Tree functional traits, forest biomass, and tree species diversity interact with site properties to drive forest soil carbon

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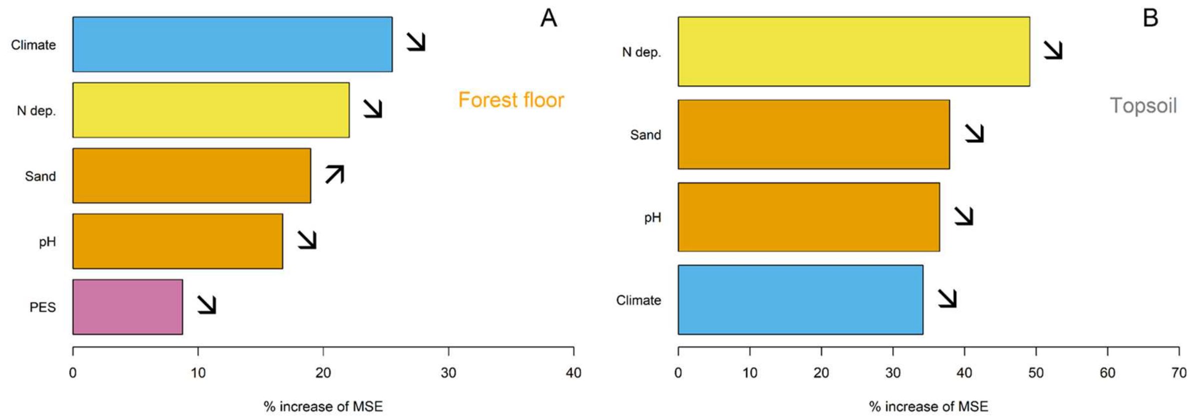
Supplementary Information

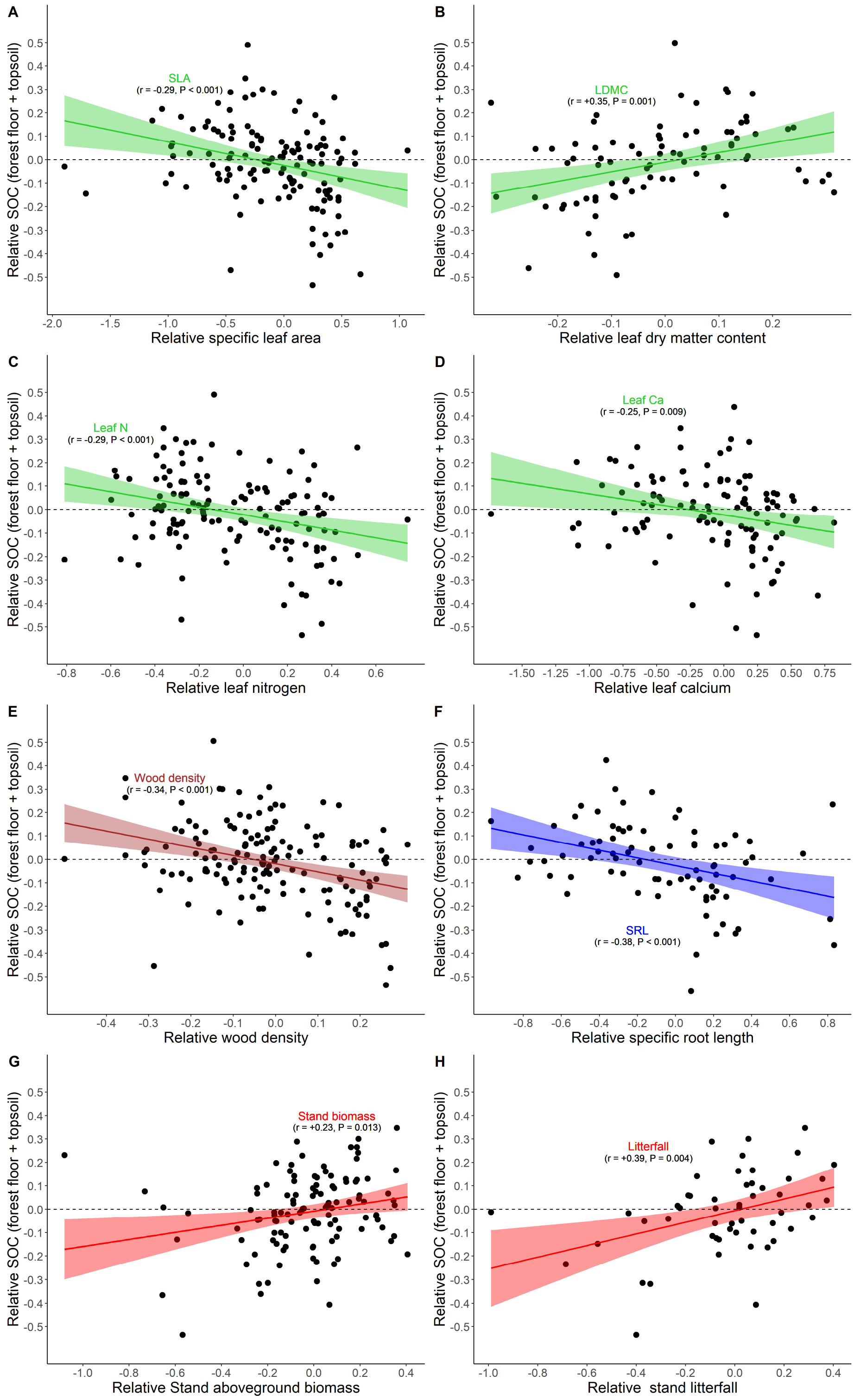
<u>Supplementary Figures</u> (S1 to S23)

<u>Supplementary Tables</u> (S1 to S9)

