Supplementary Materials for

Mycorrhizal Association as a Primary Control of the CO_2 Fertilization Effect

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This PDF file includes:

Materials and Methods
Figs. S1 to S8
Tables S1 to S4
References

Materials and Methods

Data collection

We collected published and unpublished data on total, aboveground and belowground biomass (g m^{-2}) from eCO_2 experiments. We consulted the list of CO_2 experiments from INTERFACE (https://www.bio.purdue.edu/INTERFACE/experiments.php), the Global List of FACE Experiments from the Oak Ridge National Laboratory (http://facedata.ornl.gov/global_face.html), the ClimMani database on manipulation experiments (www.climmani.org), and the database described by Dieleman *et al.* (*35*), and freely available (https://www.researchgate.net/publication/276839560_Database_of_Global_Change_Manipulation_Experiments). We used Google Scholar to locate the most recent publications for each of the previously listed experiments, and collected data on total, aboveground and belowground plant biomass for ambient and elevated CO_2 treatments. When the data were presented in figures we extracted mean values and standard error using GraphClick. Additionally, we collected available data about the vegetation, sample size, soil fertility, land use history, MAP, MAT and the age of the vegetation at the start of the experiment. Some experiments were not included in the meta-analysis if they met any of the following exclusion criteria: i) species did not form associations with AM or ECM; ii) papers did not report biomass data; iii) standard error or standard deviation was not provided; iv) information about the fertility of the site was not reported (e.g. soil type, pH, or qualitative assessments of N-availability); v) duration of the experiment was less than 3 months.

Experimental units

Where possible, data were collected at the species level, and different species within experiments were considered independent when grown in monoculture; when available data were pooled across several species, these were only included in the analysis if all the species were associated with the same type of mycorrhizal fungi. Experiments in which the most abundant species were C_4 or N_2-fixing species were excluded from the main analysis to avoid confounding effects. Different N-fertilization treatments within experiments were considered independent. These selection criteria allowed us to assess N-status and mycorrhizal association in the individual experimental units. Overview of the experiments included in the dataset is in table S1, and the data included in the meta-analysis in figs. S1-3.

Nitrogen classification

N-classification followed a similar approach as refs. *17*, *36*, *37*, but did not consider limitations of nutrients other than N. Experiments were classified as “low” or “high” in terms of N-availability based on the amount of N-fertilizer applied (if so), as well as the original N-availability at the sites, as a function of available data such as soil type, nitrogen and carbon content, pH, land use history, and the assessment of N-availability (reported in the literature or provided by the site principal investigators -PIs-). For example, sandy soils have an inherently low nitrogen retention capacity, and are typically N poor if not fertilized or exposed to high N deposition. The C:N ratio of soil is indicative of the decomposability of soil organic matter. Especially high C:N ratios (>25) suggest low availability of N and potential N immobilization by microorganisms (*38*).

For some experiments, the available soil data were scarce. We then requested direct expert assessment by the PIs. More information regarding the classification of each experiment and the underlying reasons is given in Table S2. We classified all sites that had indications of N limitation to “low N”; sites that were unlikely N-limited (e.g., where N fertilization had no effects on plant growth) were designated as “high N”. We created an alternative N-classification with an additional “medium” class that grouped all those experiments with intermediate N-availability (e.g. moderately fertile soils with no N-fertilization, or N-poor soils with modest N-fertilization, but in the range in which N-availability limits growth). This alternative classification was used as a sensitivity analysis to test that the observed effects were not driven by sites with intermediate N availability classified as “low N” in the main classification.

Mycorrhizal status classification

We used the check-list in ref. *39*, with additional classifications derived from the literature, to classify plant species as ECM, or AM. Species that form associations with both ECM and AM fungi (e.g. Populus spp.) were classified as ECM because these species can potentially benefit from increased N-availability due to the presence of ECM-fungi, as hypothesized. Overall, CO_2 responses from species associated with AM and ECM were similar to strictly ECM species, and their exclusion did not alter the results of the meta-analysis.

N-fixing species.

When the data were presented at the plot level, with specification of the species present in each plot, all plots containing N-fixing species were not included in the main analysis because they might be particularly responsive to eCO_2 (*40*). We analysed the role of N-fixing species in a separate meta-analysis that included AM-species in N-limited ecosystems only, using the same methods as in the main meta-analysis, and including the responses from both N-fixing and their accompanying non N-fixing species. There were three N-limited-AM-dominated experiments that included N-fixing experiments for total biomass and seven for aboveground biomass. Therefore, the analysis of N-fixing species was performed using aboveground biomass only. The list of experiments with N-fixing species included in the analysis is in Table S3.

ΔCO_2

Ambient CO_2 treatments had concentrations ranging from 280 to 400 μmol mol^{-1}, whereas elevated CO_2 treatments had concentrations ranging from 420 to 780 μmol mol^{-1}, with an average of ~650 μmol mol^{-1}. ΔCO_2 was calculated as the natural log of the difference in CO_2 concentrations between elevated and ambient treatments: $\Delta CO_2 = \ln(eC_a/aC_a)$. Results from meta-analysis shown here were normalised for ΔCO_2 from 400 (current) to 650 (average [eCO_2]) μmol mol^{-1}, after including ΔCO_2 400-650 as a variable in a mixed-effects meta-regression.

MAT, MAP and age of the vegetation

MAT and MAP data were collected from the original source or from WorldClim Global Climate Data (*41*). When the experimental units were irrigated we did not use MAP data in the analysis, but instead we assigned the maximum value of MAP in the dataset (1750 mm y^{-1}) to all irrigated experimental units. When the age of the vegetation at the start of the experiment was not specified in the study, we assigned a value of 1 for seedlings, annuals, frequently grazed vegetation, or experiments under controlled burning, and the maximum value in the dataset (50 years) when the site was classified as "intact" or similar.

Calculation of effect sizes

We used the response ratio (*RR*, mean response in elevated to ambient CO_2 plots) to measure effect sizes (*42*). We calculated the natural logarithm of the response ratio (log *RR*) and its variance for each experimental unit to obtain a single response metric (*42*) in a weighted, mixed-effects model using the R package *metafor* (*43*). Measurements across different time-points (e.g. over several years or harvests) were considered non-independent, and we computed a combined effect across time-points so that only one effect size was analysed per experimental unit. The combined variance that takes account of the correlation among the different time-point measurements was calculated following the method described in Borenstein *et al.* (*44*):

$$\mathrm{var}\left(\frac{1}{m}\sum_{i=1}^{m} Y_i\right) = \left(\frac{1}{m}\right)^2 \left(\sum_{i=1}^{m} V_i + \sum_{i \neq j} (r_{ij}\sqrt{V_i}\sqrt{V_j})\right) \quad (1)$$

where V_i is the variance of effect size Y_i for several time-points i=1,...,m and r_{ij} as the correlation between Y_i and Y_j, with r=0 equivalent to treating two outcomes as independent, underestimating the error (and overestimating the precision). We used a conservative approach with r=1 (assuming non independence). The outcome was not sensitive to the assumption of r=1, with r=0 (independence) and r=0.5 rendering slightly different SE terms (and *P-value*) that did not alter the conclusions (Table S4).

Weighting functions

Effect size measurements from individual studies in meta-analysis are commonly weighted by the inverse of the variance (*45*) (W_V). For this particular analysis, not only well replicated, but also long-term studies provide more reliable estimates of ecosystem CO_2 responses (*46*). Thus, we weighted the individual effects by both replication and experimental duration by using the function in refs *11, 47*:

$$W_{NY} = (n_a * n_e)/(n_a + n_e) + (yr * yr)/(yr + yr) \quad (2)$$

with n_a and n_e as the number of replicates under ambient and elevated CO_2, and *yr* as the length of the study in years. Both weighting functions were used, but W_V assigned about half of the total weight to two experiments with very low variance creating a sub-optimal imbalance, and the results using W_V are only shown for comparison purposes in Fig. S6). Results shown in the main report and figures correspond to the meta-analysis using W_{NY} as weights. In all cases, the conclusions were consistent across various weighting functions.

Calculation of the overall true effect

We used the R package *metafor* (*43*) to calculate overall effect sizes and 95% confidence intervals (CI). The mixed-effects meta-regression model was fitted using maximum likelihood for the amount of residual heterogeneity. The Knapp and Hartung method (*48*) was included as an adjustment to the standard errors of the estimated coefficients to control the Type I error rate (*49*). This method leads to an F-test for sets of model predictors (test of moderators) to test their significance to influence the average effect of CO_2. For individual model coefficients, the method leads to t-tests. We inferred CO_2 effects if the calculated 95 % CI did not overlap with zero. The log response ratio was back-transformed and expressed as percentage CO_2 effect ([log *RR*-1] × 100) to ease interpretation in figures and text.

Model selection

We analysed the plausibility of models containing all potential combinations of the studied predictors in a mixed-effects meta-regression model using maximum likelihood estimation. For this purpose, we used the R packages *gmulti* (*50*) and *metafor* (*43*). Model selection was based on AICc. The relative importance value for a particular predictor was equal to the sum of the Akaike weights (probability that a model is the most plausible model) for the models in which the predictor appears. Hence, a predictor that is included in models with large Akaike weights will receive a high importance value. These values can be regarded as the overall support for each variable across all models. A cut-off of 0.8 was set to differentiate between important and non-essential predictors.

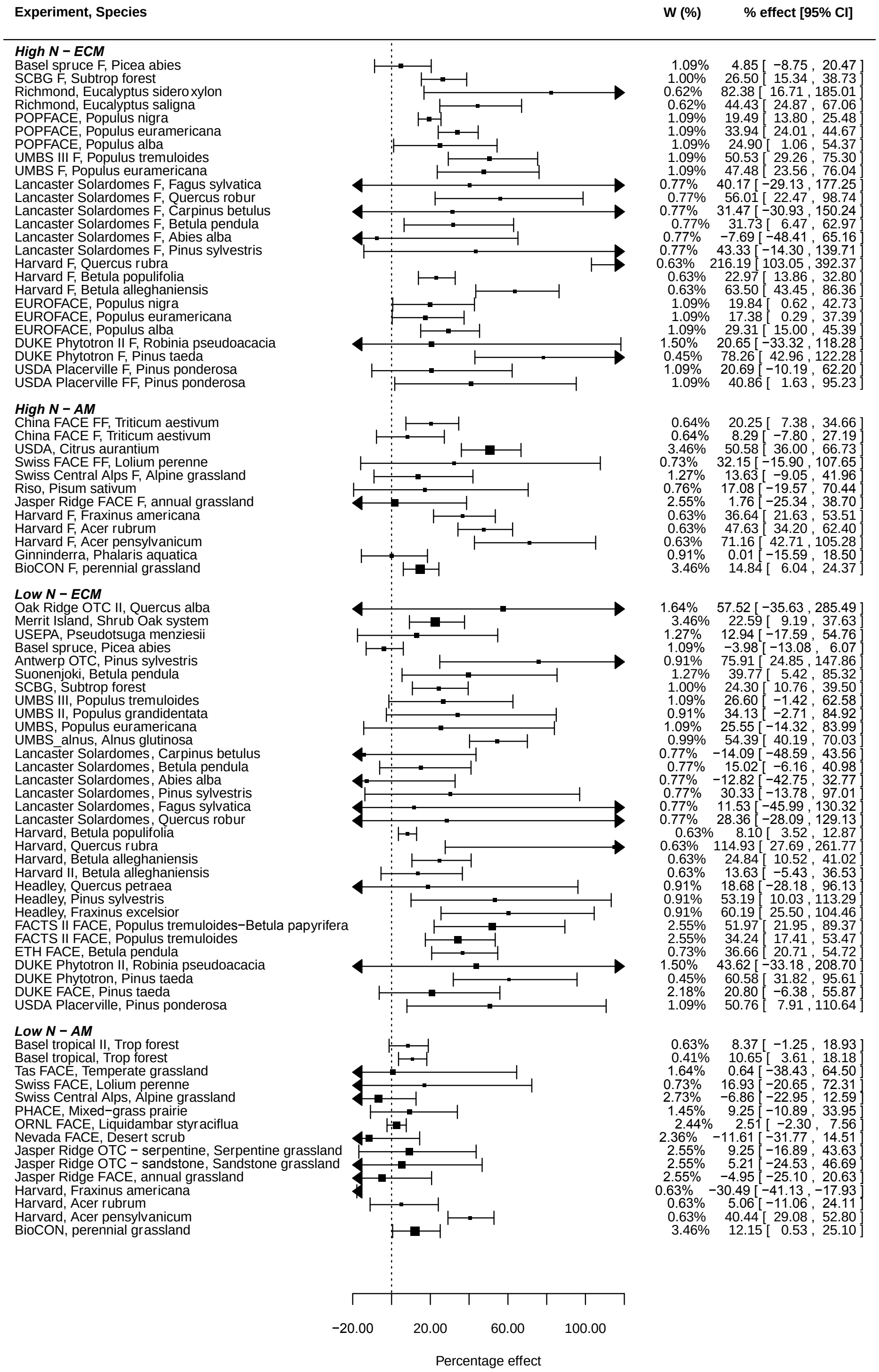

Fig. S1.

