Supporting Information

Plants and mycorrhizal symbionts acquire substantial soil nitrogen from gaseous ammonia transport

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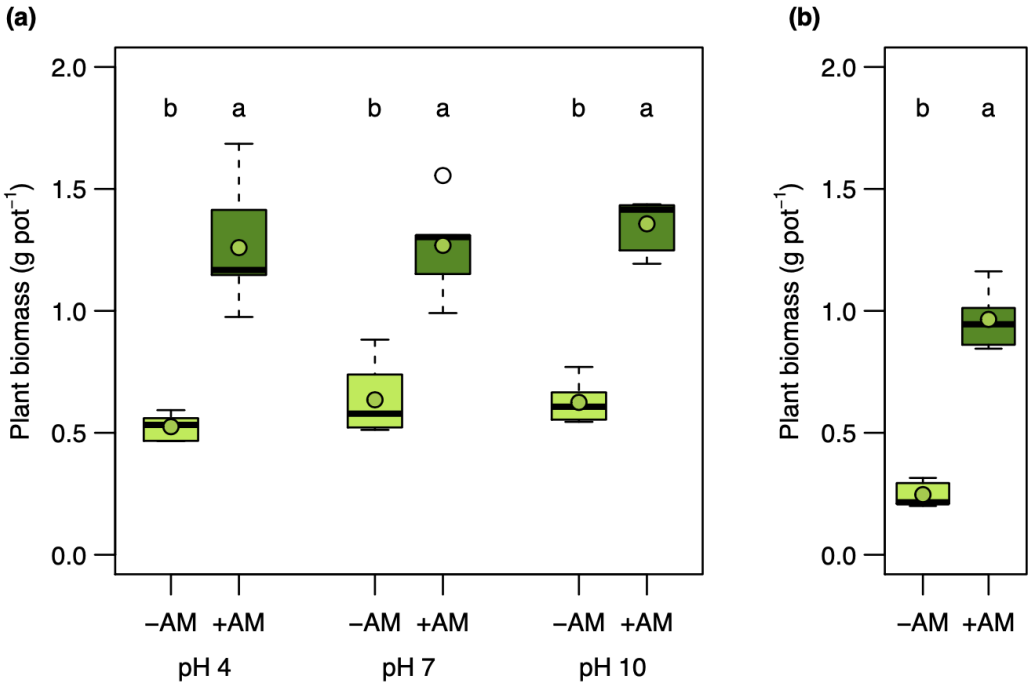

Figure S1. Total plant biomass (dry weight). Total biomass of uncolonized and AM-colonized plants harvested from three-compartmented mesocosms (a) and two-compartmented mesocosms (b). Colonization by AM fungi was significantly associated with greater plant biomass in both experiments. Bold black lines represent the median values; green circles represent the mean values; open circles represent the outliers; whiskers represent the upper and lower quartiles (n = 6 replicates per treatment for three-compartmented mesocosms; n = 5 replicates per treatment for two-compartmented mesocosms). Letters denote the results of a Tukey's HSD test performed on log-transformed data ($p < 0.05$).