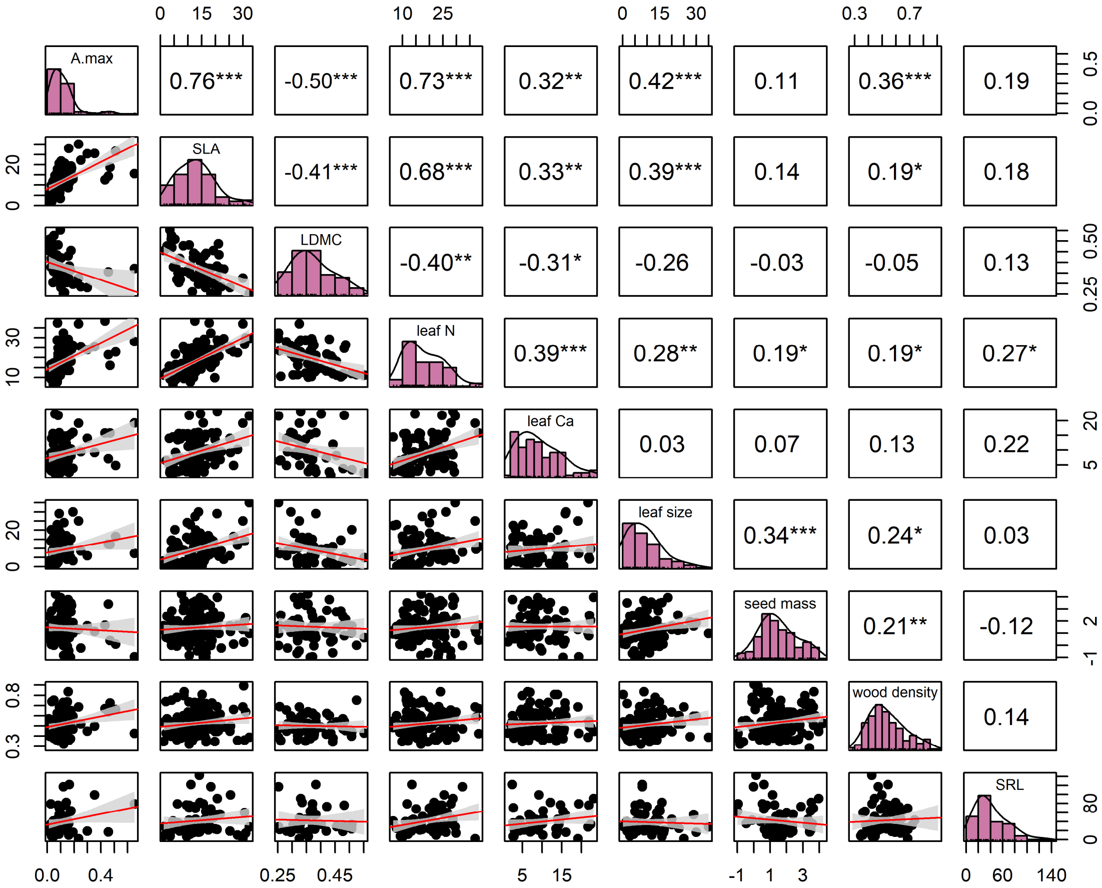
<u>Supplementary References</u>



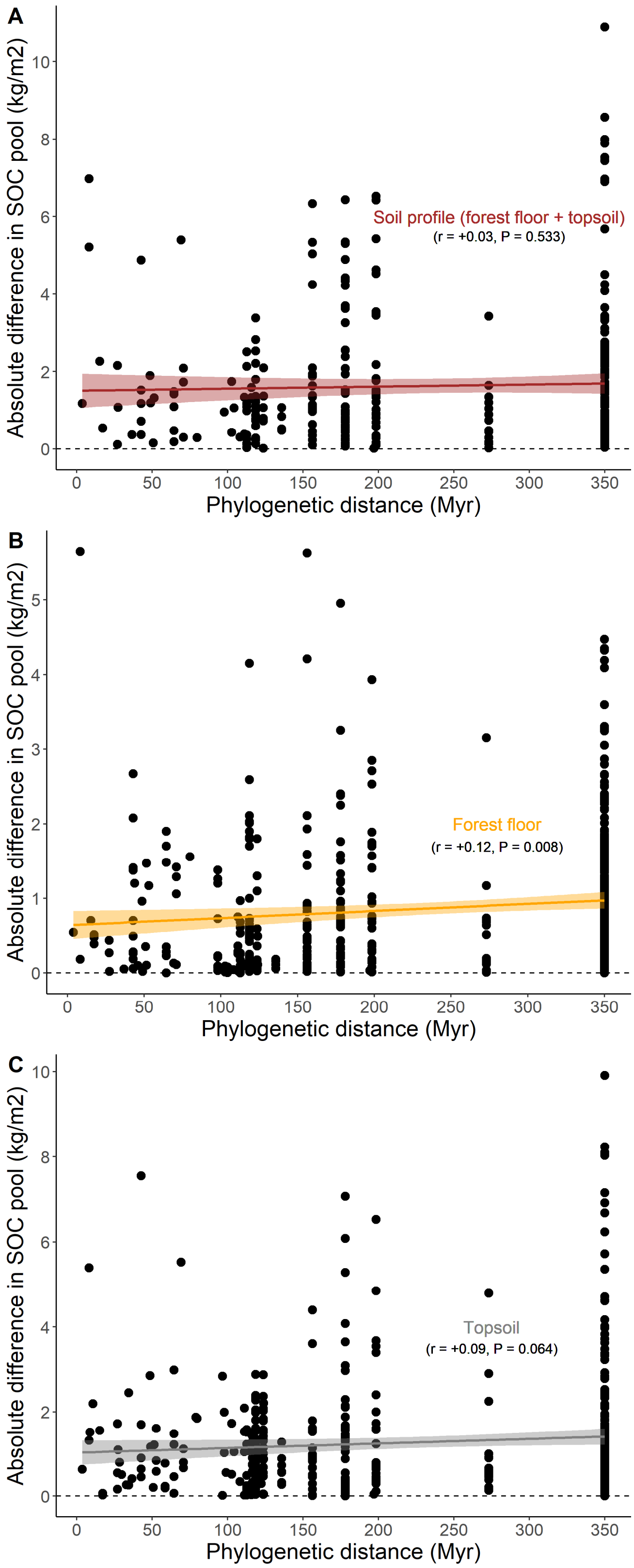
Supplementary Fig. S1 | Main variables explaining the SOC pools at the global scale. The SOC pool was modelled using their absolute values, enabling the evaluation of the influence of the site properties on SOC content. The studied pools were: the forest floor layer (A), and the topsoil layer (B). The predictors were a climatic descriptor ($f_{climate}$ ranging from 0 [unfavourable to biological activity] to 1 [favourable], in blue; see Methods), soil properties, in brown (sand content and pH value), nitrogen atmospheric deposition, in yellow, and the index score of the Plant Economics Spectrum (PES; see Methods) of the tree species, in violet. The influence of the variables was assessed using the percentage of increase of mean square error (MSE) after running the Random Forest approach (see Methods). Arrows indicate positive (↗) or negative (↘) effects of the predictors on SOC.



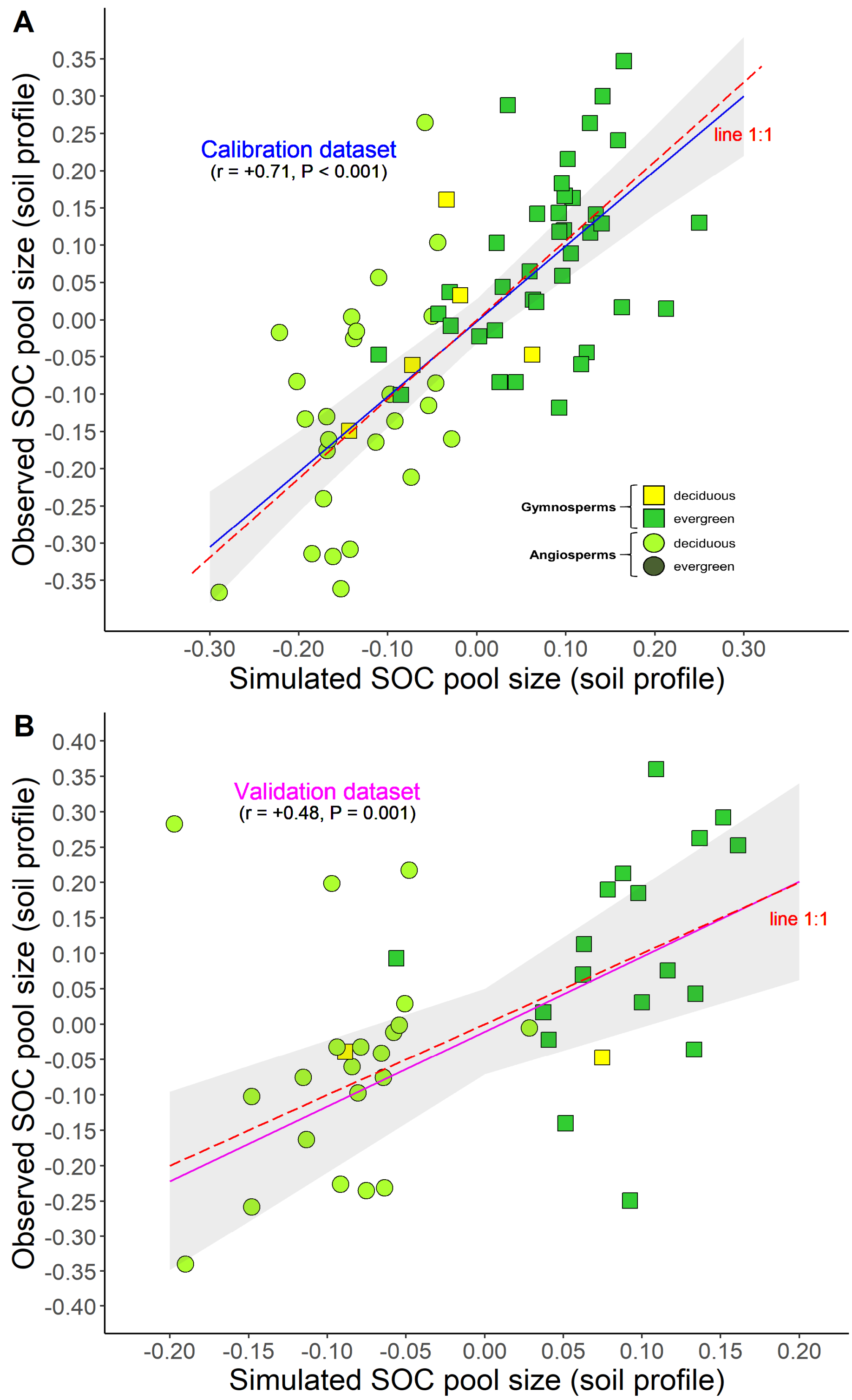
Supplementary Fig. S2 | Global influence of plant traits and forest biomass on SOC pools. Values are normalised (see Methods). Values of r^2 are 0.05-0.15 (see panels for r values and P values). Results for the leaf photosynthetic capacity (A_{max}), leaf size, leaf C:N, and seed mass are not shown here (see Figure 2 for A_{max}). For these latter traits, the relationships were significant ($|r| = 0.21$-0.46; $r^2 = 0.04$-0.21; $P < 0.050$). Linear regressions were fitted (level of confidence of the error band = 0.95).