Total biomass data included in meta-analysis in Fig. 2A. W (%) are the weights used in the meta-analysis, based on the number of replicates and the length (years) of the studies.

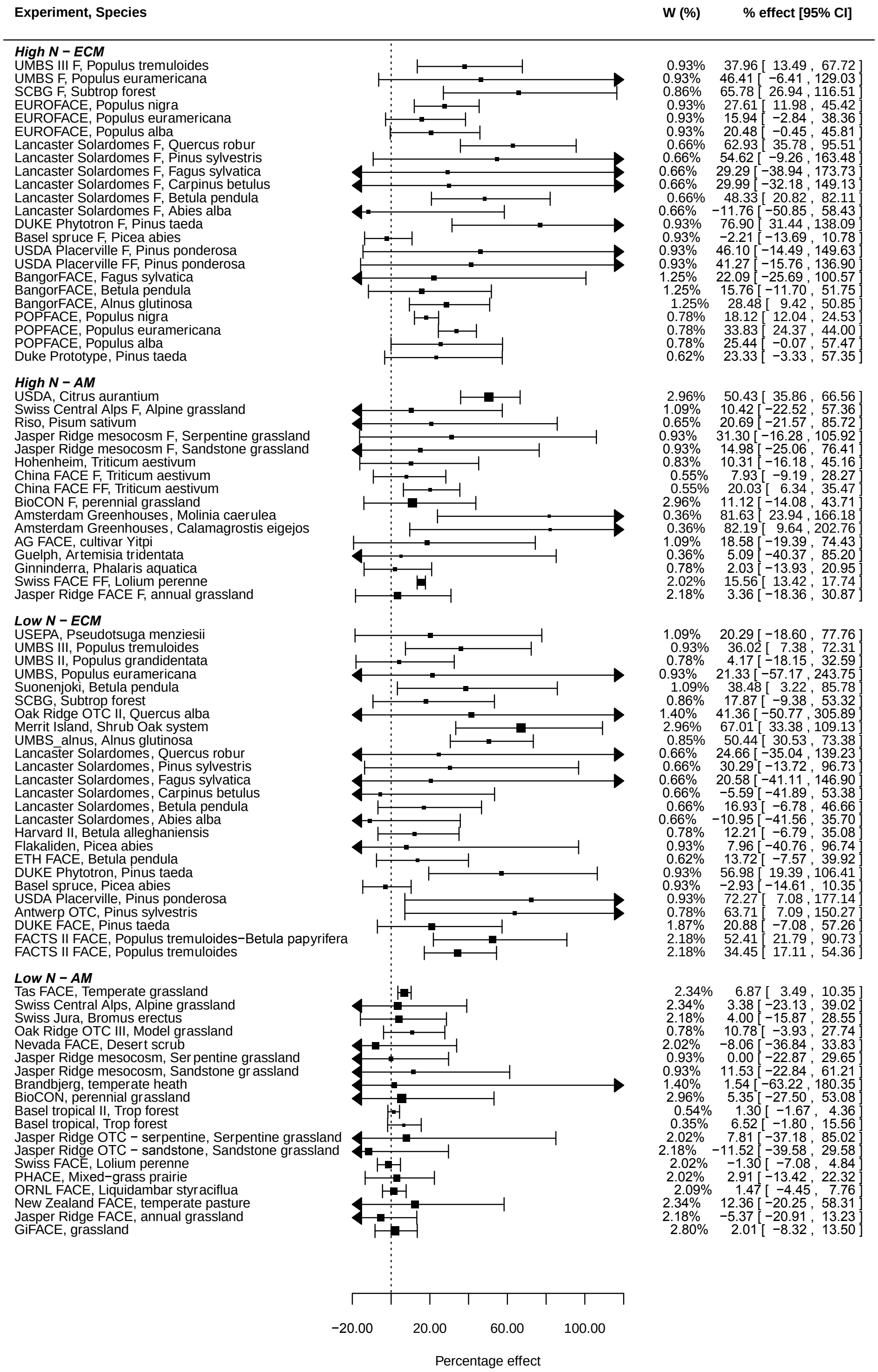

Fig. S2.

Aboveground biomass data included in meta-analysis in Fig. 2B. W (%) are the weights used in the meta-analysis, based on the number of replicates and the length (years) of the studies.

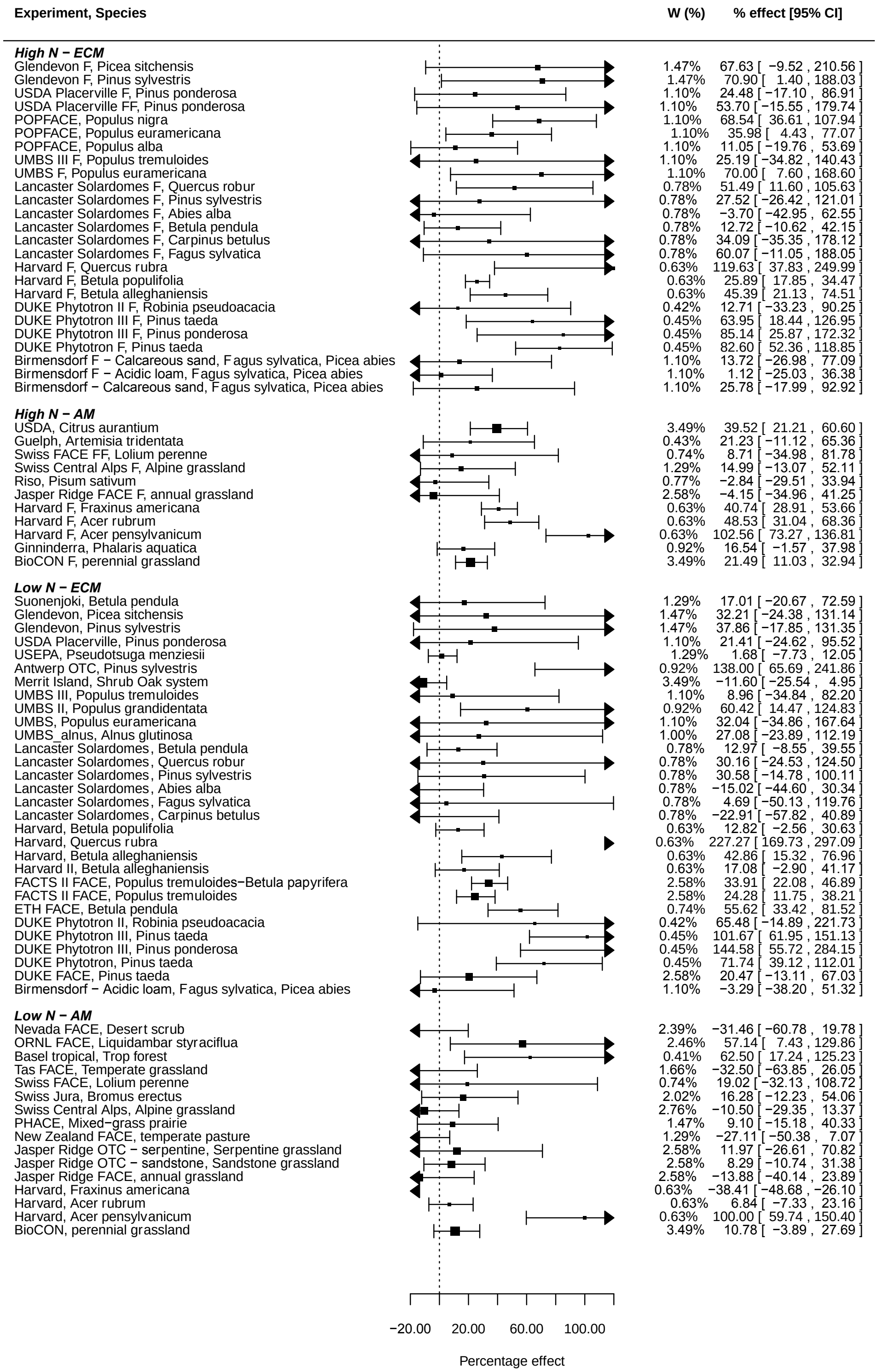

Fig. S3.

Belowground biomass data included in meta-analysis in Fig. 2C. W (%) are the weights used in the meta-analysis, based on the number of replicates and the length (years) of the studies.

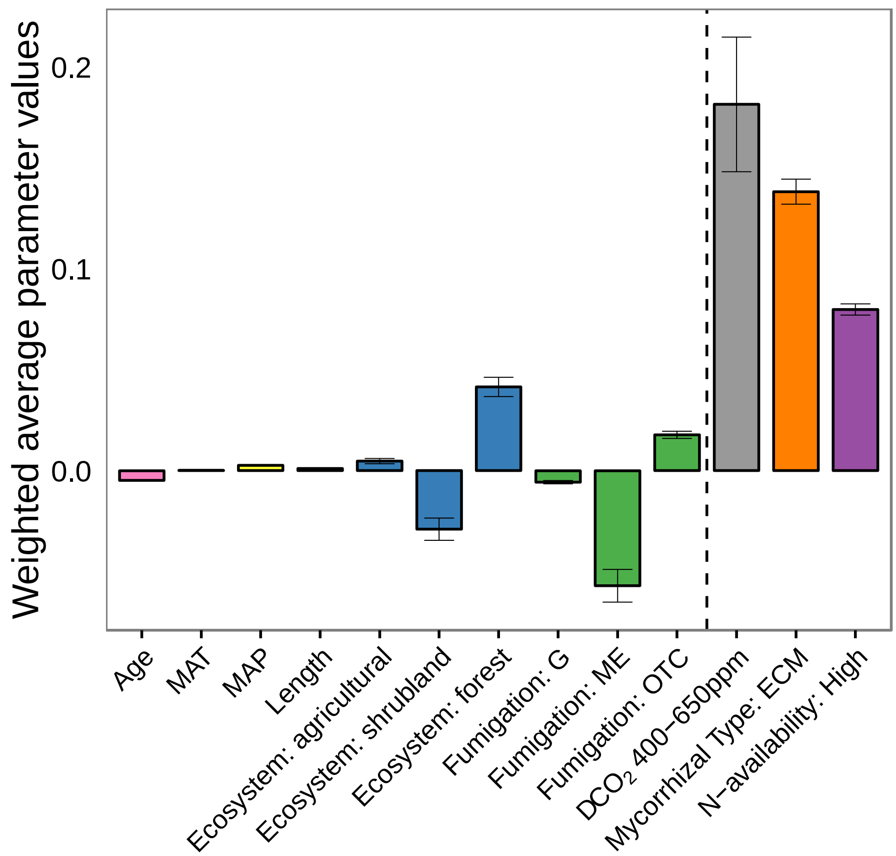

Fig. S4.

Weighted average parameter values of model coefficients. Weights equal to the model probabilities. Error bars are weighted SE. Model parameters in increasing relative importance, with predictors on the right side of the dashed line as the terms included in the AICc-selected best model and sum of Akaike weights > 0.8. G = Greenhouse/Growth chamber, ME = Model ecosystem, OTC = Open Top Chamber, ΔCO_2 = [CO_2] increment from 400 to 650 ppm. Reference parameters for qualitative factors are Fumigation: FACE, Ecosystem: grassland, Mycorrhizal type: AM, N-availability: Low.

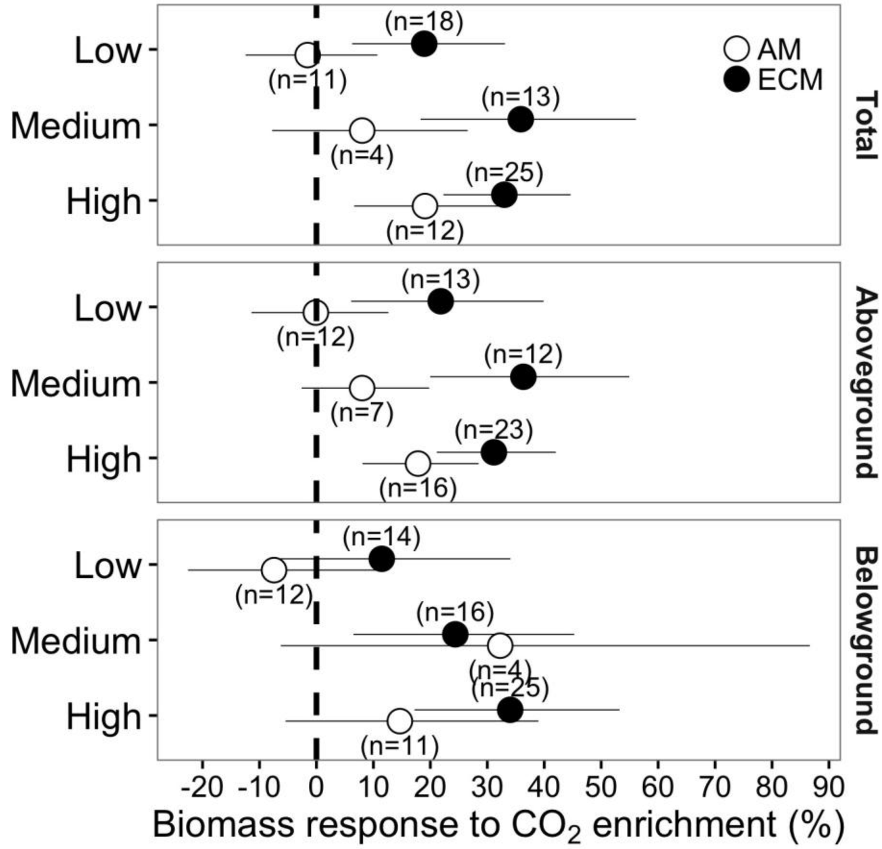

Fig. S5.

