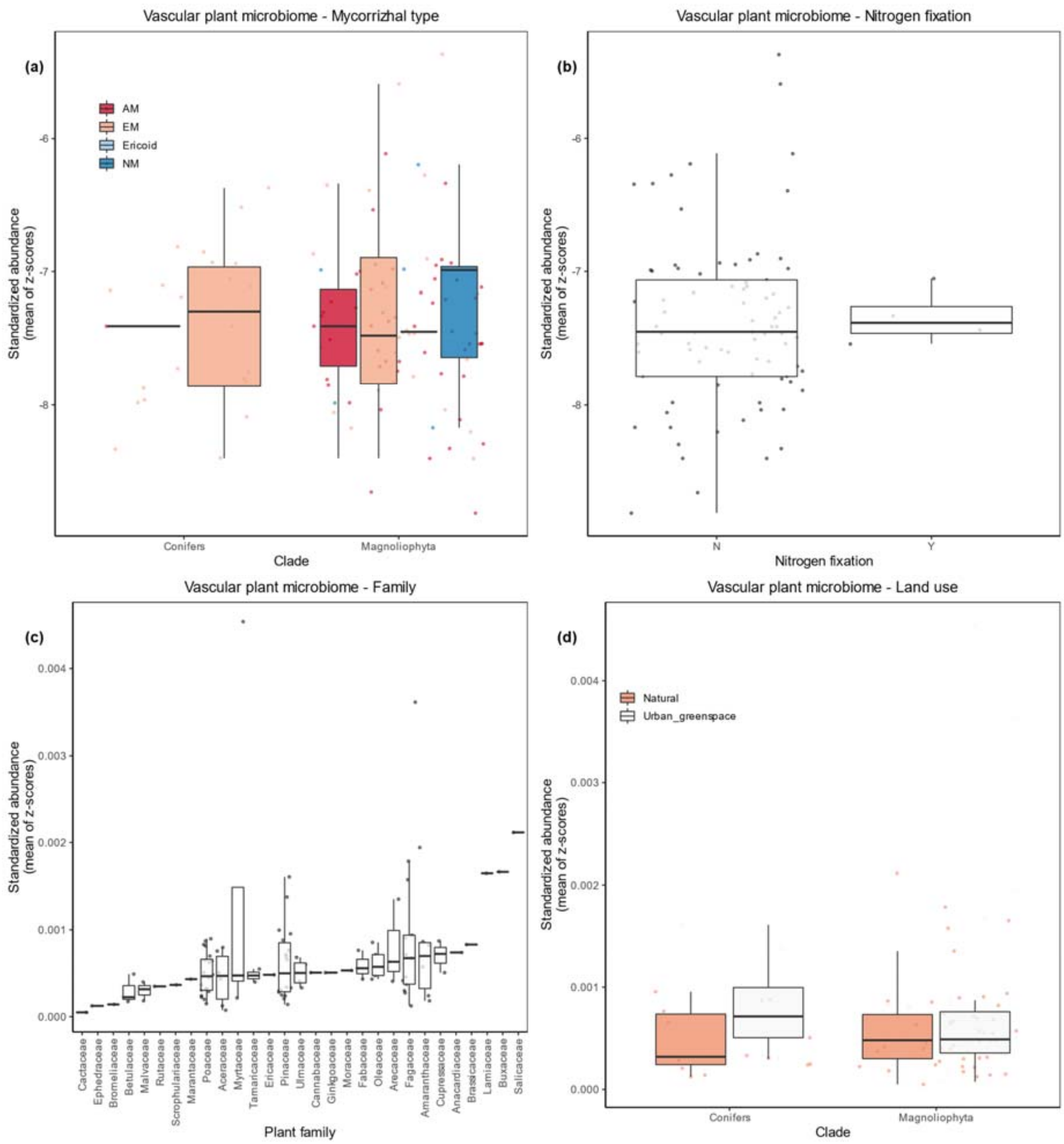


Figure S4. Standardised relative abundance of microbial taxa forming part of the soil-borne microbiome of mosses depending on taxonomy (family), functional traits (growth type and perenniality), and land management (natural vs. urban environments). The abundance of soil-borne organisms uniquely linked with mosses was greater in acrocarpous and ephemeral mosses (see Results section). Pleurocarpous = prostate growth. Acrocarpous = erect growth.