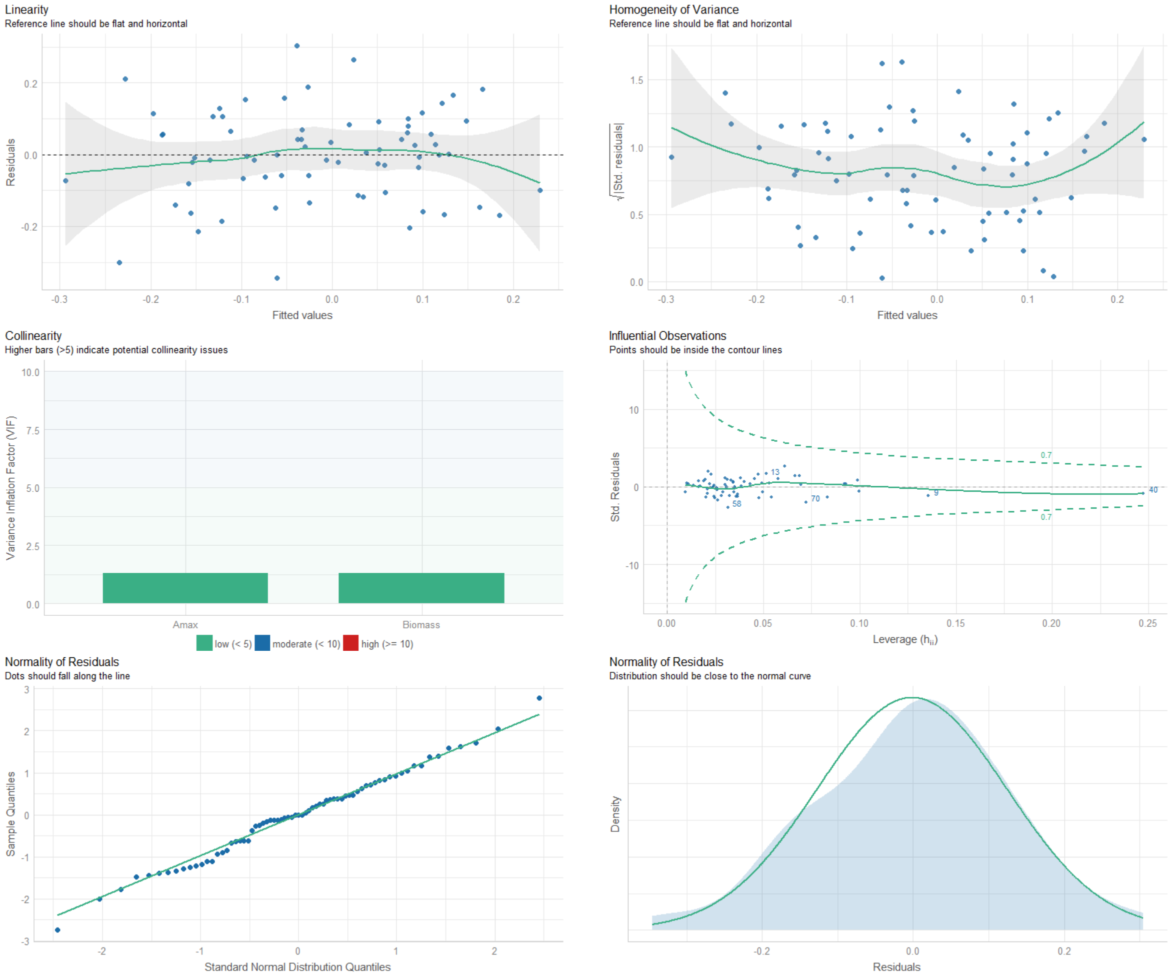
Supplementary Fig. S3 | Relationships among the traits that constitute the Plant Economics Spectrum. To avoid pseudo-replications, we used only a subset of our data, containing one set of trait values per tree species (n = 59-178, depending on the trait). The matrix shows the results of Spearman's rank correlation coefficients. The symbols *, **, and *** indicate correlations with P values respectively as follows: $P < 0.05$, $P < 0.01$, and $P < 0.001$.