Overall effects of CO_2 on total, aboveground, and belowground biomass for two types of mycorrhizal plants species (AM: arbuscular mycorrhizae and ECM: ectomycorrhizae) in strongly N limited experiments (low N), moderately N limited experiments (medium N) or experiments that are unlikely N limited (high N). Overall means and 95% confidence intervals are given; we interpret CO_2 effects when the zero line is not crossed.

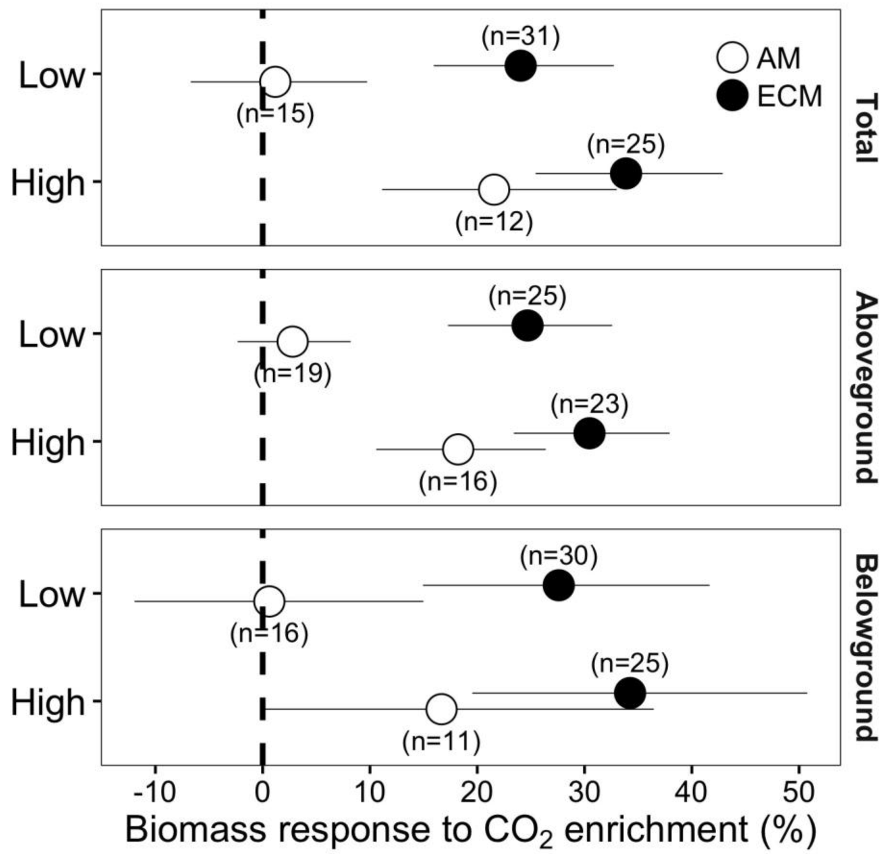

Fig. S6.

Overall effects of CO_2 on total, aboveground, and belowground biomass for two types of mycorrhizal plants species (AM: arbuscular mycorrhizae and ECM: ectomycorrhizae) in N limited experiments (low N) or experiments that are unlikely N limited (high N). Experiments in this meta-analysis are weighted by the inverse of the variance, whereas weights in main meta-analysis in Fig. 2 are based on sample size and length (years) of the experiments. Overall means and 95% confidence intervals are given; we interpret CO_2 effects when the zero line is not crossed.

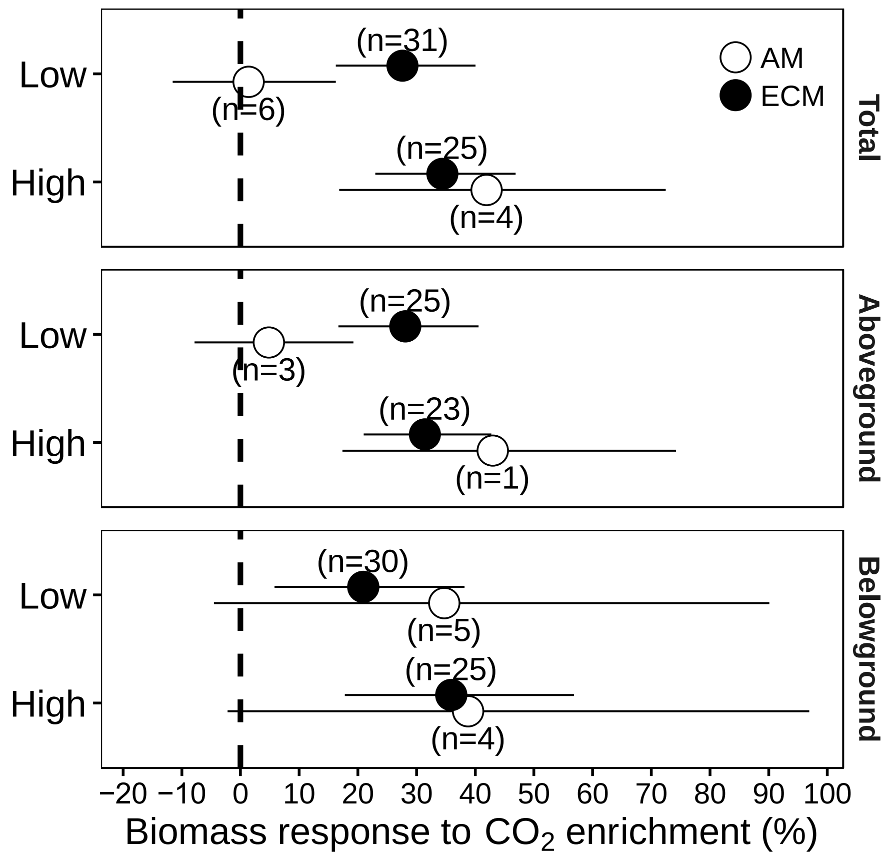

Fig. S7.

Meta-analysis output for the subset of experiments with tree species, showing the effects of CO_2 on total, aboveground, and belowground biomass for two types of mycorrhizal plants species (AM: arbuscular mycorrhizae and ECM: ectomycorrhizae) in N limited experiments (low N) or experiments that are unlikely N limited (high N). Overall means and 95% confidence intervals are given; we interpret CO_2 effects when the zero line is not crossed.

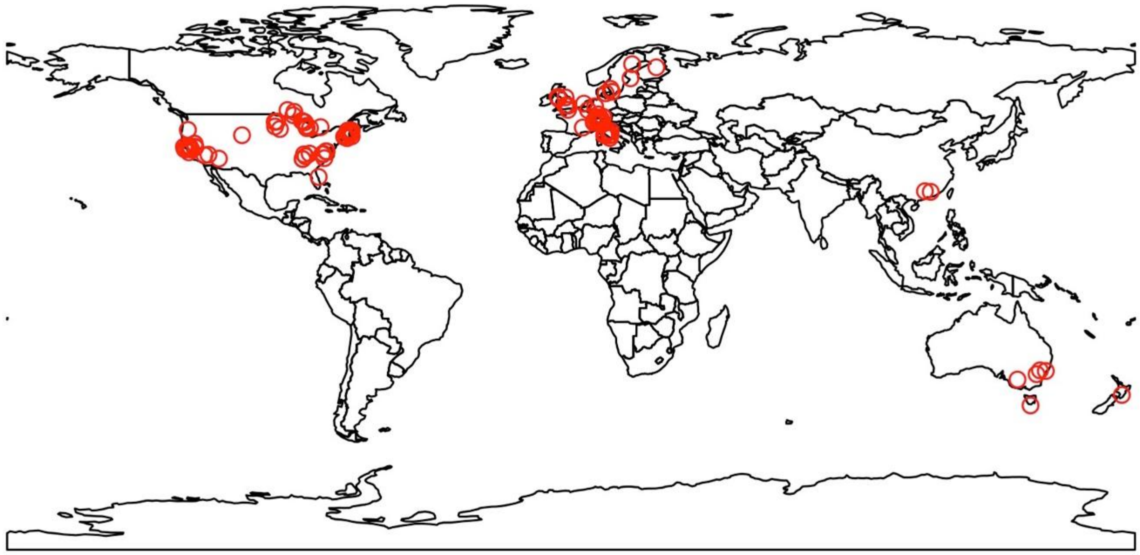

Fig. S8.

Location of elevated CO_2 experiment with total biomass data included in the dataset (Fig. S1). Experiments from the same site are spaced to avoid overlapping.

Table S1.

Overview of CO_2 enrichment experiments included in our analysis. Abbreviations: Myc: mycorrhizal type (AM: arbuscular mycorrhizae, ECM: ectomycorrhizae); N-class: main soil N availability classification (L: low, H: high); N-class2: alternative N-availability classification (L: low, M: medium, H: high); TB = Total Biomass, AB = Aboveground Biomass, BB = Belowground Biomass, FACE = Free Air Carbon Dioxide Enrichment, G = Greenhouse/Growth chamber, ME = Model ecosystem, OTC = Open Top Chamber.

Site	Species	Country	Myc	N-class	N-class2	Facility	References		
							TB	AB	BB
AG FACE	cultivar Yitpi	Australia	AM	H	H	FACE		*51*	
Amsterdam Greenhouses	Calamagrostis eigejos	The Netherlands	AM	H	H	G		*52*	
Amsterdam Greenhouses	Molinia caerulea	The Netherlands	AM	H	H	G		*52*	
Antwerp OTC	Pinus sylvestris	Belgium	ECM	L	L	OTC	*53*	*53*	*53*
BangorFACE	Alnus glutinosa	UK	ECM	H	H	FACE		*54*	
BangorFACE	Betula pendula	UK	ECM	H	H	FACE		*54*	
BangorFACE	Fagus sylvatica	UK	ECM	H	H	FACE		*54*	
Basel spruce	Picea abies	Switzerland	ECM	L	L	ME	*55*	*55*	
Basel spruce F	Picea abies	Switzerland	ECM	H	H	ME	*55*	*55*	
Basel tropical	Trop forest	Switzerland	AM	L	M	ME	*56*	*56*	*56*
Basel tropical II	Trop forest	Switzerland	AM	L	M	ME	*57*	*57*	
BioCON	perennial grassland	USA	AM	L	L	FACE	*5*	*5*	*5*
BioCON F	perennial grassland	USA	AM	H	H	FACE	*5*	*5*	*5*
Birmensdorf - Acidic loam	Fagus sylvatica, Picea abies	Switzerland	ECM	L	M	OTC			*58*
Birmensdorf - Calcareous sand	Fagus sylvatica, Picea abies	Switzerland	ECM	H	H	OTC			*58*
Birmensdorf F - Acidic loam	Fagus sylvatica, Picea abies	Switzerland	ECM	H	H	OTC			*58*
Birmensdorf F - Calcareous sand	Fagus sylvatica, Picea abies	Switzerland	ECM	H	H	OTC			*58*
Brandbjerg	temperate heath	Denmark	AM	L	L	FACE		*59*	