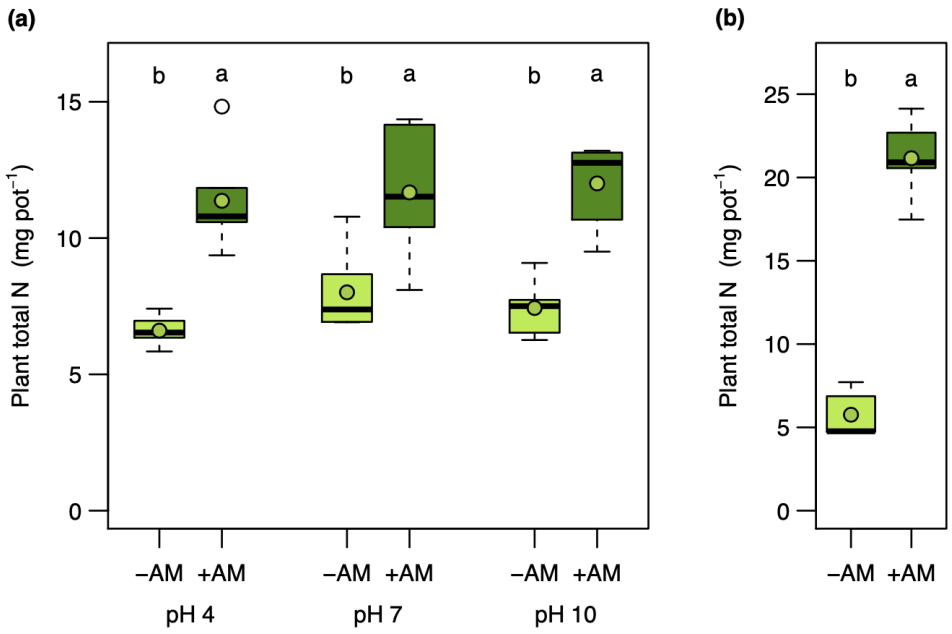

Figure S2. Total plant N uptake. Total plant N uptake in three-compartmented mesocosms (a) and two-compartmented mesocosms (b). Uncolonized and AM-colonized plants are shown in light green and dark green boxplots, respectively. Bold black lines represent the median values; green circles represent the mean values; open circles represent the outliers; whiskers represent the upper and lower quartiles (n = 6 replicates per treatment for three-compartmented mesocosms; n = 5 replicates per treatment for two-compartmented mesocosms). Letters denote the results of a Tukey's HSD test ($p < 0.05$) performed on log-transformed data.

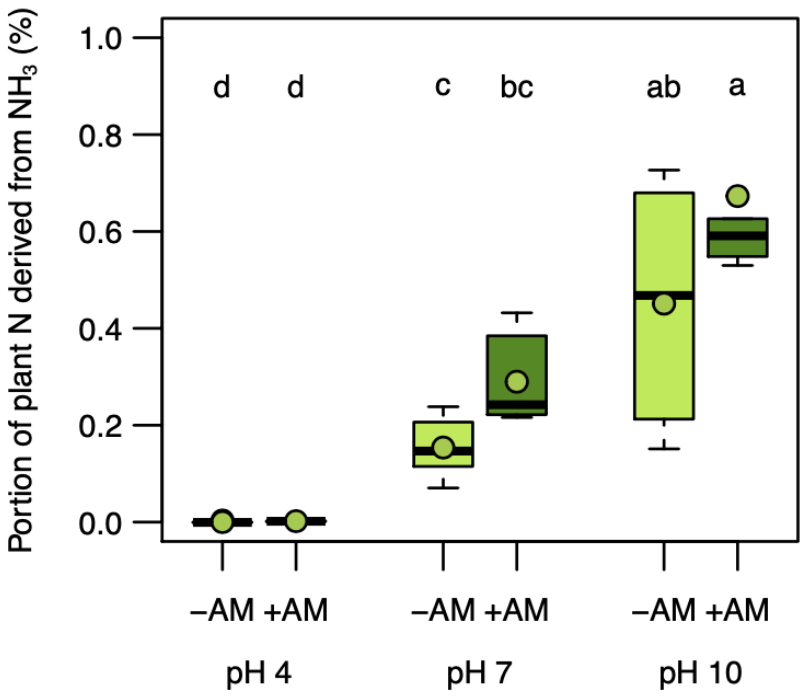

Figure S3. Percent of total plant N derived from NH_3. Proportion of total N that uncolonized and AM-colonized plants derived from NH_3 gas is shown in light green and dark green boxplots, respectively. Bold black lines represent the median values; green circles represent the mean values; open circles represent the outliers; whiskers represent the upper and lower quartiles (n = 6 replicates per treatment). Letters denote the results of a Tukey's HSD test ($p < 0.01$) performed on log-transformed data.