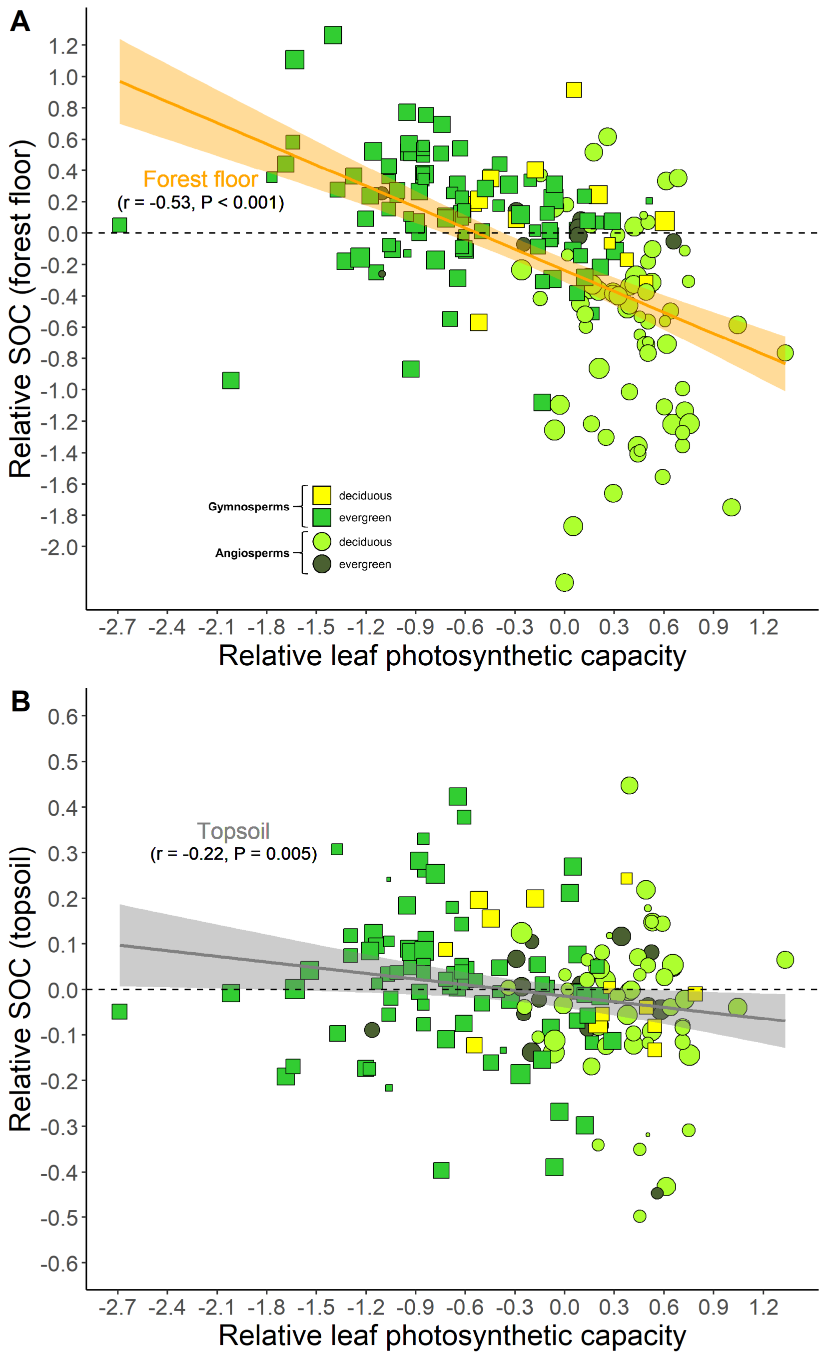
Supplementary Fig. S4 | SOC pools and phylogenetic distance among tree species. SOC pools are: whole soil profile (A), forest floor (B), and topsoil (C). Values are normalised (see Methods). Each dot is a pair of mono-specific stands of different tree species growing in the same site. The phylogenetic distance between the two species of a given pair is in millions of years. Linear regressions were fitted (level of confidence of the error band = 0.95).



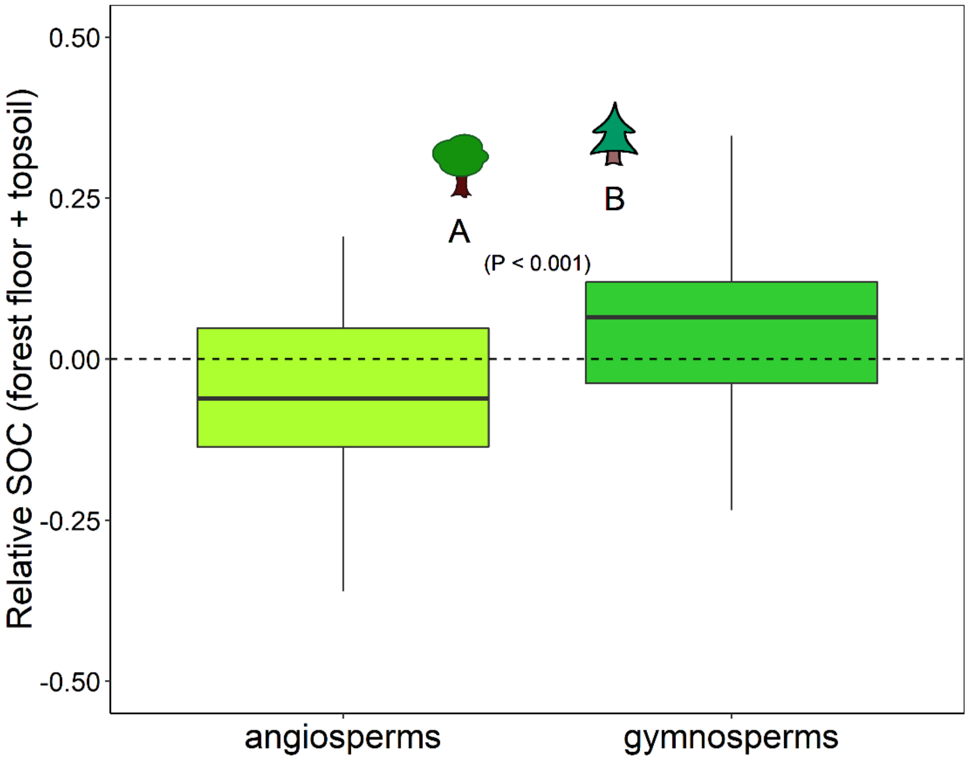
Supplementary Fig. S5 | Model explaining the SOC pools as a function of the photosynthetic capacity of tree species and stand biomass. SOC pools are for the soil profile (forest floor + topsoil). Panels show the performance of the model (based on leaf photosynthetic capacity of tree species and standing biomass of stands) with: the calibration dataset (A) and an independent dataset used for validation (B). Values are normalised (see Methods). Linear regressions were fitted (level of confidence of the error band = 0.95). Linear regressions take into account data reliability as weighting factor.



Supplementary Fig. S6 | Evaluation of the model using the calibration dataset (see Figure S5A). The SOC pool was modelled using the values found in the original articles of the data compilation. The predictors retained by the model were: maximal photosynthetic capacity of tree species (A_{max}) and stand biomass (Biomass). Other predictors were not significant.



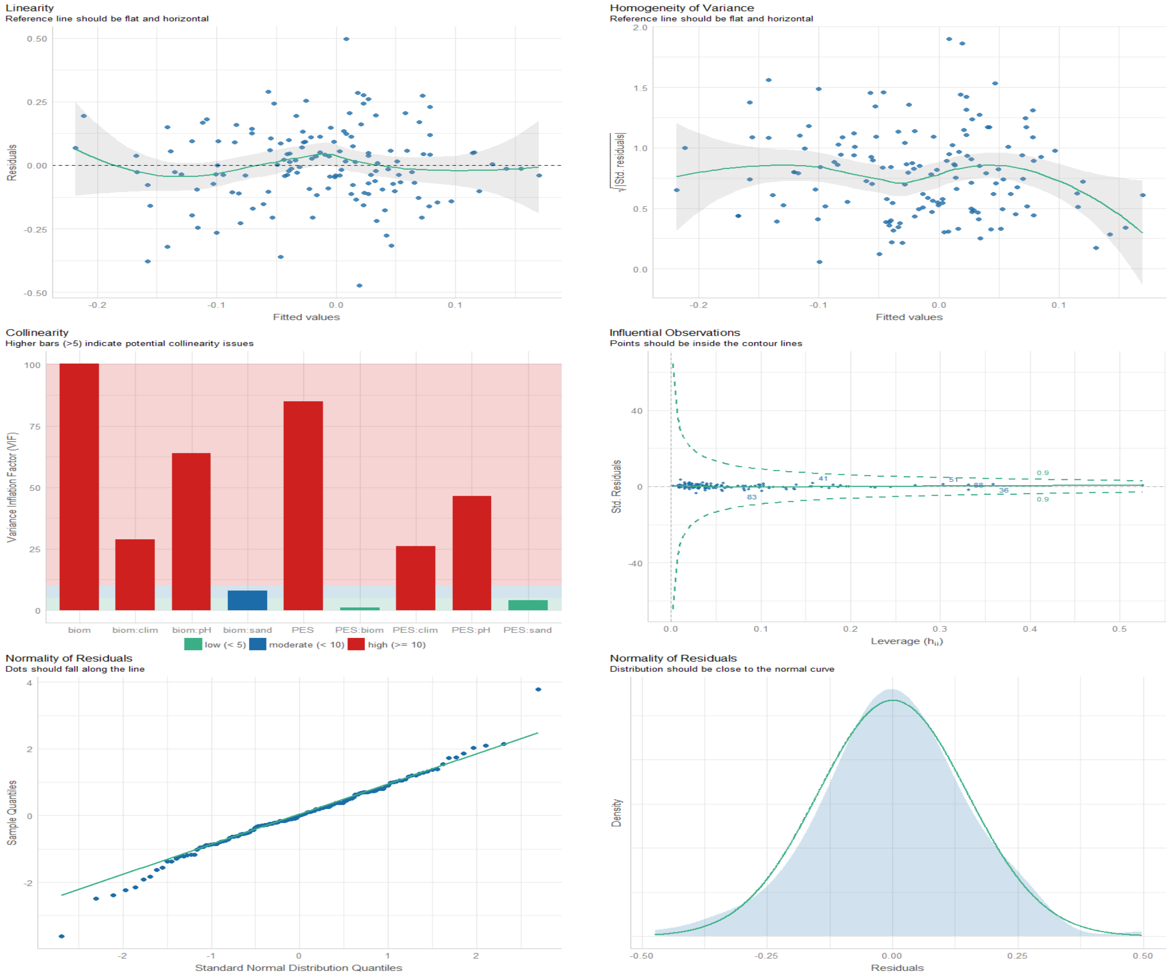
Supplementary Fig. S7 | Global influence of the photosynthetic capacity of tree species on SOC pools. SOC pools are: forest floor (*i.e.* the uppermost organic layer supplied by litterfall; panel A), and topsoil (*i.e.* upper layer of mineral soil with an Equivalent Soil Mass of 3000 Mg ha^{-1}; panel B). Values are normalised (see Methods). Linear regressions were fitted (level of confidence of the error band = 0.95). The symbol size is proportional to data reliability (see Methods), which was taken into account as a weighting factor in the regression.