China FACE F	Triticum aestivum	China	AM	H	H	FACE	*60*	*60*	
China FACE FF	Triticum aestivum	China	AM	H	H	FACE	*60*	*60*	
DUKE FACE	Pinus taeda	USA	ECM	L	M	FACE	*25*	*25*	*25*
DUKE Phytotron	Pinus taeda	USA	ECM	L	M	G	*61*	*61*	*61*
DUKE Phytotron F	Pinus taeda	USA	ECM	H	H	G	*61*	*61*	*61*
DUKE Phytotron II	Pinus ponderosa	USA	ECM	L	M	G			*62*
DUKE Phytotron II	Pinus taeda	USA	ECM	L	M	G			*62*
DUKE Phytotron II F	Pinus ponderosa	USA	ECM	H	H	G			*62*
DUKE Phytotron II F	Pinus taeda	USA	ECM	H	H	G			*62*
Duke Prototype	Pinus taeda	USA	ECM	H	H	FACE		*8*	
ETH FACE	Betula pendula	Switzerland	ECM	L	M	FACE	*63*	*63*	*63*
EUROFACE	Populus alba	Italy	ECM	H	H	FACE	*64*	*64*	
EUROFACE	Populus euramericana	Italy	ECM	H	H	FACE	*64*	*64*	
EUROFACE	Populus nigra	Italy	ECM	H	H	FACE	*64*	*64*	
FACTS II FACE	Populus tremuloides	USA	ECM	L	M	FACE	*9*	*9*	*9*
FACTS II FACE	Populus tremuloides-Betula papyrifera	USA	ECM	L	M	FACE	*9*	*9*	*9*
Flakaliden	Picea abies	Sweden	ECM	L	L	OTC		*65*	
GiFACE	grassland	Germany	AM	L	M	FACE		*66*	
Ginninderra	Phalaris aquatica	Australia	AM	H	H	G	*67*	*67*	*67*
Glendevon	Pinus sylvestris	UK	ECM	L	M	OTC			*68*
Glendevon	Picea sitchensis	UK	ECM	L	M	OTC			*68*
Glendevon F	Pinus sylvestris	UK	ECM	H	H	OTC			*68*
Glendevon F	Picea sitchensis	UK	ECM	H	H	OTC			*68*
Guelph	Artemisia tridentata	Canada	AM	H	H	G		*69*	*69*
Harvard	Acer pensylvanicum	USA	AM	L	L	G	*70*		*70*
Harvard	Acer rubrum	USA	AM	L	L	G	*70*		*70*

Harvard	Betula alleghaniensis	USA	ECM	L	L	G	*70*		*70*
Harvard	Fraxinus americana	USA	AM	L	L	G	*70*		*70*
Harvard	Quercus rubra	USA	ECM	L	L	G	*70*		*70*
Harvard	Betula populifolia	USA	ECM	L	L	G	*70*		*70*
Harvard F	Acer pensylvanicum	USA	AM	H	H	G	*70*		*70*
Harvard F	Acer rubrum	USA	AM	H	H	G	*70*		*70*
Harvard F	Betula alleghaniensis	USA	ECM	H	H	G	*70*		*70*
Harvard F	Betula populifolia	USA	ECM	H	H	G	*70*		*70*
Harvard F	Fraxinus americana	USA	AM	H	H	G	*70*		*70*
Harvard F	Quercus rubra	USA	ECM	H	H	G	*70*		*70*
Harvard II	Betula alleghaniensis	USA	ECM	L	L	G	*71*	*71*	*71*
Headley	Fraxinus excelsior	UK	ECM	L	L	OTC	*72*		
Headley	Pinus sylvestris	UK	ECM	L	L	OTC	*72*		
Headley	Quercus petraea	UK	ECM	L	L	OTC	*72*		
Hohenheim	Triticum aestivum	Germany	AM	H	H	FACE		*73*	
Jasper Ridge FACE	annual grassland	USA	AM	L	L	FACE	*74*	*74*	*74*
Jasper Ridge FACE F	annual grassland	USA	AM	H	H	FACE	*74*	*74*	*74*
Jasper Ridge OTC	Sandstone grassland	USA	AM	L	L	OTC	*75*, *76*	*75-77*	*75*, *76*
Jasper Ridge OTC	Serpentine grassland	USA	AM	L	L	OTC	*75*	*75*, *77*	*75*
Jasper Ridge mesocosm	Sandstone grassland	USA	AM	L	L	G		*78*	
Jasper Ridge mesocosm	Serpentine grassland	USA	AM	L	L	G		*78*	
Jasper Ridge mesocosm F	Sandstone grassland	USA	AM	H	H	G		*78*	
Jasper Ridge mesocosm F	Serpentine grassland	USA	AM	H	H	G		*78*	
Lancaster Solardomes	Quercus robur	UK	ECM	L	L	G	*79*	*79*	*79*
Lancaster Solardomes	Fagus sylvatica	UK	ECM	L	L	G	*79*	*79*	*79*
Lancaster Solardomes	Pinus sylvestris	UK	ECM	L	L	G	*79*	*79*	*79*
Lancaster Solardomes	Abies alba	UK	ECM	L	L	G	*79*	*79*	*79*

Lancaster Solardomes	Betula pendula	UK	ECM	L	L	G	*79*	*79*	*79*
Lancaster Solardomes	Carpinus betulus	UK	ECM	L	L	G	*79*	*79*	*79*
Lancaster Solardomes F	Pinus sylvestris	UK	ECM	H	H	G	*79*	*79*	*79*
Lancaster Solardomes F	Abies alba	UK	ECM	H	H	G	*79*	*79*	*79*
Lancaster Solardomes F	Betula pendula	UK	ECM	H	H	G	*79*	*79*	*79*
Lancaster Solardomes F	Carpinus betulus	UK	ECM	H	H	G	*79*	*79*	*79*
Lancaster Solardomes F	Quercus robur	UK	ECM	H	H	G	*79*	*79*	*79*
Lancaster Solardomes F	Fagus sylvatica	UK	ECM	H	H	G	*79*	*79*	*79*
Merrit Island	Shrub Oak system	USA	ECM	L	L	OTC	*80*	*80*	*80*
Nevada FACE	Desert scrub	USA	AM	L	L	FACE	*81*	*81*	*81*
New Zealand FACE	temperate pasture	New Zealand	AM	L	M	FACE		*82*	*83*
Oak Ridge OTC	Liriodendron tulipifera	USA	AM	-	-	OTC	*84*	*84*	*84*
Oak Ridge OTC	Acer saccharum, Acer rubrum	USA	AM	-	-	OTC			*85*
Oak Ridge OTC II	Quercus alba	USA	ECM	L	M	OTC	*86*	*86*	
Oak Ridge OTC III	Model grassland	USA	AM	L	M	OTC		*87*	
ORNL FACE	Liquidambar styraciflua	USA	AM	L	M	FACE	*6*	*6*	*88*
PHACE	Mixed-grass prairie	USA	AM	L	L	FACE	*89*	*89*	*89*, *90*
POPFACE	Populus alba	Italy	ECM	H	H	FACE	*91*	*91*	*91*
POPFACE	Populus euramericana	Italy	ECM	H	H	FACE	*91*	*91*	*91*
POPFACE	Populus nigra	Italy	ECM	H	H	FACE	*91*	*91*	*91*
Richmond	Eucalyptus saligna	Australia	ECM	H	H	G	*92*		
Richmond	Eucalyptus sideroxylon	Australia	ECM	H	H	G	*92*		
Riso	Pisum sativum	Denmark	AM	H	H	G	*93*	*93*	*93*
SCBG	Subtrop forest	China	ECM	L	M	OTC	*94*	*94*	
SCBG F	Subtrop forest	China	ECM	H	H	OTC	*94*	*94*	
Suonenjoki	Betula pendula	Finland	ECM	L	M	OTC	*95*	*95*	*96*

Swiss Central Alps	Alpine grassland	Switzerland	AM	L	L	OTC	*97*	*97*	*97*
Swiss Central Alps F	Alpine grassland	Switzerland	AM	H	H	OTC	*97*	*97*	*97*
Swiss FACE	Lolium perenne	Switzerland	AM	L	M	FACE	*98*	*99*	*98*
Swiss FACE FF	Lolium perenne	Switzerland	AM	H	H	FACE	*98*	*99*	*98*
Swiss Jura	Bromus erectus	Switzerland	AM	L	L	G		*100*	*101*
Tas FACE	Temperate grassland	Australia	AM	L	L	FACE	*102*	*14*	*102*
UMBS	Populus euramericana	USA	ECM	L	L	OTC	*103*	*103*	*103*
UMBS F	Populus euramericana	USA	ECM	H	H	OTC	*103*	*103*	*103*
UMBS II	Populus grandidentata	USA	ECM	L	L	OTC	*104*	*104*	*104*
UMBS III	Populus tremuloides	USA	ECM	L	M	OTC	*105*	*105*	*105*
UMBS III F	Populus tremuloides	USA	ECM	H	H	OTC	*105*	*105*	*105*
UMBS_alnus	Alnus glutinosa	USA	ECM	L	M	OTC	*106*	*106*	*106*
USDA	Citrus aurantium	USA	AM	H	H	OTC	*107*	*107*	*108*
USDA Placerville	Pinus ponderosa	USA	ECM	L	M	OTC	*109*	*109*	*109*
USDA Placerville F	Pinus ponderosa	USA	ECM	H	H	OTC	*109*	*109*	*109*
USDA Placerville FF	Pinus ponderosa	USA	ECM	H	H	OTC	*109*	*109*	*109*
USEPA	Pseudotsuga menziesii	USA	ECM	L	M	G	*110*	*110*	*110*

Table S2.

Justification for the soil nitrogen (N) availability classification. N-class: main soil N availability classification (L: low, H: high); N-class2: alternative N-availability classification (L: low, M: medium, H: high); N-fert: fertilized site (yes or no) and indication of the amount of N fertilizer in g N m^{-2} y^{-1}, unless other units are specified; %N: soil N content (%); %C: soil carbon content (%); pH: when available pH in CaCl2 was reported, otherwise from water solution; C:N: C:N ratio; Report: N-availability or soil fertility assessment of the site found in the literature or confirmed by the site PI. Lack of information on N-availability in some experiments did not allow to assess them in N-class, but were classified as "medium" in N-class2.

Site	N-class	N-class2	N-fert.	Extra fert.	Soil type	Soil texture	%N	%C	pH	C:N	Ref	Remarks
AG FACE	H	H	0 -13.8	P, S		clay (60%)	0.03 - 0.10	1.24	8.4	12	*51*	1
Amsterdam Greenhouses	H	H	yes	P, K					5.5		*52*	2
Antwerp OTC	L	L	no		poor forest soil	sandy	0.12		4.3		*53*	3
BangorFACE	H	H	no		Dystric Cambisol	Fine loamy brown earth over gravel; 62.2 sand, 28.5 silt, 9.3 clay	2.6		4.6	10.5	*111*	4
Basel spruce	L	L	no		podzol				4.5		*55*	5
Basel spruce F	H	H	9		podzol				4.5		*55*	6
Basel tropical	L	M	13.3	fertilizer pellets	fresh tropical soil						*56*	7
Basel tropical II	L	M	11.8	Osmocote and OM	fresh tropical soil						*57*	8
BioCON	L	L	no		Nymore series, subgroup Typic Upidsamment, suborder Psamments, Order Entisols	93% sand, 3% silt, and 4% clay	0.001				*112*	9
BioCON F	H	H	4		Nymore series, subgroup Typic Upidsamment, suborder Psamments, Order Entisols	93% sand, 3% silt, and 4% clay	0.001				*112*	10
Birmensdorf - Acidic loam	L	M	0.5 - 0.7		Haplic Halisol	acidic sandy loamy; 55% sand, 29% silt, 16% clay		12.9 mg kg^{-1}	4.1		*113*	11
Birmensdorf - Calcareous sand	H	H	0.5 - 0.7		Fluvisol	calcareous loamy sandy; 84% sand, 10% silt, 6% clay		13.1 mg kg^{-1}	7.2		*113*	12
Birmensdorf F - Acidic loam	H	H	5 - 7		Haplic Halisol	acidic sandy loamy; 55% sand, 29% silt, 16% clay		12.9 mg kg^{-1}	4.1		*113*	13