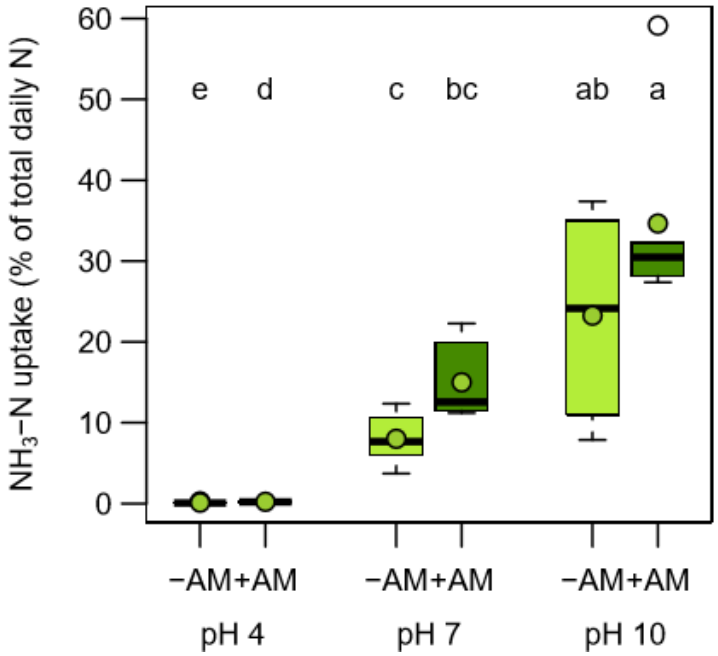

Figure S4. Estimated proportion of daily plant N uptake from subsurface NH_3-N. The proportion of daily N uptake that uncolonized and AM-colonized plants acquired from subsurface NH_3 is shown in light green and dark green boxplots, respectively. Bold black lines represent the median values; green circles represent the mean values; open circles represent the outliers; whiskers represent the upper and lower quartiles (n = 6 replicates per treatment). Letters denote the results of a Tukey's HSD test ($p < 0.01$) performed on log-transformed data.