Supplementary Fig. S8 | Soil organic carbon under gymnosperms and angiosperms. Values are normalised (see Methods). The difference was tested with a pairwise *t*-test (*F* value = 16.76). Values: n = 68 pairs. Boxplots represent the median, the first and third quartiles, and 1.5 × the inter-quartile range. The difference between the two groups was tested with a pairwise t-test (two-sided).

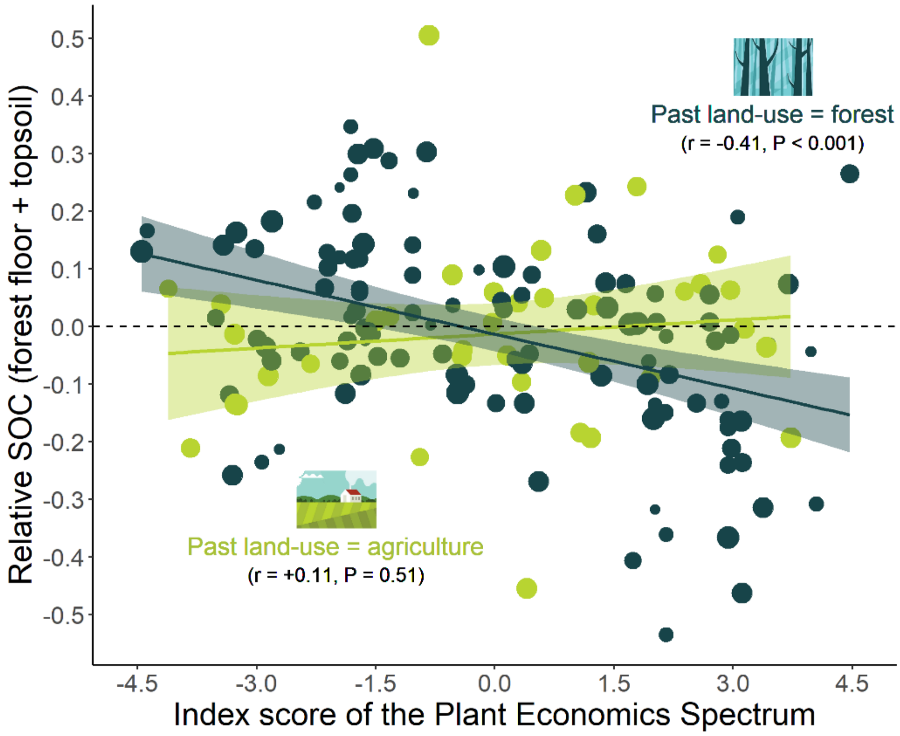
Supplementary Fig. S9 | Evaluation of the model based on imputed values, including past land-use (see Figure 4A). The SOC pool was modelled using imputed values based on a PCA approach (see Methods). The predictors were: an integrated value of the functional traits constituting the plant economics spectrum (PES), stand biomass (Biomass), a climatic index ($f_{climate}$), soil sand content, soil pH, and past land-use (PLU). The tested model was as follows:

$$SOC \sim (PES \times Biomass) + \{(PES + Biomass) : (f_{climate} + Sand + pH + PLU)\}$$

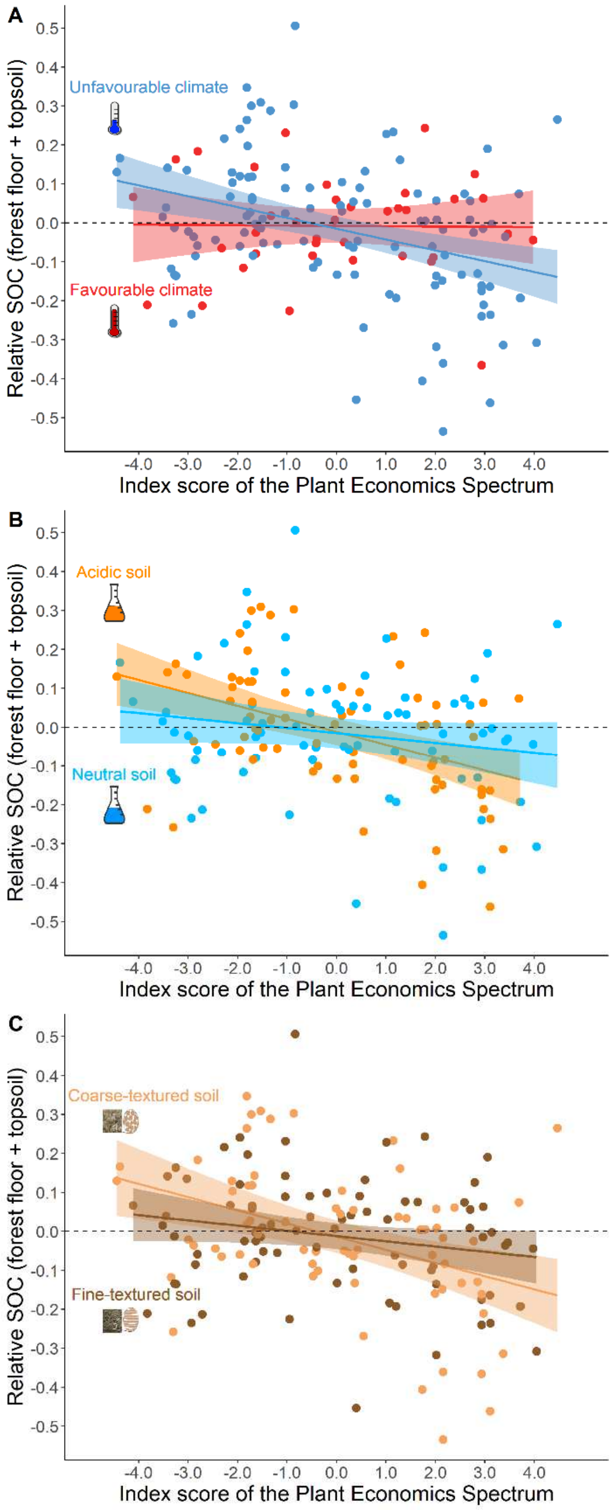


Supplementary Fig. S10 | Evaluation of the model based on imputed values, without past land-use (see Figure 4B). The SOC pool was modelled using imputed values based on a PCA approach (see Methods). The predictors were: an integrated value of the functional traits constituting the plant economics spectrum (PES), stand biomass (Biomass), a climatic index (f_{climate}), soil sand content, and soil pH. The tested model was as follows:

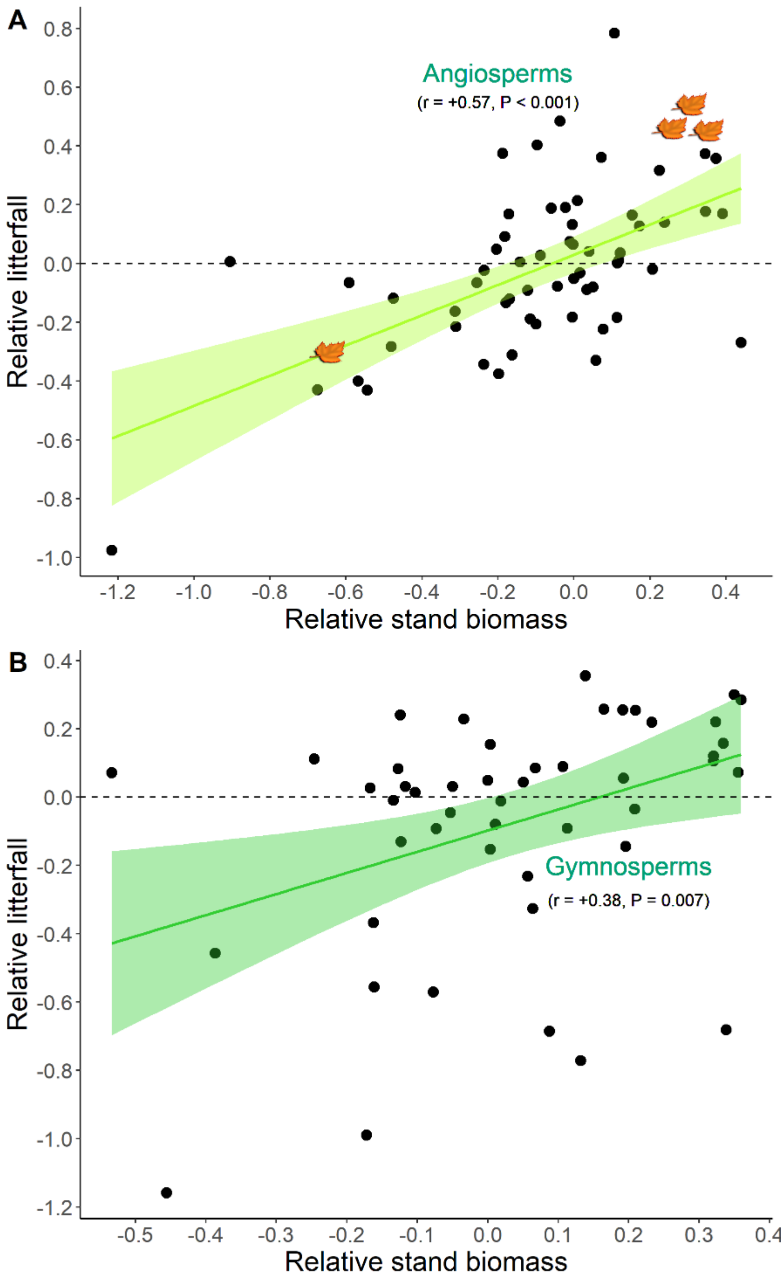
$$\text{SOC} \sim (\text{PES} \times \text{Biomass}) + \{(\text{PES} + \text{Biomass}) : (f_{\text{climate}} + \text{Sand} + \text{pH})\}$$



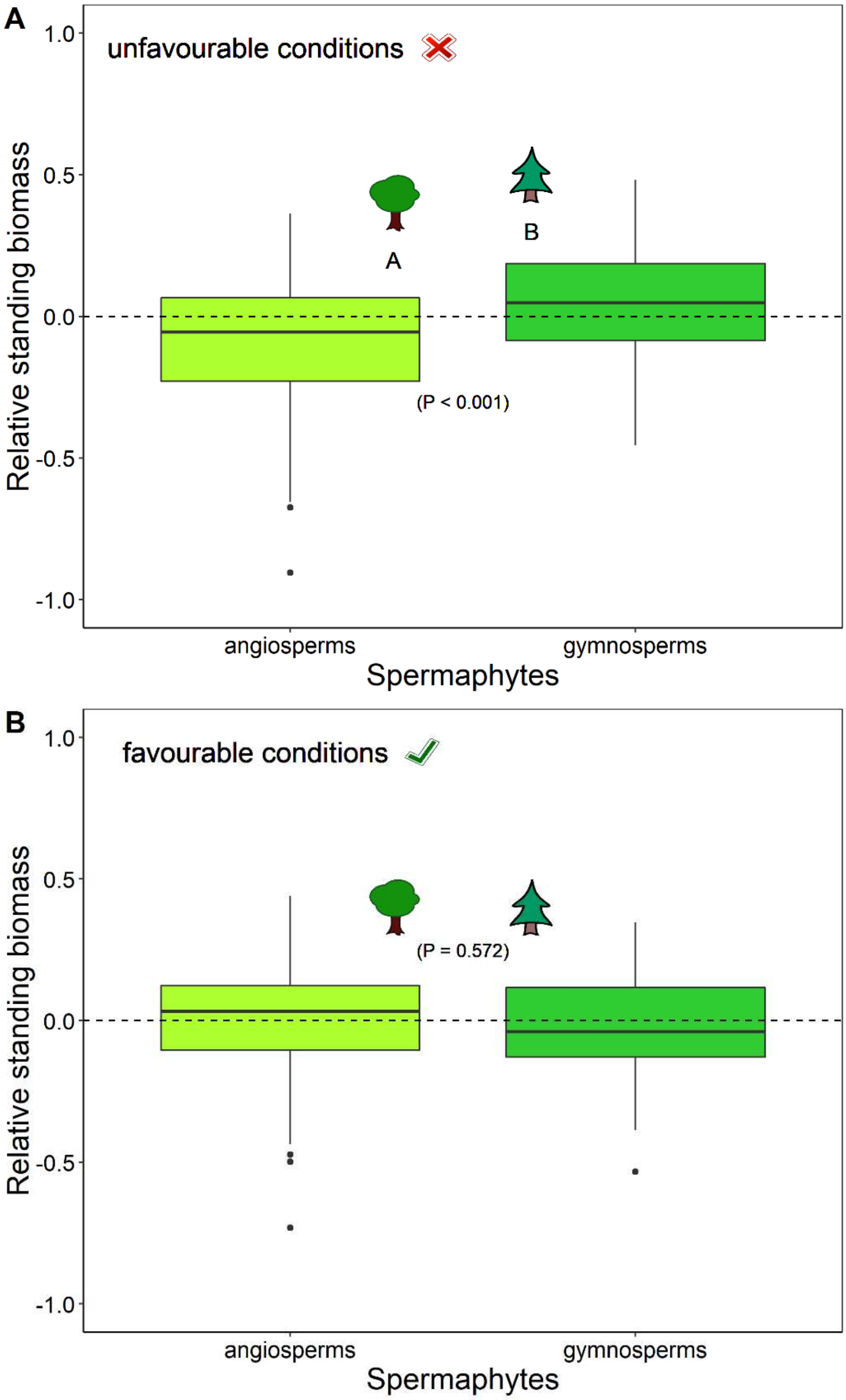
Supplementary Fig. S11 | Modulation of the imprint of tree species on forest SOC by past land-use and site fertilisation. Different colours indicate different past land-use of the studied forest. "agriculture" (green symbols) includes mainly grasslands, but also a few croplands and land treated with inorganic fertilisers; "forest" (dark grey symbols) includes mainly forests, but also a few shrublands. Values are normalised (see Methods). Linear regressions were fitted (level of confidence of the error band = 0.95). The symbol size is proportional to data reliability (see Methods), and regressions take it into account as a weighting factor.