Birmensdorf F - Calcareous sand	H	H	5 - 7		Fluvisol	calcareous loamy sandy; 84% sand, 10% silt, 6% clay		13.1 mg kg^{-1}	7.2		*113*	14
Brandbjerg	L	L	no			sandy deposit hill			5		*59*	15
China FACE F	H	H	15	P, K	Shajiang Aquic Cambisol	sandy-loamy ; total porosity: 54%; clay 13.6%, silt 28.5%, sand 57.8%	0.145	1.84	7.2		*60*	16
China FACE FF	H	H	25	P, K	Shajiang Aquic Cambiosol	sandy-loamy ; total porosity: 54%; clay 13.6%, silt 28.5%, sand 57.8%	0.145	1.84	7.2		*60*	17
DUKE FACE	L	M	no		Ultic Hapludalfs	Clay loam; well-developed soil horizons with mixed clay mineralogy.	0.079		5.75	18.9	*114*	18
DUKE Phytotron	L	M	1.75 mM	Hoagland solution	mixture of Turface, vermiculite, gravel and soil (4:2:2:1)						*61*	19
DUKE Phytotron F	H	H	5.5 mM	Hoagland solution	mixture of Turface, vermiculite, gravel and soil (4:2:2:1)						*61*	20
DUKE Phytotron II	L	M	1 mM	Hoagland solution	sterilized sand						*62*	21
DUKE Phytotron II F	H	H	5 mM	Hoagland solution	sterilized sand						*62*	22
Duke Prototype	H	H	11.2		Ultic Hapludalfs	Clay loam			5.75	18.9	*8*	23
ETH FACE	L	M	no		from an agricultural site, used for maize cultivation since 1962	5.6% clay, 17.7% loam, 76.8% sand	0.08		5.05		*63*	24
EUROFACE	H	H	21.2-29	P, K	Xeric Alfisol	heavy clay loam; 37% sand, 44% silt, 19% clay	0.13	1.06-1.13	4.89-5.18	9.31	*64*	25
FACTS II FACE	L	M	no		Alfic Haplorthods	Mixed, frigid, coarse loamy ; 56% sand, 36% silt, 8% clay	0.12		5.5	12.9-13.5	*115*	26
Flakaliden	L	L	no		Typic Haplocryods	silty-sandy till; O-layer average depth is 3cm			4.4		*65*	27
GiFACE	L	M	4		stagno-fluvic gleysol	porosity 60 - 65%; loamy-sandy sediments over clay	0.45	4.7	5.9	10.5	*116*	28
Ginninderra	H	H	10	P, K							*67*	29
Glendevon	L	M	no		brown forest soil 40-60 cm deep.	loam of shallow brown earth, locally podzolized	NO_3: 0.49; NH_4: 0.26		4.7		*117*	30
Glendevon F	H	H	7	other nutrients	brown forest soil 40-60 cm deep.	loam of shallow brown earth, locally podzolized	NO_3: 0.54; NH_4: 0.22		4.7		*117*	31

Guelph	H	H	400 ml	Hoagland solution		Turface					*69*	32
Harvard	L	L	0.18 g	P, K + micronutrients	pots with a 1:1:1 mixture of sand:perlite:peat			5			*70*	33
Harvard F	H	H	1.8 g	P, K + micronutrients	pots with a 1:1:1 mixture of sand:perlite:peat			5			*70*	34
Harvard II	L	L	no		Canton	low density O2 horizon; stony to sandy loams					*71*	35
Headley	L	L	no		humo-ferric podzol	Sandy					*72*	36
Hohenheim	H	H	14		slightly stagnic luvisol						*73*	37
Jasper Ridge FACE	L	L	no		Typic Haploxeralfs						*74*	38
Jasper Ridge FACE F	H	M	7		Typic Haploxeralfs						*74*	39
Jasper Ridge OTC - serpentine	L	L	no		Lithic Haploxerolls	Clay loam	0.16	1.8	6.6	11.2	*118*	40
Jasper Ridge OTC - sandstone	L	L	no		Lithic Xerochrepts	Loamy	0.12	1.2	5.5	10	*76*	41
Jasper Ridge mesocosm	L	L	no		0.8 m subsoil from serpentine quarry and 0.15 m serpentine topsoil						*78*	42
Jasper Ridge mesocosm F	H	H	20	P, K	0.8 m subsoil from serpentine quarry and 0.15 m serpentine topsoil						*78*	43
Lancaster Solardomes	L	L	no		Udertic Paleustoll	silt loam or silty clay loam (clay 26-34%)					*79*	44
Lancaster Solardomes F	H	H	2.5 g L^{-1}	P, K, Mg and trace elements	Udertic Paleustoll	silt loam or silty clay loam (clay 26-34%)					*79*	45
Merrit Island	L	L	no		Pomello (Arenic Haplahumod) and Poala sands (Spodic Quartzipsamment)	moderately well drained sandy soils		2-7	3.9-4.1		*119*	46
Nevada FACE	L	L	no		Aridosols derived from calcareous alluvium	Loamy and coarse sand; well-drained	0.01-0.08	0.18-1.8	7-8		*120*	47
New Zealand FACE	L	M	no	P, S, K	Mollic Psammaquent	fine sand; 0.25m black loamy top horizon underlain by grayish-brown horizon	0.37-0.41	4.52-5.02	5.9-6	12.4	*82*, *121*	48
Oak Ridge OTC	-	-	no								*84*	49

Oak Ridge OTC II	L	M	no			silt loam					*86*	50
Oak Ridge OTC III	L	M	no		Typic Fragiudult	well-drained; fine-silty, siliceous, mesic					*87*	51
ORNL FACE	L	M	no		Aquic Hapludult	silty clay loam, moderately well drained; 21% sand, 55% silt, 24% clay	0.112	1.08	5.7		*114*	52
PHACE	L	L	no		Aridic Argiusstoll	fine-loamy, mixed mesic			7.9		*89*	53
POPFACE	H	H	no		Xeric Alfisol	loam; 37% sand, 44% silt, 19% clay	0.11-0.14	0.9 - 1.13	4.9-5.18	8.7-9.9	*91*	54
Richmond	H	H	0.2 g N L^{-1}	P, K, S, Fe, Mn, B		loamy sand	<1 mg kg^{-1}	0.7	5.5		*92*	55
Riso	H	H	20 mg N kg^{-1}		from an arable layer	49.9% sand, 31.8% silt, 16% clay	0.14	1.36			*122*	56
SCBG	L	M	no		from an evergreen broadleaved forest						*94*	57
SCBG F	H	H	10		from an evergreen broadleaved forest						*94*	58
Suonenjoki	L	M	2.2 - 4.1		soil composed of sand and clay; no humus layer on top of the mineral soil	0.046			21		*123*	59
Swiss Central Alps	L	L	no		alpine stagnic pseudo-gleysols				4		*97*	60
Swiss Central Alps F	H	H	4	P, K	alpine stagnic pseudo-gleysols				4		*97*	61
Swiss FACE	L	M	10 - 14		eutric Cambisol	clay loam; 28% clay, 33% silt, 36% sand	0.28-0.46	2.9-5.1	6.5-7.6		*124*	62
Swiss FACE FF	H	H	40 -56		eutric Cambisol	clay loam; 28% clay, 33% silt, 36% sand	0.28-0.46	2.9-5.1	6.5-7.6		*124*	63
Swiss Jura	L	L	no	P		silty clay-loam underlain with calcareous debris.	0.33		7-8		*100, 125*	64
Tas FACE	L	L	no		black Vertisol	formed of basaltic clay	0.2		6		*126*	65
UMBS	L	L	no		Rubicon sand + Kalkaska series topsoil		0.45-0-46	1			*127*	66
UMBS F	H	H	no		Kalkaska series topsoil		1.5-1.52	2.7			*127*	67
UMBS II	L	L	4.5		Entic Haplorthod	sandy, mixed, frigid	0.0079-0.01				*104*	68
UMBS III	L	L	no		Rubicon sand + Kalkaska series topsoil	93% sand, 2.5% clay	0.021		6.74	14.8	*105*	69
UMBS III F	H	H	no		Kalkaska series topsoil	72% sand, 10.1% clay	0.097		6.08	13.3	*105*	70

UMBS_alnus	L	M	no		Rubicon sand + Kalkaska series topsoil		0.016 - 0.020			*106*	71
USDA	H	H	ample	ample	Avondale	loam				*107*	72
USDA Placerville	L	L	no		Aiken clay loam		0.09	5.1 - 5.5	24-25	*109*	73
USDA Placerville F	H	M	yes		Aiken clay loam		0.1	5.1 - 5.5	24-25	*109*	74
USDA Placerville FF	H	H	yes		Aiken clay loam		0.11	5.1 - 5.5	24-25	*109*	75
USEPA	L	M	no		Typic Hapludand	coarse, loamy, mixed, frigid	0.06-0.11	6.2-6.3		*110*	76

1. Large soil mineral N content (~300 kg N ha^{-1}) at the site precluded any significant effect of applied N, indicating the site was initially N-rich.
2. The experiment simulates conditions of mesotrophic soils, thereby, inherently fertile.
3. Sandy soils with low pH, classified by the authors as “poor forest soils”.
4. Former agricultural field, fertile soil type and low C:N, therefore high nitrogen availability. Analysis of P-availability indicates that plants in this site are P-limited, but not N-limited (pers. comm).
5. Authors reported the soil is “natural nutrient-poor montane soil”.
6. N-fertilization in the site increased fertility from “nutrient-poor” to “medium-high” N availability, as reported by the authors.
7. Low-fertility litter compost mix was added to the soil to simulate nutrient cycling, but no fertilizer was applied. Nutrients were kept low, and plants showed visual signs of nutrient limitations in CO_2-fumigated plots as seen by the yellowish appearance of the vegetation. PI described the soils as N-low to moderately fertile (pers. comm).
8. Low-fertility litter compost mix was added to the soil to simulate nutrient cycling, but no fertilizer was applied. Nutrients were kept low, and plants showed visual signs of nutrient limitations in CO_2-fumigated plots as seen by the yellowish appearance of the vegetation. PI described the soils as N-low to moderately fertile (pers. comm).
9. Authors reported that plants in this low SOM (1.4%), low N (10 µg g^{-1}) and high P content (46.5 µg g^{-1}) sandy soil were “N-limited”. In addition, N-availability constrained the CO_2 biomass response (*128*).
10. Same soils as in 9, but N-amended with 4 g N m^{-2}, corresponding to high N deposition rates.
11. Authors reported this acidic soil as “nutrient-poor”, with low SOC content in the subsoil (2.3 g kg^{-1}). N-addition simulated “low levels of N deposition”, and higher levels of N-fertilization in adjacent plots increased growth further, indicating N-limitations in these plots, therefore N-class2=M.

12. This Fluvisol is reported as "nutrient-rich" by the authors, with high SOC content, pH and CEC (127 mmol/kg soil), therefore N-class=H. Although N-addition addition levels simulated "low levels of N deposition", increasing N-fertilization in adjacent plots did not increase biomass further, therefore N-class2=H.
13. Soils in 11 with higher levels of N-fertilization.
14. Soil in 12 with higher levels of N-fertilization.
15. Sandy soils reported as "nutrient-poor".
16. Soil type and texture indicate intermediate fertility, but fertilization is high.
17. Soils in 16 with even higher fertilization.
18. Soil type and high C:N ratio indicate low N-availability. The soil is classified as "moderately low fertile" by the authors (*8*), and forest production showed a substantial response to N fertilization (*129*), indicating N-limitations. However, plants initially had not yet fully explored soil resources due to high initial spacing among seedlings (expanding systems), which may increase N availability at the individual plant level (*130*), therefore N-class2=M.
19. Artificial soil with modest N-fertilization. The authors reported that "N is believed to be the primary limiting factor". Based on the scarce soil data, the soil was classified as L-M despite N-fertilization, because fertilization with higher amount of N in soil 20 increased biomass by 20%.
20. Same soil as 19 with higher N fertilization.
21. Available soil data scarce, but artificial soil (sand) with modest N-fertilization.
22. Same soil as 21 with higher N fertilization.
23. Same soil as 18 with N amendments.
24. CEC is low and the site was not N-fertilized, but it was formerly a maize field, reason we assumed it was fertilized in the past and we assigned N-class2=M.
25. Fertile soils (Alfisol) with good texture (loam) and former agriculture land. The site was classified as "nutrient-rich" by the authors. N-fertilization in the second rotation of the experiment did not enhance plant growth, indicating high N availability.
26. According to the authors N-availability is medium due to previous agricultural use prior to 1972, hence N-class2=M. N-class=L because the soil is sandy, SOM is relatively low (pers. comm) and it is not fertilized.
27. Boreal forest, classified as "strongly nutrient limited" (*131*). Long term (25 years) fertilization of experimental plots in this forest quadrupled productivity (pers. comm.).
28. Classified as "nitrogen limited" by the authors (pers. comm). The fertilization rate is smaller than what is removed by the harvest, so the site is considered N limited even though it is fertilized (pers. comm), hence N-class=L. However, the soil is moderately fertile based on soil texture and intermediate C:N, therefore N-class2=M.
29. No soil information was available, but N and other nutrients are supplied in abundance.