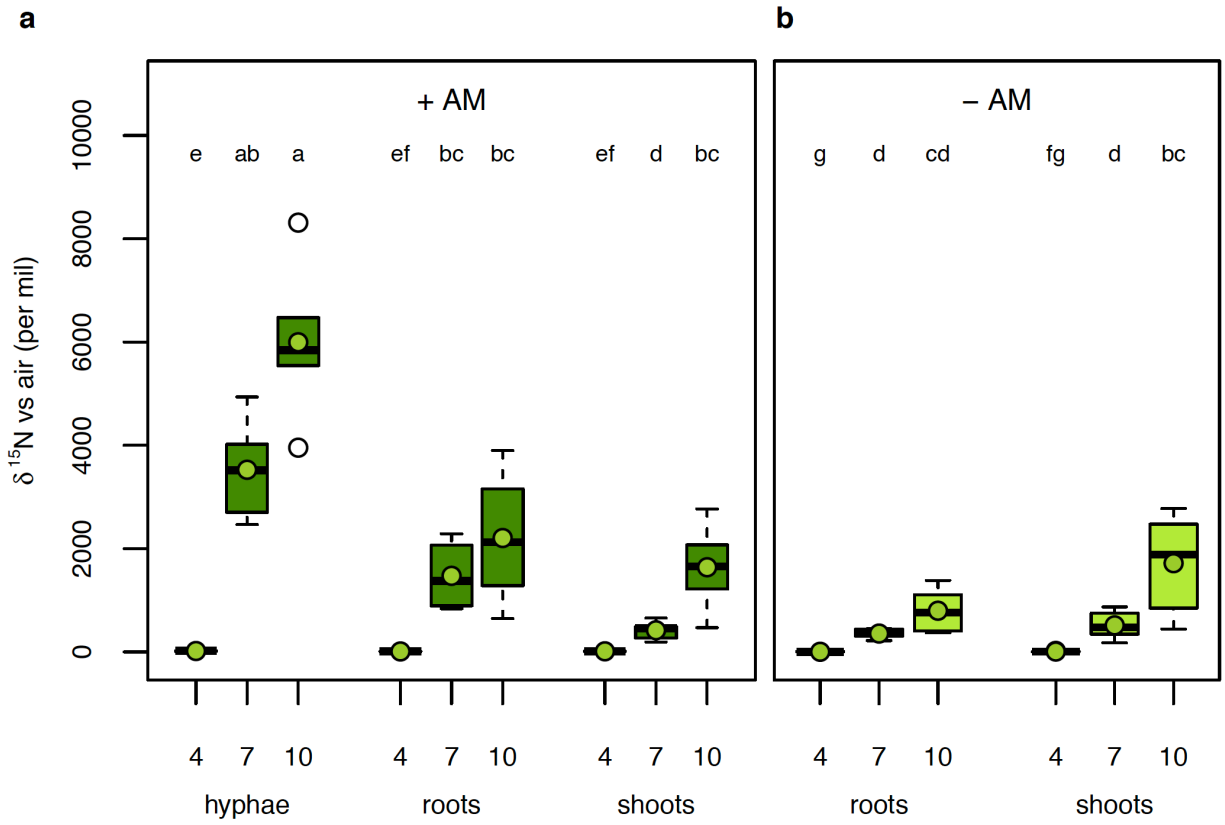

Figure S5. ^{15}N enrichment of fungi and plants following $^{15}NH_3$ injection through acidic, neutral, and alkaline subsurface substrates. (a) ^{15}N enrichment of AM hyphae and plant roots and shoots grown with AM fungi shown in dark green boxplots. (b) ^{15}N enrichment of plant roots and shoots grown without AM fungi shown in light green boxplots. Tissue type (plant roots, plant shoots, fungal hyphae) and subsurface substrate pH (4, 7, 10) are indicated along the x axis. Bold black lines represent the median values; green circles represent the mean values; open circles represent the outliers; whiskers represent the upper and lower quartiles (n = 6 replicates per treatment). Letters denote the results of a Tukey's HSD test ($p < 0.01$) performed on the full set of log-transformed data.