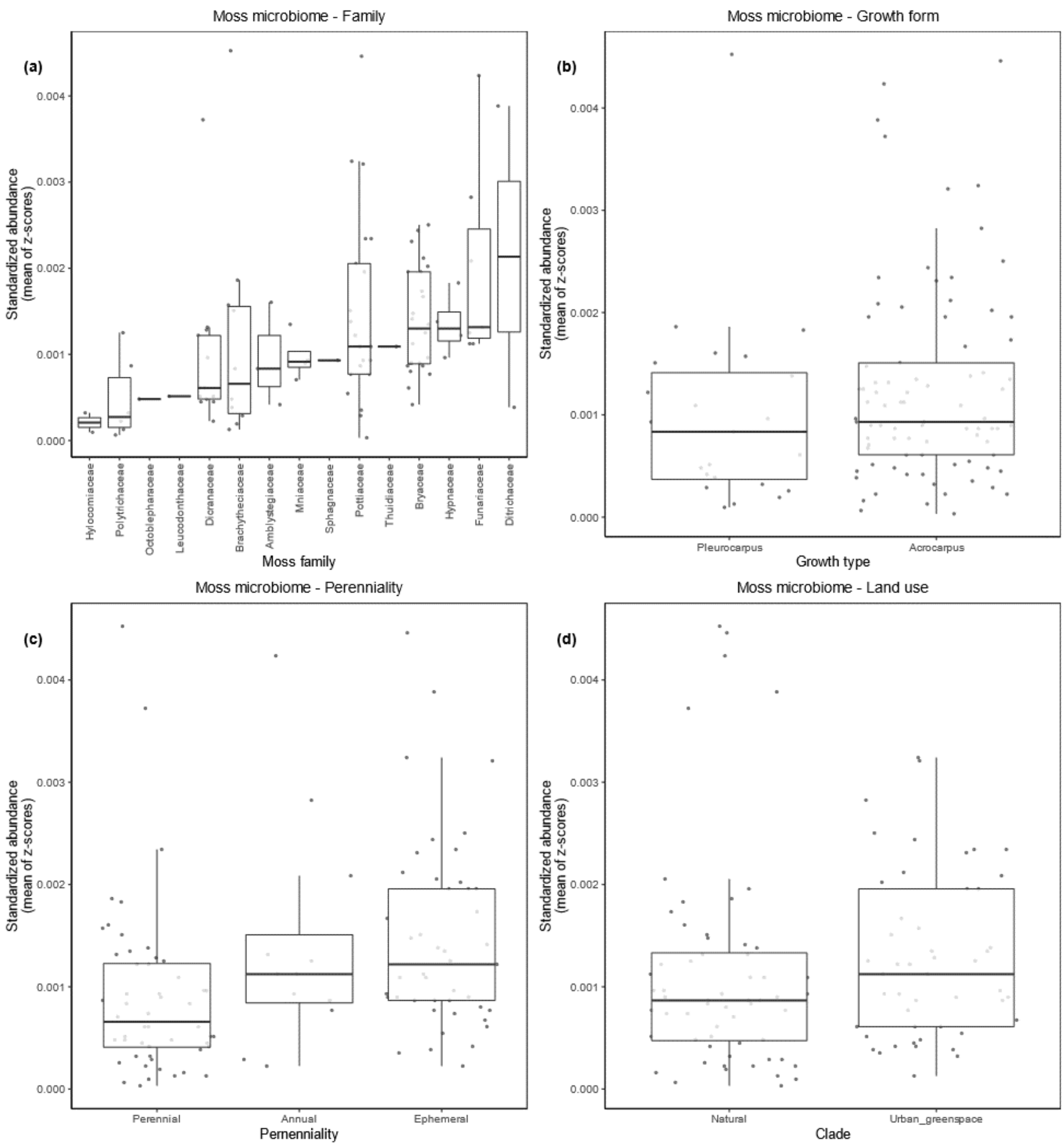


Figure S5. Selected examples of microbial taxa whose relative abundance was consistently higher in vascular plant-associated soils. For associated stats, see Table S15.