30. The soil was classified as “intermediate nutrient status” by the authors, hence N-class2=M. Based on the lack of fertilization, N-class=L.
31. Same soil as 30 with intermediate nutrient availability with extra N and other nutrients.
32. Soil was sterilized Turface, low-nutrient calcined clay (AM fungi inoculation), but plants were fertilized frequently with Hoagland’s solution.
33. The soil “simulated poor-nutrient forest soil at Harvard Forest”. They further showed that nitrogen mineralization rates were low in this forest (34 kg ha^{-1} y^{-1}) (*132*), and higher N supply in adjacent plots greatly increased plant growth, therefore N-class=L.
34. The nutrient treatment simulated high N deposition and organic matter mineralization rates (400 kg N ha^{-1} yr^{-1}).
35. They used a 1:1:1 mix of coarse sand, peat and field soil (from a nutrient poor forest soil). No fertilized was supplied, therefore N availability was low.
36. Sandy soils classified as “nutrient-poor” and “low soil N content” by the authors.
37. Soil type typically nutrient-rich, and very high N-fertilization.
38. Soil classified as “nutrient-poor” by the authors, and N addition increased plant growth significantly.
39. Same soil as 38 but N-fertilized. N-class2=H because even though Haploxeralfs soils are N-poor, the supply of N is high.
40. Soil reported as “low nutrient availability”, and “low N availability” (pers. comm). Serpentine grasslands at Jasper Ridge consistently respond to N and P additions, with N almost doubling growth (*133*). CEC=0.7 mmhos cm^{-1}, SOM=7.5%.
41. This sandstone-derived soil had lower CEC (0.1 mmhos cm^{-1}), N content and SOM (5.2%) than soil 40.
42. Same soil as 40.
43. Same soil as 40 and 42, but highly fertilized.
44. Authors reported this soil was characterised by “low organic matter content” and “low nitrogen availability” (pers. comm), as also observed by the increase in growth upon fertilization.
45. Same as 44 but fertilized with N and other nutrients.
46. Sandy soils with nutrient content. Reported “infertile sandy soils”.
47. Calcareous soil with very high C:N ratio. Authors reported “low N concentration”.
48. Sheep create N-rich urine patches with larger CO_2 response, which indicates that the site is N-limited in general (pers. comm). Classified as “N-limited” (*134*). N-class2=M because C:N ratio is moderate, and sheep excrete and N_2-fixing species may increase N-availability.
49. Not included in the meta-analysis due to the lack of available soil information.
50. “Low in available P and estimated annual N availability of 50 μg g^{-1}”. N-class2=M because it was not possible to assign N availability with certainty based on available information.

51. Soil type and low C:N indicate intermediate N-availability, but given the lack of fertilization we classified this soil as L-M.
52. Plant productivity is N-limited at this site (*6*), N-class=L. Moderately fertile soil type, low C:N ratio and evidence for nitrogen fixation (*135*, *136*), therefore N-class2=M.
53. The high pH suggests low availability of P and some other nutrients. Reported as “nutrient-poor”, and N-availability limits plant growth.
54. Same soil as in 25, except fertilizer was not used. Nevertheless, these soils were “nutrient-rich” given past agricultural use and soil type. N-fertilization did not enhance plant growth, indicating high N-availability.
55. Even though soil organic matter content was low, we classified these soils as high due to fertilization with N and other nutrients.
56. Soil type is fertile with low C:N ratio, and was also N-fertilized. Reported as “nutrient rich”.
57. N-fertilization enhanced plant growth in the experiment, suggesting N-limitations, therefore we classified the soil as L-M.
58. Same soil as 57 but heavily fertilized with N.
59. N fertilization was kept modest so trees would not become totally deficient of it, but plants were N-limited (pers. comm).
60. Very nutrient-poor soils, in situ, very old, late successional system (pers. comm).
61. Same soil as in 60, amended with NPK.
62. Soil type characterized by high fertility. However, the authors reported that the “reduced availability of N constantly limited the response of harvestable biomass to elevated CO_2 throughout the experiment”. These plots were fertilized with 15 g N m^{-2}, and yet, fertilization with 45 g N m^{-2} in adjacent plots produced more yield (*137*), suggesting that 15 g N m^{-2} fertilization is in the range of N-limitations (*138*), classifying plants in these plots as moderately N-limited (pers. comm).
63. Same soil as in 62 with high levels of N-fertilization.
64. “Very nutrient poor despite high rates of N deposition” (pers. comm), with P probably at least as limiting as N.
65. Many Vertisols are N-deficient, in line with low SOM, and have low available P (http://www.fao.org/docrep/003/y1899e/y1899e06.htm#P381_59788). Authors reported “low total N and extractable P”.
66. Sandy soils, low in organic matter content and %N. N Mineralization = 45 µg N g^{-1} day^{-1}. Authors reported “low soil N” and “P not limiting”.
67. N Mineralization = 348 µg N g^{-1} day^{-1}. Authors reported “high soil N”. Since plants were well watered and and P was not limiting, the major difference between soils 67 and 66 was N content, therefore, we classified it as H.
68. Nutrient-poor sandy soil, despite modest N-fertilization.
69. Equivalent to soil 66. N Mineralization = 89 µg N g^{-1} day^{-1}. Plants received an initial dose of N-fertilizer, and for that reason N-class2=M.
70. Equivalent to soil 67. N Mineralization = 333 µg N g^{-1} day^{-1}.

71. Similar to soils 66 and 69, and authors reported "nutrient-poor" and "low soil N". However, Alnus spp. is a N_2-fixing species, therefore N-class2=M.
72. Avondale are very fertile soils used for growing cultivated crops and pasture under irrigation. Ample nutrients were added.
73. The low N treatment consisted of unamended soil which had a total N concentration of approximately 900 µg g^{-1}, that we assume as low to moderate, therefore N-class2=M. N-fertilization in adjacent plots increased growth, therefore plants were N-limited and N-class=L.
74. "Intermediate soil N fertility treatment" was imposed by supplying soil 73 with sufficient $(NH_4)_2 SO_4$ to increase total soil N by 100 µg g^{-1} N. Higher levels of N-fertilization in soil 75 did not significantly increase growth, suggesting plants in this soils were not N-limited, therefore N-class2=H.
75. "High soil N fertility treatment" was imposed by supplying soil 73 with sufficient $(NH_4)_2 SO_4$ to increase total soil N by 200 µg g^{-1} N.
76. Typic Hapludand soils are usually moderately fertile, and pH is good, therefore N-class2=M. Authors reported that the soil was "nutrient-poor", with "soil N concentration lower than optimum for highly productive Douglas-fir forest in Oregon", hence N-class=L.

Table S3

Experiments with arbuscular mycorrhizal plant species under low N-availability grown with N-fixing species. es: effect size, var: varianze, W_{NY}: weights used for the meta-analysis, based on the number of replicates and the duration (years) of the experiment. The data used for the analysis is aboveground biomass for all the species sampled (i.e. non N-fixing and N-fixing species).

Site	Species	Data source	es	var	W_{NY}
GiFACE	grassland	*66*	0.0198	0.0029	9
New Zealand FACE	temperate pasture	*82*	0.1165	0.0305	7.5
ORNL FACE	Liquidambar styraciflua	*6*	0.0146	0.0009	6.7
Swiss Central Alps	Alpine grassland	*97*	0.0331	0.0228	7.5
Tas FACE	Temperate grassland	*14*	0.0664	0.0002	7.5
Swiss Jura	Calcareous grassland	*100*	0.1870	0.0158	7
BioCON	perennial grassland	*5*	0.0892	0.0013	9.5

GIFACE: legumes (mainly Lathyrus pratensis) contribute less than 0.5% to the total plant biomass (*116*); New Zealand FACE: mixture of plant species including legumes, principally Trifolium repens L. And Trifolium subterraneum L. (*139*); ORNL FACE: evidence for nitrogen fixation, and an increasing presence of Elaeagnus umbellata (an invasive actinorhizal N fixing shrub) (*135*, *136*); Swiss Central Alps: Trifolium alpinum L. is the only legume species and comprises less than 2% of the total phanerogam biomass; Tas FACE: N fixing forbs, including Trifolium subterraneum and T. striatum, form an extremely small fraction (0.01%) of the biomass. The community also contains the N-fixing woody twining species Bossiaea prostrata, that forms only a small fraction of the total biomass (1%) (*126*); Swiss Jura: data pooled across all species.

Table S4

Meta-analysis output with three different correlation factors (*r*) to aggregate repeated measurements over time. %es=effect size (%), se=standard error, Myc=mycorrhizal status, N=nitrogen availability.

			***r*=1**			***r*=0.5**			***r*=0**		
Biomass	**Myc**	**N**	**%es**	**se**	***P*-value**	**%es**	**se**	***P*-value**	**%es**	**se**	***P*-value**
Total	AM	High	19.71	5.92	0.002	19.71	5.72	0.001	19.71	5.55	0.001
		Low	0.35	5.29	0.946	0.35	5.13	0.945	0.35	4.98	0.943
	ECM	High	33.21	4.35	0	33.21	4.34	0	33.21	4.34	0
		Low	27.98	4.64	0	27.98	4.65	0	27.98	4.68	0
Aboveground	AM	High	18.36	4.44	0	18.04	4.49	0	18.36	4.49	0
		Low	2.3	4.36	0.595	3.55	5.59	0.523	2.3	4.45	0.425
	ECM	High	31.09	4.03	0	31.14	3.75	0	31.09	3.5	0
		Low	30.16	4.71	0	29.84	4.73	0	30.16	4.72	0
Belowground	AM	High	16.49	10.29	0.123	16.49	10.11	0.117	16.49	9.95	0.111
		Low	-0.92	8.25	0.907	-0.92	8.11	0.906	-0.92	7.99	0.905
	ECM	High	35.39	7.01	0	35.39	6.74	0	35.39	6.47	0
		Low	20.38	6.36	0.003	20.38	6.3	0.003	20.38	6.27	0.003

References:

1. P. Ciais *et al.*, in *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, T. F. Stocker et al., Eds. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013), pp. 465–570.

2. C. L. Quéré *et al.*, Global Carbon Budget 2015. *Earth System Science Data*. **7**, 349–396 (2015).

3. B. A. Hungate, J. S. Dukes, M. R. Shaw, Y. Luo, C. B. Field, Nitrogen and climate change. *Science*. **302**, 1512–1513 (2003).

4. W. R. Wieder, C. C. Cleveland, W. K. Smith, K. Todd-Brown, Future productivity and carbon storage limited by terrestrial nutrient availability. *Nature Geosci*. **8**, 441–444 (2015).

5. P. B. Reich, P. B. Reich, S. E. Hobbie, S. E. Hobbie, Decade-long soil nitrogen constraint on the CO_2 fertilization of plant biomass. *Nature Climate change*. **3**, 278–282 (2013).

6. R. J. Norby, J. M. Warren, C. M. Iversen, B. E. Medlyn, R. E. McMurtrie, CO_2 enhancement of forest productivity constrained by limited nitrogen availability. *Proc Natl Acad Sci U S A*. **107**, 19368–19373 (2010).

7. P. B. Reich, B. A. Hungate, Y. Luo, Carbon-Nitrogen Interactions in Terrestrial Ecosystems in Response to Rising Atmospheric Carbon Dioxide. *Annu. Rev. Ecol. Evol. Syst.* **37**, 611–636 (2006).

8. H. R. McCarthy *et al.*, Re-assessment of plant carbon dynamics at the Duke free-air CO_2 enrichment site: interactions of atmospheric [CO_2] with nitrogen and water availability over stand development. *New Phytol*. **185**, 514–528 (2010).

9. A. F. Talhelm *et al.*, Elevated carbon dioxide and ozone alter productivity and ecosystem carbon content in northern temperate forests. *Global Change Biology*. **20**, 2492–2504 (2014).

10. B. A. Newingham *et al.*, No cumulative effect of 10 years of elevated [CO_2] on perennial plant biomass components in the Mojave Desert. *Global Change Biology*. **19**, 2168–2181 (2013).

11. M.-A. de Graaff, K. J. van Groenigen, J. Six, B. Hungate, C. van Kessel, Interactions between plant growth and soil nutrient cycling under elevated CO_2: a meta-analysis. *Global Change Biology*. **12**, 2077–2091 (2006).

12. E. A. Ainsworth, S. P. Long, What have we learned from 15 years of free-air

CO_2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol*. **165**, 351–372 (2005).

13. C. Körner *et al.*, Carbon flux and growth in mature deciduous forest trees exposed to elevated CO_2. *Science*. **309**, 1360–1362 (2005).

14. M. J. Hovenden, P. C. D. Newton, K. E. Wills, Seasonal not annual rainfall determines grassland biomass response to carbon dioxide. *Nature*. **511**, 583–586 (2014).

15. S. Baig, B. E. Medlyn, L. M. Mercado, S. Zaehle, Does the growth response of woody plants to elevated CO_2 increase with temperature? A model-oriented meta-analysis. *Global Change Biology*. **21**, 4303–4319 (2015).

16. M. C. Brundrett, Coevolution of roots and mycorrhizas of land plants. *New Phytol*. **154**, 275–304 (2002).

17. S. Vicca *et al.*, Fertile forests produce biomass more efficiently. *Ecol Lett*. **15**, 520–526 (2012).

18. M. G. A. van der Heijden *et al.*, Mycorrhizal fungal diversity determines plant biodiversity, ecosystem variability and productivity. *Nature*. **396**, 69–72 (1998).

19. N. C. Johnson, G. W. T. Wilson, J. A. Wilson, R. M. Miller, M. A. Bowker, Mycorrhizal phenotypes and the Law of the Minimum. *New Phytol*. **205**, 1473–1484 (2015).