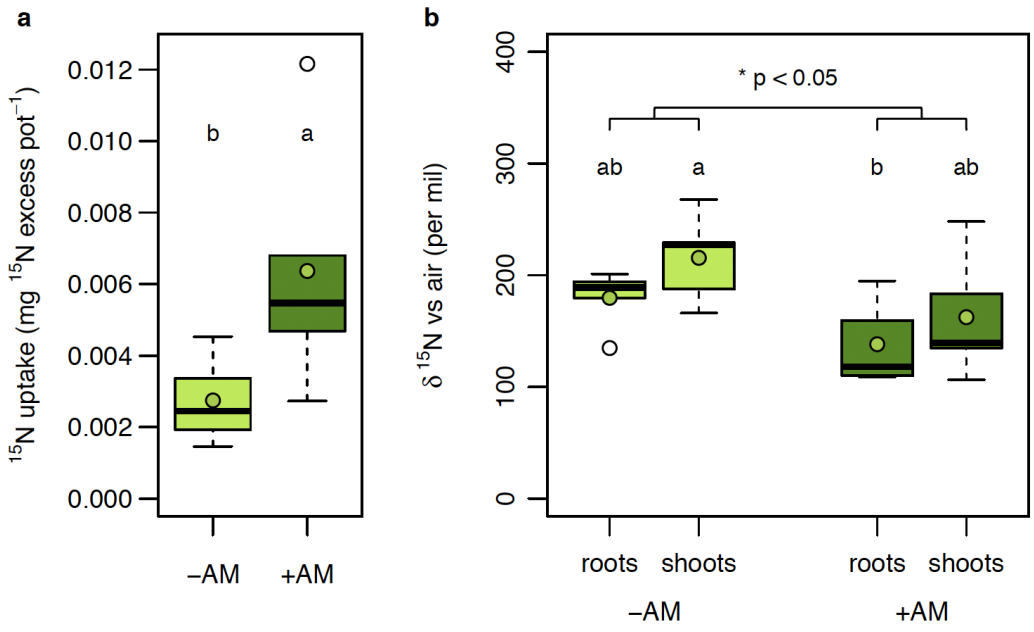

Figure S6. Total (a) and proportional (b) plant ^{15}N acquisition from subsurface gas produced during organic matter (OM) decomposition. (a) Uncolonized plants acquired significantly less total ^{15}N than AM-colonized plants, shown in light green and dark green boxplots, respectively. Letters denote the results of a Tukey's HSD test performed on log-transformed data ($p < 0.05$). (b) AM-colonized plants acquired a smaller proportion of their total N from OM compared to uncolonized plants, as indicated by plant δ^{15}N values. Within each fungal treatment, the isotopic N compositions of above- and belowground plant tissues were not significantly different. Letters denote the results of a Tukey's HSD test performed on untransformed data ($p < 0.05$). In both plots, bold black lines represent the median values; green and tan circles represent the mean values; open circles represent the outliers; whiskers represent the upper and lower quartiles ($n = 5$ replicates per treatment).

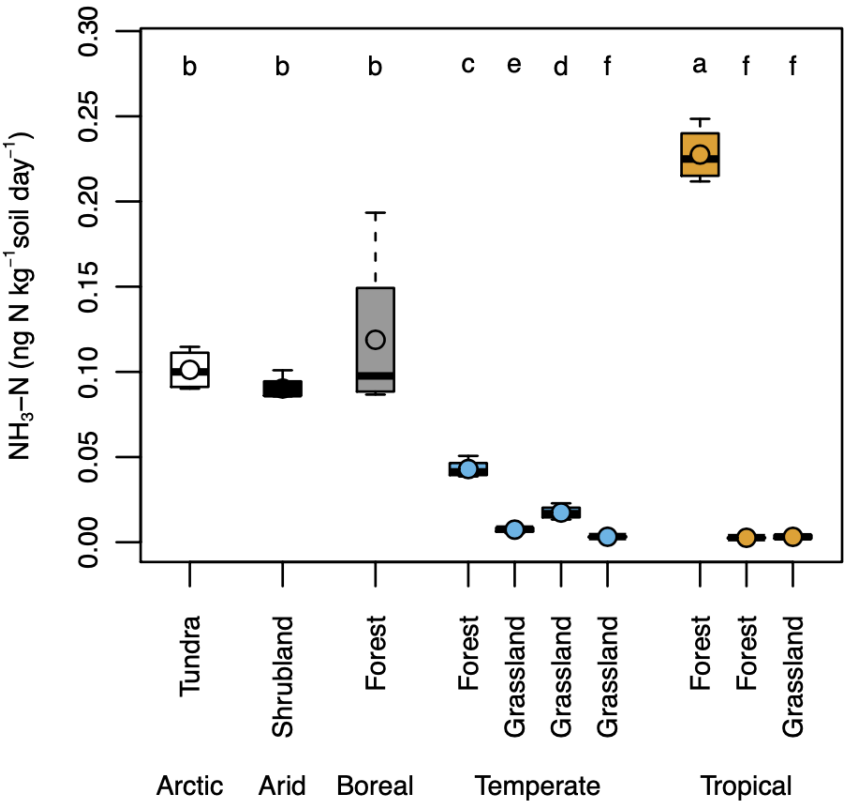

Figure S7. Variation in NH_3-N efflux from natural soils. Daily NH_3-N efflux measured during a laboratory incubation of soils collected from natural ecosystems is represented in box-and-whisker plots. Black lines represent the median values; whiskers represent the upper and lower quartiles (n = 4 replicates per treatment). Soils originating from arctic, arid, boreal, temperate, and tropical climates are represented in white, black, grey, blue, and orange, respectively (n = 4 replicates per location). Letters denote the results of a Tukey's HSD test performed on log-transformed data ($p < 0.05$).

Table S1. ANOVA table for the relationship between pH, mycorrhizal colonization, and plant ^{15}N derived from $^{15}NH_3$.