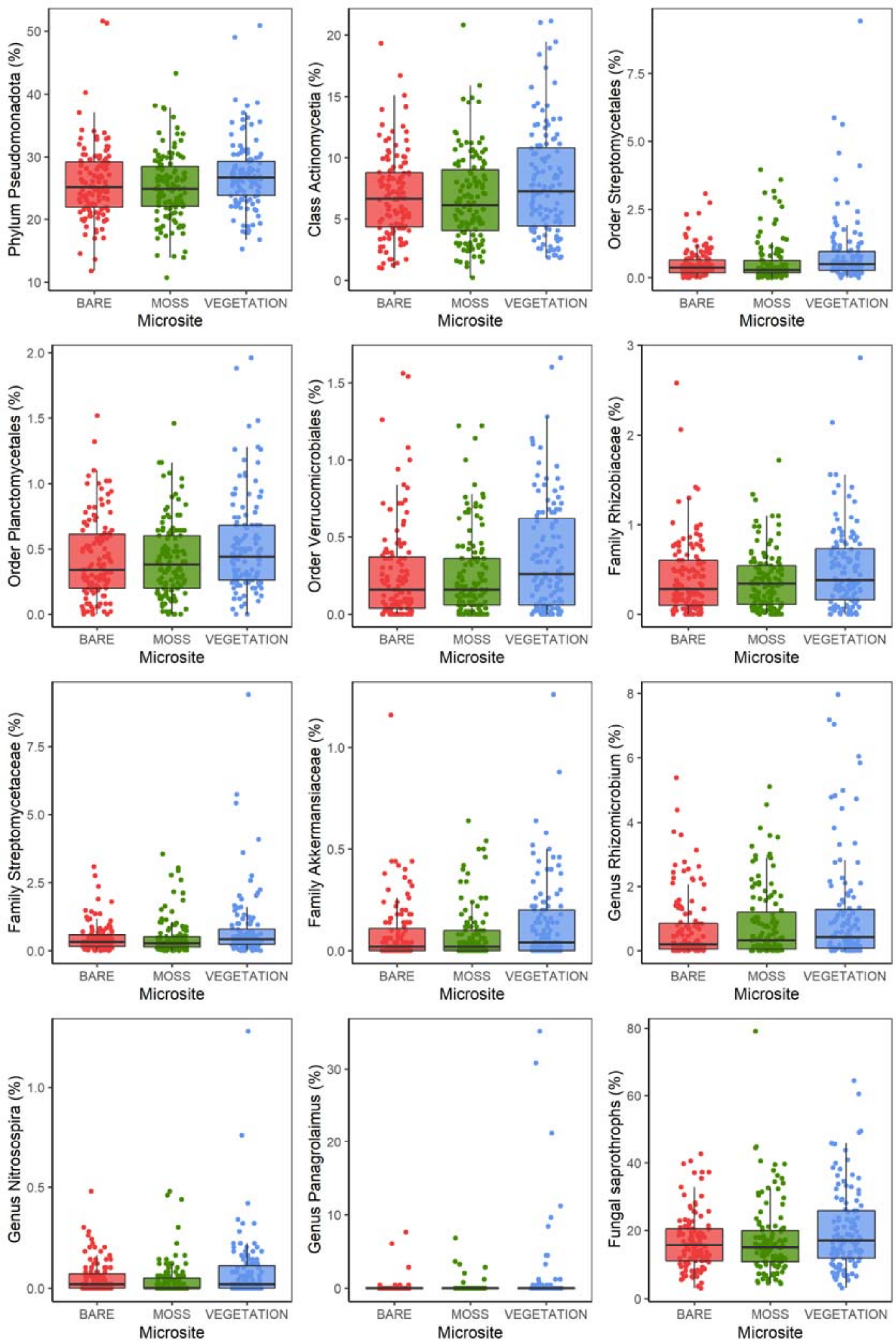
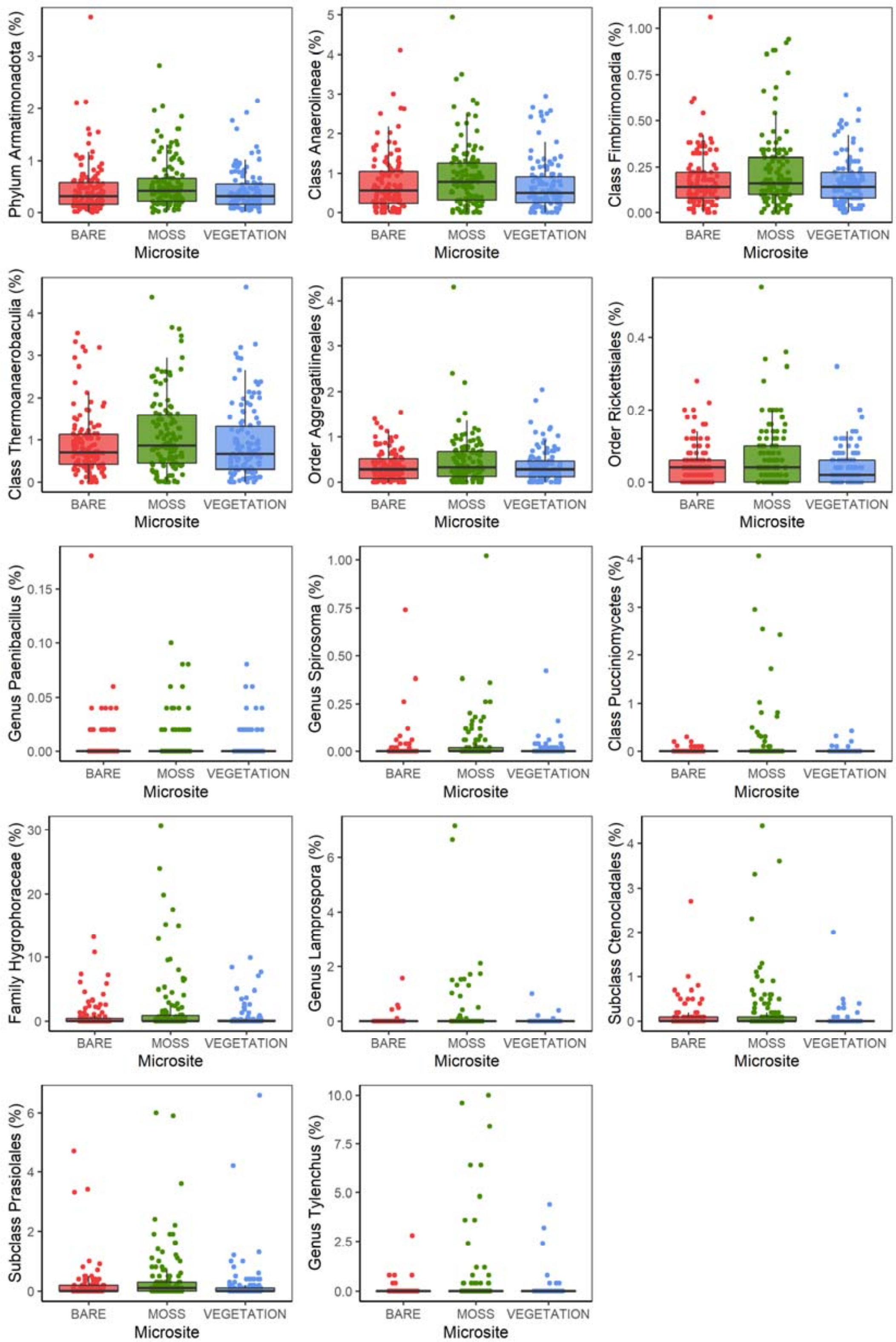