20. R. P. Phillips, E. Brzostek, M. G. Midgley, The mycorrhizal-associated nutrient economy: a new framework for predicting carbon–nutrient couplings in temperate forests. *New Phytol*. **199**, 41–51 (2013).

21. C. Averill, B. L. Turner, A. C. Finzi, Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. *Nature*. **505**, 543–545 (2015).

22. K. K. Treseder, A meta-analysis of mycorrhizal responses to nitrogen, phosphorus, and atmospheric CO_2 in field studies. *New Phytol*. **164**, 347–355 (2004).

23. O. Alberton, T. W. Kuyper, A. Gorissen, Taking mycocentrism seriously: mycorrhizal fungal and plant responses to elevated CO_2. *New Phytol*. **167**, 859–868 (2005).

24. M. Shi, J. B. Fisher, E. R. Brzostek, R. P. Phillips, Carbon cost of plant nitrogen acquisition: global carbon cycle impact from an improved plant nitrogen cycle in the Community Land Model. *Global Change Biology*. **22**, 1299–1314 (2016).

25. J. E. Drake *et al.*, Increases in the flux of carbon belowground stimulate nitrogen

uptake and sustain the long-term enhancement of forest productivity under elevated CO_2. *Ecol Lett*. **14**, 349–357 (2011).

26. R. J. Norby *et al.*, Model-data synthesis for the next generation of forest free-air CO_2 enrichment (FACE) experiments. *New Phytol*. **209**, 17–28 (2015).

27. J. Perez-Moreno, D. J. Read, Mobilization and transfer of nutrients from litter to tree seedlings via the vegetative mycelium of ectomycorrhizal plants. *New Phytol*. **145**, 301–309 (2000).

28. R. P. Phillips, A. C. Finzi, E. S. Bernhardt, Enhanced root exudation induces microbial feedbacks to N cycling in a pine forest under long-term CO_2 fumigation. *Ecol Lett*. **14**, 187–194 (2011).

29. B. A. Hungate *et al.*, Fire, hurricane and carbon dioxide: effects on net primary production of a subtropical woodland. *New Phytol*. **200**, 767–777 (2013).

30. J. Cornelissen, R. Aerts, B. Cerabolini, M. Werger, M. van der Heijden, Carbon cycling traits of plant species are linked with mycorrhizal strategy. *Oecologia*. **129**, 611–619 (2001).

31. M. F. Cotrufo *et al.*, Formation of soil organic matter via biochemical and physical pathways of litter mass loss. *Nature Geosci*. **8**, 776–779 (2015).

32. B. N. Sulman, R. P. Phillips, A. C. Oishi, E. Shevliakova, S. W. Pacala, Microbe-driven turnover offsets mineral-mediated storage of soil carbon under elevated CO_2. *Nature Climate change*. **4**, 1099–1102 (2014).

33. Z. Zhu *et al.*, Greening of the Earth and its drivers. *Nature Climate change*, advance online publication (2016), doi:10.1038/nclimate3004.

34. V. B. Chaudhary *et al.*, MycoDB, a global database of plant response to mycorrhizal fungi. *Sci. Data*. **3**, 160028 (2016).

35. W. I. J. Dieleman *et al.*, Simple additive effects are rare: a quantitative review of plant biomass and soil process responses to combined manipulations of CO_2 and temperature. *Global Change Biology*. **18**, 2681–2693 (2012).

36. M. Fernández-Martínez *et al.*, Nutrient availability as the key regulator of global forest carbon balance. *Nature Climate change*. **4**, 471–476 (2014).

37. M. Campioli *et al.*, Biomass production efficiency controlled by management in temperate and boreal ecosystems. *Nature Geosci*. **8**, 843–846 (2015).

38. R. G. McLaren, K. C. Cameron, *Soil science: an introduction to the properties and management of New Zealand soils* (Oxford University Press, Auckland, N.Z., 1990).

39. B. Wang, Y. L. Qiu, Phylogenetic distribution and evolution of mycorrhizas in land plants. *Mycorrhiza*. **16**, 299–363 (2006).

40. K. E. Mueller, S. E. Hobbie, D. Tilman, P. B. Reich, Effects of plant diversity, N fertilization, and elevated carbon dioxide on grassland soil N cycling in a long-term experiment. *Global Change Biology*. **19**, 1249–1261 (2013).

41. R. J. Hijmans, S. E. Cameron, J. L. Parra, P. G. Jones, A. Jarvis, Very high resolution interpolated climate surfaces for global land areas. *Int. J. Climatol.* **25**, 1965–1978 (2005).

42. L. V. Hedges, J. Gurevitch, P. S. Curtis, The meta-analysis of response ratios in experimental ecology. *Ecology*. **80**, 1150 (1999).

43. W. Viechtbauer, Conducting Meta-Analyses in R with the metafor Package. *Journal of Statistical Software*. **36** (2010).

44. M. Borenstein, L. V. Hedges, J. P. T. Higgins, H. R. Rothstein, in *Introduction to Meta-Analysis* (John Wiley & Sons, Ltd, Chichester, UK, 2009), pp. 225–238.

45. C. W. Osenberg, O. Sarnelle, S. D. Cooper, R. D. Holt, Resolving ecological questions through meta-analysis: goals, metrics, and models. *Ecology*. **80**, 1105–1117 (1999).

46. B. A. Hungate, R. B. Jackson, C. B. Field, F. S. Chapin III, Detecting changes in soil carbon in CO_2 enrichment experiments. *Plant Soil*. **187**, 135–145 (1996).

47. K. J. van Groenigen *et al.*, Element interactions limit soil carbon storage. *Proceedings of the National Academy of Sciences*. **103**, 6571–6574 (2006).

48. G. Knapp, J. Hartung, Improved tests for a random effects meta-regression with a single covariate. *Statistics in Medicine*. **22**, 2693–2710 (2003).

49. W. Viechtbauer, J. A. López-López, J. Sánchez-Meca, F. Marín-Martínez, A comparison of procedures to test for moderators in mixed-effects meta-regression models. *Psychological Methods*. **20**, 360–374 (2015).

50. V. Calcagno, C. de Mazancourt, glmulti: an R package for easy automated model selection with (generalized) linear models. *Journal of Statistical Software*. **34** (2010).

51. G. J. O'Leary *et al.*, Response of wheat growth, grain yield and water use to elevated CO_2 under a Free-Air CO_2 Enrichment (FACE) experiment and modelling in a semi-arid environment. *Global Change Biology*. **21**, 2670–2686 (2015).

52. B. Hoorens, R. Aerts, M. Stroetenga, Is there a trade-off between the plant's growth response to elevated CO_2 and subsequent litter decomposability? *Oikos*.

103, 17–30 (2003).

53. I. A. Janssens *et al.*, Carbon budget of Pinus sylvestris saplings after four years of exposure to elevated atmospheric carbon dioxide concentration. *Tree Physiol*. **25**, 325–337 (2005).

54. A. R. Smith *et al.*, Elevated CO_2 enrichment induces a differential biomass response in a mixed species temperate forest plantation. *New Phytol*. **198**, 156–168 (2013).

55. S. Hättenschwiler, C. Körner, Biomass allocation and canopy development in spruce model ecosystems under elevated CO_2 and increased N deposition. *Oecologia*. **113**, 104–114 (1998).

56. C. Körner, J. A. Arnone III, Responses to Elevated Carbon Dioxide in Artificial Tropical Ecosystems. *Science*. **257**, 1672–1675 (1992).

57. J. A. Arnone III, C. Körner, Soil and biomass carbon pools in model communities of tropical plants under elevated CO_2. *Oecologia*. **104**, 61–71 (1995).

58. D. Spinnler, P. Egli, C. Körner, Four-year growth dynamics of beech-spruce model ecosystems under CO_2 enrichment on two different forest soils. *Trees*. **16**, 423–436 (2002).

59. L. C. Andresen, A. Michelsen, S. Jonasson, C. Beier, P. Ambus, Glycine uptake in heath plants and soil microbes responds to elevated temperature, CO_2 and drought. *Acta Oecologica*. **35**, 786–796 (2009).

60. T. Kou, J. Zhu, Z. Xie, T. Hasegawa, K. Heiduk, Effect of elevated atmospheric CO_2 concentration on soil and root respiration in winter wheat by using a respiration partitioning chamber. *Plant Soil*. **299**, 237–249 (2007).

61. A. Larigauderie, J. F. Reynolds, B. R. Strain, Root response to CO_2 enrichment and nitrogen supply in loblolly pine. *Plant Soil*. **165**, 21–32 (1994).

62. J. S. King, R. B. Thomas, B. R. Strain, Growth and carbon accumulation in root systems of Pinus taeda and Pinus ponderosa seedlings as affected by varying CO_2, temperature and nitrogen. *Tree Physiol*. **16**, 635–642 (1996).

63. P. Ineson, M. F. Cotrufo, R. Bol, D. D. Harkness, H. Blum, Quantification of soil carbon inputs under elevated CO_2: C3 plants in a C4 soil. *Plant Soil*. **187**, 345–350 (1996).

64. M. Liberloo *et al.*, Woody biomass production during the second rotation of a bio-energy Populus plantation increases in a future high CO_2 world. *Global Change Biology*. **12**, 1094–1106 (2006).

65. K. Kostiainen *et al.*, Stem wood properties of mature Norway spruce after 3 years of continuous exposure to elevated [CO_2] and temperature. *Global Change Biology*. **15**, 368–379 (2009).

66. J. Kongstad *et al.*, High Resilience in Heathland Plants to Changes in Temperature, Drought, and CO_2 in Combination: Results from the CLIMAITE Experiment. *Ecosystems*. **15**, 269–283 (2011).

67. A. Volder, R. M. Gifford, J. R. Evans, Effects of elevated atmospheric CO_2, cutting frequency, and differential day/night atmospheric warming on root growth and turnover of Phalaris swards. *Global Change Biology*. **13**, 1040–1052 (2007).

68. P. G. Jarvis, A. M. Aitken, *European Forests and Global Change* (Cambridge University Press, 1998).

69. J. N. Klironomos, M. Ursic, M. Rillig, M. F. Allen, Interspecific differences in the response of arbuscular mycorrhizal fungi to Artemisia tridentata grown under elevated atmospheric CO_2. *New Phytol*. **138**, 599–605 (1998).

70. F. A. Bazzaz, S. L. Miao, Successional Status, Seed Size, and Responses of Tree Seedlings to CO_2, Light, and Nutrients. *Ecology*. **74**, 104 (1993).

71. G. M. Berntson, P. M. Wayne, F. A. Bazzaz, Below-ground architectural and mycorrhizal responses to elevated CO_2 in Betula alleghaniensis populations. *Functional Ecology*. **11**, 684–695 (1997).

72. M. S. J. Broadmeadow, S. B. Jackson, Growth responses of Quercus petraea, Fraxinus excelsior and Pinus sylvestris to elevated carbon dioxide, ozone and water supply. *New Phytol*. **146**, 437–451 (2000).

73. P. Högy, M. Keck, K. Niehaus, J. Franzaring, A. Fangmeier, Effects of atmospheric CO_2 enrichment on biomass, yield and low molecular weight metabolites in wheat grain. *Journal of Cereal Science*. **52**, 215–220 (2010).

74. J. Dukes *et al.*, Responses of Grassland Production to Single and Multiple Global Environmental Changes. *PLoS Biology*. **3**, e319 (2005).

75. B. A. Hungate *et al.*, The fate of carbon in grasslands under carbon dioxide enrichment. *Nature*. **388**, 576–579 (1997).

76. P. A. T. Higgins, R. B. Jackson, J. M. Des Rosiers, C. B. Field, Root production and demography in a california annual grassland under elevated atmospheric carbon dioxide. *Global Change Biology*. **8**, 841–850 (2002).

77. C. B. Field, F. S. Chapin III, N. R. Chiariello, E. A. Holland, H. A. Mooney, in *Carbon Dioxide and Terrestrial Ecosystems* (Academic Press, San Diego CA, 1996), pp. 121–145.

78. N. R. Chiariello, C. B. Field, in *Carbon Dioxide, Populations, and Communities* (Elsevier, 1996), pp. 139–157.

79. J. Heath *et al.*, Rising atmospheric CO_2 reduces sequestration of root-derived soil carbon. *Science*. **309**, 1711–1713 (2005).

80. B. A. Hungate *et al.*, Cumulative response of ecosystem carbon and nitrogen stocks to chronic CO_2 exposure in a subtropical oak woodland. *New Phytol*. **200**, 753–766 (2013).

81. R. D. Evans *et al.*, Greater ecosystem carbon in the Mojave Desert after ten years exposure to elevated CO_2. *Nature Climate change*. **4**, 394–397 (2014).