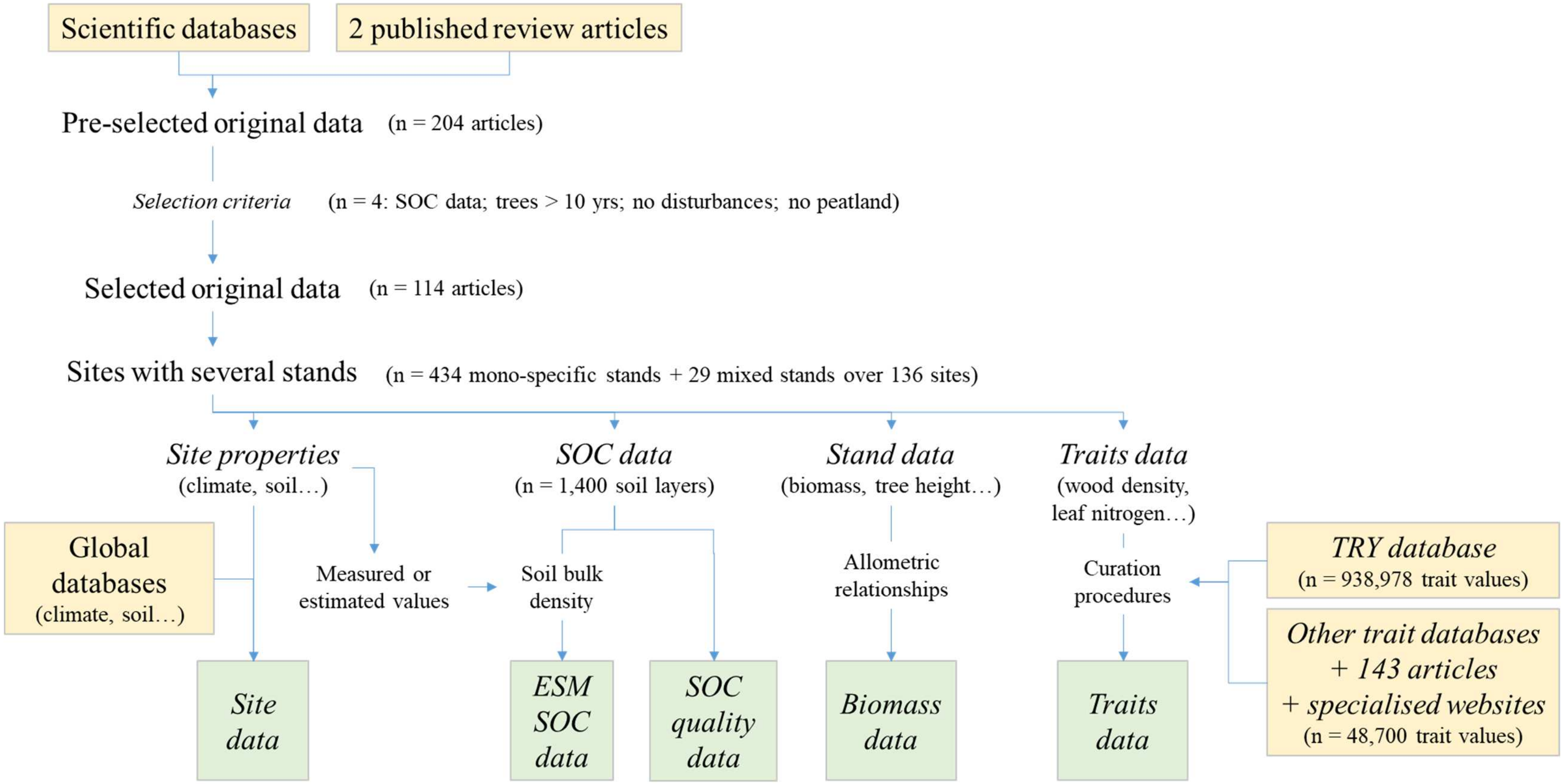
Supplementary Fig. S12 | Modulation of the imprint of tree species on SOC by climate and soil properties. Graphs show the relationships between the index score of the Plant Economics Spectrum and SOC pool in interaction with climate (A), soil texture (B), and soil acidity (C). Values are normalised values (see Methods). Linear regressions take data reliability into account as a weighting factor. Categories are based on threshold values close to the median values of (A) $f_{climate}$ = 0.35 (unitless), (B) soil pH = 5.0, (C) soil sand content = 500 mg g^{-1}. Low values, and high, values of $f_{climate}$ indicate respectively unfavourable climatic conditions (cold and/or dry), and favourable climatic conditions (warm and wet). Linear regressions were fitted (level of confidence of the error band = 0.95).



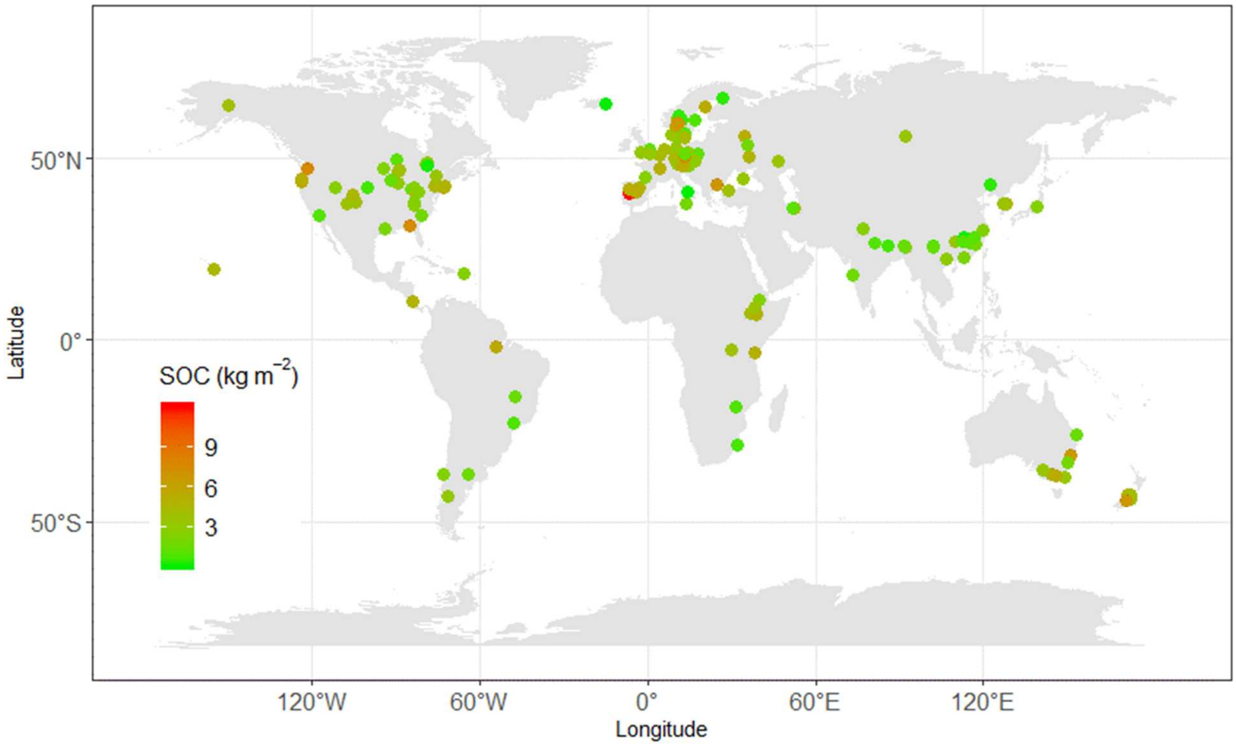
Supplementary Fig. S13 | Influence of stand aboveground biomass on stand litterfall flux. Values are normalised (see Methods). Linear regressions were fitted (level of confidence of the error band = 0.95).