Phylum Pseudomonadota (%)
Class Actinomycetia (%)
Order Streptomycetales (%)
Order Planctomycetales (%)
Order Verrucomicrobiales (%)
Family Rhizobiaceae (%)
Family Streptomycetaceae (%)
Family Akkermansiaceae (%)
Genus Rhizomicrobium (%)
Genus Nitrosospira (%)
Genus Panagrolaimus (%)
Fungal saprothrophs (%)
BARE
MOSS
VEGETATION
Microsite

Figure S6. Selected examples of microbial taxa whose relative abundance was consistently higher in moss-associated soils. For associated stats, see Table S15.



Appendix 1. Extended methods

Environmental thresholds

The linear model is the null hypothesis and assumes a gradual response of a given ecosystem attribute in response to increases in the environmental factor of interest. Quadratic and GAM models indicate a nonlinear, but continuous, trend throughout the environmental gradient. We chose quadratic models to synthetize the simplest case of nonlinear trends, and GAMs to summarize more complex trends (through smoothing parameters). Therefore, we explored the presence of thresholds only when non-linear models were a better fit to the data. We did so because threshold models (e.g., segmented, step and segmented regressions) force the existence of at least one threshold, and therefore applying these methods to relationships that best fit linear regressions will lead to over-fitting and the detection of spurious thresholds.

We typified the responses of a non-linear trend by actively searching the two types of thresholds according to the definition in Groffman *et al.* (2006): continuous and discontinuous. Following this definition, we considered a threshold as the point in the environmental drivers at which a given variable either changes its value abruptly (discontinuous threshold, or breaking point) or its relationship with the environmental threshold (continuous threshold). Continuous thresholds may be well fitted to segmented regressions (i.e., a linear regression that modifies its slope at a certain value of the predictor, or threshold). Also, when fitting segmented regressions to models that are better fitted with smooth nonlinear continuous trends (such as models that best fit GAM regressions), segmented regressions indicate the point of maximum curvature of the fit. This point can be considered a threshold in the sense that it shows a peak of change in the response of the variable to the environmental driver, even if the fit of segmented regressions is poorer than that of GAM or other nonlinear models. Discontinuous thresholds involve an overall change in the intercept, apart from the slope, and may be fitted to either step (linear regressions that change only the intercept at a given point or threshold) or a combination of step + segmented regressions (stegmented; exhibits changes in both the intercept and slope at a given point or threshold).