82. P. Newton, M. Lieffering, W. Bowatte, S. C. Brock, The rate of progression and stability of progressive nitrogen limitation at elevated atmospheric CO_2 in a grazed grassland over 11 years of Free Air CO_2 enrichment. *Plant Soil*. **336**, 433–441 (2010).

83. V. Allard *et al.*, Increased Quantity and Quality of Coarse Soil Organic Matter Fraction at Elevated CO_2 in a Grazed Grassland are a Consequence of Enhanced Root Growth Rate and Turnover. *Plant Soil*. **276**, 49–60 (2005).

84. R. J. Norby, C. A. Gunderson, S. D. Wullschleger, E. G. O'neill, Productivity and compensatory responses of yellow-poplar trees in elevated CO_2. *Nature*. **357**, 322–324 (1992).

85. S. Wan, R. J. Norby, K. S. Pregitzer, J. Ledford, E. G. O'Neill, CO_2 enrichment and warming of the atmosphere enhance both productivity and mortality of maple tree fine roots. *New Phytol*. **162**, 437–446 (2004).

86. R. J. Norby, S. D. Wullschleger, C. A. Gunderson, C. T. Nietch, Increased growth efficiency of Quercus alba trees in a CO_2-enriched atmosphere. *New Phytol*. **131**, 91–97 (1995).

87. P. Kardol *et al.*, Climate change effects on plant biomass alter dominance patterns and community evenness in an experimental old-field ecosystem. *Global Change Biology*. **16**, 2676–2687 (2010).

88. C. M. Iversen, J. K. Keller, C. T. Garten Jr, R. J. Norby, Soil carbon and nitrogen cycling and storage throughout the soil profile in a sweetgum plantation after 11 years of CO_2-enrichment. *Global Change Biology*. **18**, 1684–1697 (2012).

89. J. A. Morgan *et al.*, C4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. *Nature*. **476**, 202–205 (2011).

90. F. A. Dijkstra *et al.*, Contrasting effects of elevated CO_2 and warming on nitrogen cycling in a semiarid grassland. *New Phytol*. **187**, 426–437 (2010).

91. B. Gielen *et al.*, Net carbon storage in a poplar plantation (POPFACE) after three years of free-air CO_2 enrichment. *Tree Physiol*. **25**, 1399–1408 (2005).

92. O. Ghannoum *et al.*, Exposure to preindustrial, current and future atmospheric CO_2 and temperature differentially affects growth and photosynthesis in Eucalyptus. *Global Change Biology*. **16**, 303–319 (2010).

93. M. E. Gavito, P. Schweiger, I. Jakobsen, P uptake by arbuscular mycorrhizal hyphae: effect of soil temperature and atmospheric CO_2 enrichment. *Global Change Biology*. **9**, 106–116 (2003).

94. Q. Deng *et al.*, Responses of soil respiration to elevated carbon dioxide and nitrogen addition in young subtropical forest ecosystems in China. *Biogeosciences*. **7**, 315–328 (2010).

95. J. Riikonen *et al.*, Silver birch and climate change: variable growth and carbon allocation responses to elevated concentrations of carbon dioxide and ozone. *Tree Physiol*. **24**, 1227–1237 (2004).

96. A. Kasurinen *et al.*, Below-ground responses of silver birch trees exposed to elevated CO_2 and O_3 levels during three growing seasons. *Global Change Biology*. **11**, 1167–1179 (2005).

97. B. Schäppi, C. Körner, Growth responses of an alpine grassland to elevated CO_2. *Oecologia*. **105**, 43–52 (1996).

98. S. Bazot, L. Ulff, H. Blum, C. Nguyen, C. Robin, Effects of elevated CO_2 concentration on rhizodeposition from Lolium perenne grown on soil exposed to 9 years of CO_2 enrichment. *Soil Biology and Biochemistry*. **38**, 729–736 (2006).

99. M. K. Schneider *et al.*, Ten years of free-air CO_2 enrichment altered the mobilization of N from soil in Lolium perenne L. swards. *Global Change Biology*. **10**, 1377–1388 (2004).

100. P. A. Niklaus, C. Körner, Synthesis of a six-year study of calcareous grassland responses to in situ CO_2 enrichment. *Ecological Monographs*. **74**, 491–511 (2004).

101. P. W. Leadley, P. A. Niklaus, R. Stocker, C. Körner, A field study of the effects of elevated CO_2 on plant biomass and community structure in a calcareous grassland. *Oecologia*. **118**, 39–49 (1999).

102. E. Pendall, Y. Osanai, A. L. Williams, M. J. Hovenden, Soil carbon storage under simulated climate change is mediated by plant functional type. *Global Change Biology*. **17**, 505–514 (2011).

103. K. S. Pregitzer *et al.*, Atmospheric CO_2, soil nitrogen and turnover of fine roots. *New Phytol*. **129**, 579–585 (1995).

104. D. R. Zak *et al.*, Elevated atmospheric CO_2 and feedback between carbon and nitrogen cycles. *Plant Soil*. **151**, 105–117 (1993).

105. C. J. Mikan, D. R. Zak, M. E. Kubiske, K. S. Pregitzer, Combined effects of atmospheric CO_2 and N availability on the belowground carbon and nitrogen dynamics of aspen mesocosms. *Oecologia*. **124**, 432–445 (2000).

106. C. S. Vogel, P. S. Curtis, R. B. Thomas, Growth and nitrogen accretion of dinitrogen-fixing Alnus glutinosa (L.) Gaertn. under elevated carbon dioxide. *Plant Ecology*. **130**, 63–70 (1997).

107. B. A. Kimball, S. B. Idso, S. Johnson, M. C. Rillig, Seventeen years of carbon dioxide enrichment of sour orange trees: final results. *Global Change Biology*. **13**, 2171–2183 (2007).

108. S. A. Prior, G. B. Runion, H. A. Torbert, S. B. Idso, B. A. Kimball, Sour orange fine root distribution after seventeen years of atmospheric CO_2 enrichment. *Agricultural and Forest Meteorology*. **162-163**, 85–90 (2012).

109. R. F. Walker, D. R. Geisinger, D. W. Johnson, J. T. Ball, Elevated atmospheric CO_2 and soil N fertility effects on growth, mycorrhizal colonization, and xylem water potential of juvenile ponderosa pine in a field soil. *Plant Soil*. **195**, 25–36 (1997).

110. D. M. Olszyk *et al.*, Whole-seedling biomass allocation, leaf area, and tissue chemistry for Douglas-fir exposed to elevated CO_2 and temperature for 4 years. *Can. J. For. Res.* **33**, 269–278 (2003).

111. A. R. Smith, M. Lukac, M. Bambrick, F. Miglietta, D. L. Godbold, Tree species diversity interacts with elevated CO_2 to induce a greater root system response. *Global Change Biology*. **19**, 217–228 (2013).

112. A. Antoninka, P. B. Reich, N. C. Johnson, Seven years of carbon dioxide enrichment, nitrogen fertilization and plant diversity influence arbuscular mycorrhizal fungi in a grassland ecosystem. *New Phytol*. **192**, 200–214 (2011).

113. F. Hagedorn, D. Spinnler, M. Bundt, P. Blaser, R. Siegwolf, The input and fate of new C in two forest soils under elevated CO_2. *Global Change Biology*. **9**, 862–872 (2003).

114. D. R. Zak, W. E. Holmes, A. C. Finzi, R. J. Norby, W. H. Schlesinger, Soil nitrogen cycling under elevated CO_2: a synthesis of forest face experiments. *Ecological Applications*. **13**, 1508–1514 (2003).

115. R. E. Dickson *et al.*, Forest atmosphere carbon transfer and storage (FACTS-II) the aspen Free-air CO_2 and O_3 Enrichment (FACE) project: an overview. General Technical Report NC-214. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Forest Experiment Station (2000).

116. H. J. Jäger *et al.*, The University of Giessen free-air carbon dioxide enrichment study: description of the experimental site and of a new enrichment system. *Journal of Applied Botany*. **77**, 117–127 (2003).

117. V. M. Temperton *et al.*, Effects of elevated carbon dioxide concentration on growth and nitrogen fixation in Alnus glutinosa in a long-term field experiment. *Tree Physiol*. **23**, 1051–1059 (2003).

118. L. F. Huenneke, S. P. Hamburg, R. Koide, H. A. Mooney, P. M. Vitousek, Effects of Soil Resources on Plant Invasion and Community Structure in Californian Serpentine Grassland. *Ecology*. **71**, 478–491 (1990).

119. P. Dijkstra *et al.*, Elevated atmospheric CO_2 stimulates aboveground biomass in a fire-regenerated scrub-oak ecosystem. *Global Change Biology*. **8**, 90–103 (2002).

120. D. N. Jordan *et al.*, Biotic, abiotic and performance aspects of the Nevada Desert Free-Air CO_2 Enrichment (FACE) Facility. *Global Change Biology*. **5**, 659–668 (1999).

121. T. Rütting, T. J. Clough, C. Müller, M. Lieffering, P. C. D. Newton, Ten years of elevated atmospheric carbon dioxide alters soil nitrogen transformations in a sheep-grazed pasture. *Global Change Biology*. **16**, 2530–2542 (2010).

122. M. E. Gavito, P. S. Curtis, T. N. Mikkelsen, I. Jakobsen, Atmospheric CO_2 and mycorrhiza effects on biomass allocation and nutrient uptake of nodulated pea (Pisum sativum L.) plants. *Journal of Experimental Botany*. **51**, 1931–1938 (2000).

123. A. Kasurinen, P. Kokko Gonzales, J. Riikonen, E. Vapaavuori, T. Holopainen, Soil CO_2 efflux of two silver birch clones exposed to elevated CO_2 and O_3 levels during three growing seasons. *Global Change Biology*. **10**, 1654–1665 (2004).

124. T. Hebeisen *et al.*, Growth response of Trifolium repens L. and Lolium perenne L. as monocultures and bi-species mixture to free air CO_2 enrichment and management. *Global Change Biology*. **3**, 149–160 (1997).

125. P. A. Niklaus, M. Wohlfender, R. Siegwolf, C. Körner, Effects of six years atmospheric CO_2 enrichment on plant, soil, and soil microbial C of a calcareous grassland. *Plant Soil*. **233**, 189–202 (2001).

126. M. J. Hovenden *et al.*, Warming prevents the elevated CO_2-induced reduction in available soil nitrogen in a temperate, perennial grassland. *Global Change Biology*. **14**, 1018–1024 (2008).

127. J. Lussenhop, A. Treonis, P. S. Curtis, J. A. Teeri, C. S. Vogel, Response of soil biota to elevated atmospheric CO_2 in poplar model systems. *Oecologia*. **113**, 247–251 (1998).

128. P. Reich *et al.*, Nitrogen limitation constrains sustainability of ecosystem response to CO_2. *Nature*. **440**, 922–925 (2006).

129. R. Oren *et al.*, Soil fertility limits carbon sequestration by forest ecosystems in a CO_2-enriched atmosphere. *Nature*. **411**, 469–472 (2001).

130. C. Körner, Plant CO_2 responses: an issue of definition, time and resource supply. *New Phytol*. **172**, 393–411 (2006).

131. P. Jarvis, S. Linder, Botany: Constraints to growth of boreal forests. *Nature*. **405**, 904–905 (2000).

132. P. S. Curtis *et al.*, Biometric and eddy-covariance based estimates of annual carbon storage in five eastern North American deciduous forests. *Agricultural and Forest Meteorology*. **113**, 3–19 (2002).

133. S. N. Turitzin, Nutrient Limitations to Plant Growth in a California Serpentine Grassland. *American Midland Naturalist*. **107**, 95 (1982).

134. T. Rütting, L. C. Andresen, Nitrogen cycle responses to elevated CO_2 depend on ecosystem nutrient status. *Nutr Cycl Agroecosyst*. **101**, 285–294 (2015).

135. R. J. Norby, D. R. Zak, Ecological lessons from free-air CO_2 enrichment (FACE) experiments. *Annual Review of Ecology*. **42**, 181–203 (2011).

136. A. P. Walker *et al.*, Predicting long-term carbon sequestration in response to CO_2 enrichment: How and why do current ecosystem models differ? *Global Biogeochem. Cycles*. **29**, 476–495 (2015).

137. D. Nyfeler *et al.*, Strong mixture effects among four species in fertilized agricultural grassland led to persistent and consistent transgressive overyielding. *Journal of Applied Ecology*. **46**, 683–691 (2009).

138. D. Nyfeler, O. Huguenin-Elie, M. Suter, E. Frossard, A. Lüscher, Grass-legume mixtures can yield more nitrogen than legume pure stands due to mutual stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agriculture, Ecosystems & Environment*. **140**, 155–163 (2011).

139. P. C. D. Newton *et al.*, Selective grazing modifies previously anticipated responses of plant community composition to elevated CO_2 in a temperate grassland. *Global Change Biology*. **20**, 158–169 (2014).