Source of variation	*df*	*SS*	*MS*	*F*	*p*
pH	2	143.06	71.53	309.42	< 0.001
AM	1	5.31	5.32	22.96	< 0.001
pH:AM	2	0.88	0.44	1.91	0.17
Residuals	30	5.78	0.23		

Degrees of freedom (df), sum of squares (SS), and mean square (MS).

Table S2. Characteristics of natural soils used in laboratory incubation.

Biome	Location	Sample Depth	pH	Clay	Bulk Density	C	N	C:N
Arctic Tundra	Alaska	0.85-1.05	7.79	15.9	0.99	3.55	0.22	16
Boreal Forest	Sweden	0-0.10	2.52	0	0.10	40.73	0.93	44
Temperate Forest	China	0-0.05	5.98	0	0.10	24.34	1.47	17
Tropical Forest	Brazil	0-0.08	3.74	26.7	0.92	1.99	0.15	13
Tropical Forest	Kenya	0-0.10	6.89	47	0.80	11.26	0.25	45
Temperate Grassland	Canada	0-0.15	6.33	25	1.24	8.34	0.38	22
Temperate Grassland	Kansas	0-0.35	5.89	34.2	1.39	3.73	1.12	3
Temperate Grassland	New York	0-0.25	5.39	16.3	1.39	1.51	0.16	9
Tropical Grassland	Colombia	0-0.05	4.22	40	1.27	1.28	0.09	14
Arid Desert Shrubland	New Mexico	0-0.13	6.95	15	1.42	2.43	0.37	7

Sample depth (m), pH measured in KCl, clay (%), bulk density (g mL^{-1}), C and N (%) of soil samples used to assess relationships between edaphic properties and NH_3 efflux from soils under natural vegetation. Aside from soil pH, the data presented here are compiled from previously published studies utilizing these soils: Zackrisson *et al.*, 1996; Liang *et al.*, 2006; Solomon *et al.*, 2009; Recha *et al.,* 2012; Cayuela *et al.,* 2013; Dharmakeerthi *et al.,* 2015; Mueller *et al.*, 2015; Ahmed *et al.*, 2017.

References

Ahmed ZU, Woodbury PB, Sanderman J, Hawke B, Jauss V, Solomon D, Lehmann J. 2017. Assessing soil carbon vulnerability in the Western USA by geospatial modeling of pyrogenic and particulate carbon stocks. *Journal of Geophysical Research-Biogeochemistry* **122**: 354-369.

Cayuela ML, Sánchez-Monedero MA, Roig A, Hanley K, Enders A, Lehmann J. 2013. Biochar and denitrification in soils: when, how much and why does biochar reduce N_2O emissions? *Scientific Reports* **3**: 1732.

Dharmakeerthi RS, Hanley K, Whitman T, Woolf D, Lehmann J. 2015. Organic carbon dynamics in soils with pyrogenic organic matter that received plant residue additions over seven years. *Soil Biology & Biochemistry* **88**: 268-274.

Liang B, Lehmann J, Solomon D, Kinyangi J, Grossman J, O'Neill B, Skjemstad JO, Thies J, Luizao FJ, Petersen J, Neves EG. 2006. Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal* **70**: 1719-1730.

Mueller CW, Rethemeyer J, Kao-Kniffin J, Löppmann S, Hinkel KM, Bockheim JG. 2015. Large amounts of labile organic carbon in permafrost soils of northern Alaska. *Global Change Biology* **21**: 2804-2817.

Recha JW, Lehmann J, Walter MT, Pell A, Verchot L, Johnson M. 2012. Stream discharge in tropical headwater catchments as a result of forest clearing and soil degradation. *Earth Interactions* **16**: 1-18.

Solomon D, Lehmann J, Kinyangi J, Pell A, Theis J, Riha S, Ngoze S, Amelung W, Preez C, *et al.* 2009. Anthropogenic and climate influences on biogeochemical dynamics and molecular-level speciation of soil sulfur. *Ecological Applications* **19**: 989-1002.

Zackrisson O, Nilsson MC, Wardle DA. 1996. Key ecological function of charcoal from wildfire in the Boreal forest. *Oikos* **77**: 10-19.