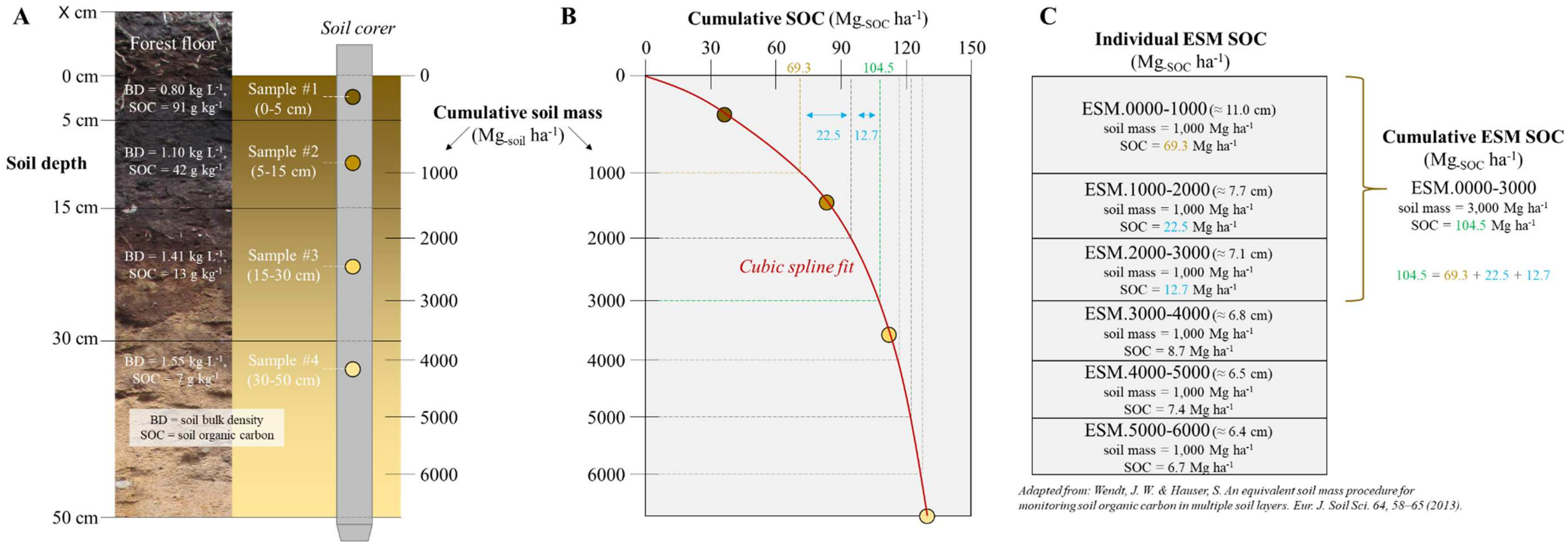
Supplementary Fig. S14 | Aboveground stand biomass in gymnosperm and angiosperm forests. Unfavourable and favourable climatic conditions were defined based on an index of potential biological activity (f_{climate}; see Methods) with 0.35 as a threshold value. Values: n = 189 and 67 pairs for panels A and B. *W* value = 3134 and 459.5 for panels A and B, respectively (Wilcoxon rank sum test; two sided). Values are normalised (see Methods). Boxplots represent the median, the first and third quartiles, and 1.5 × the inter-quartile range.



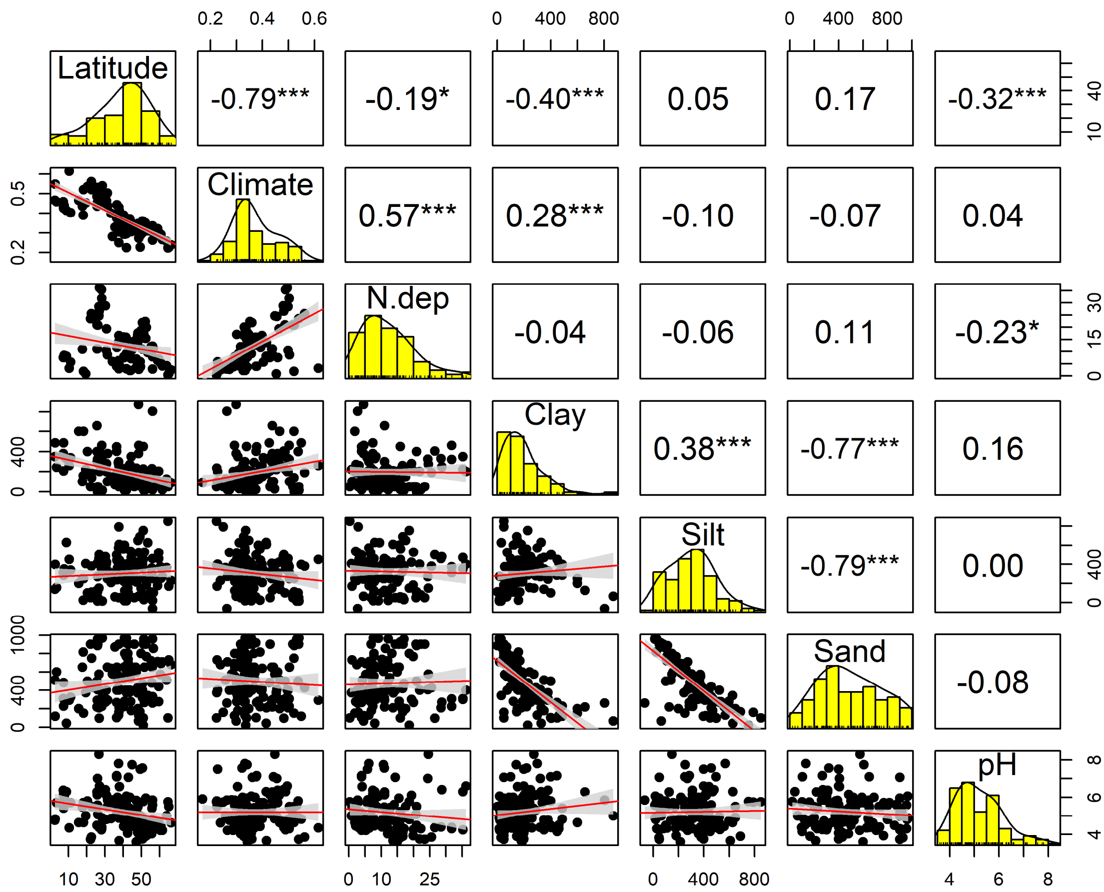
Supplementary Fig. S15 | Data flow of the study. Yellow boxes and green boxes indicate the sources of original data and the final datasets, respectively.



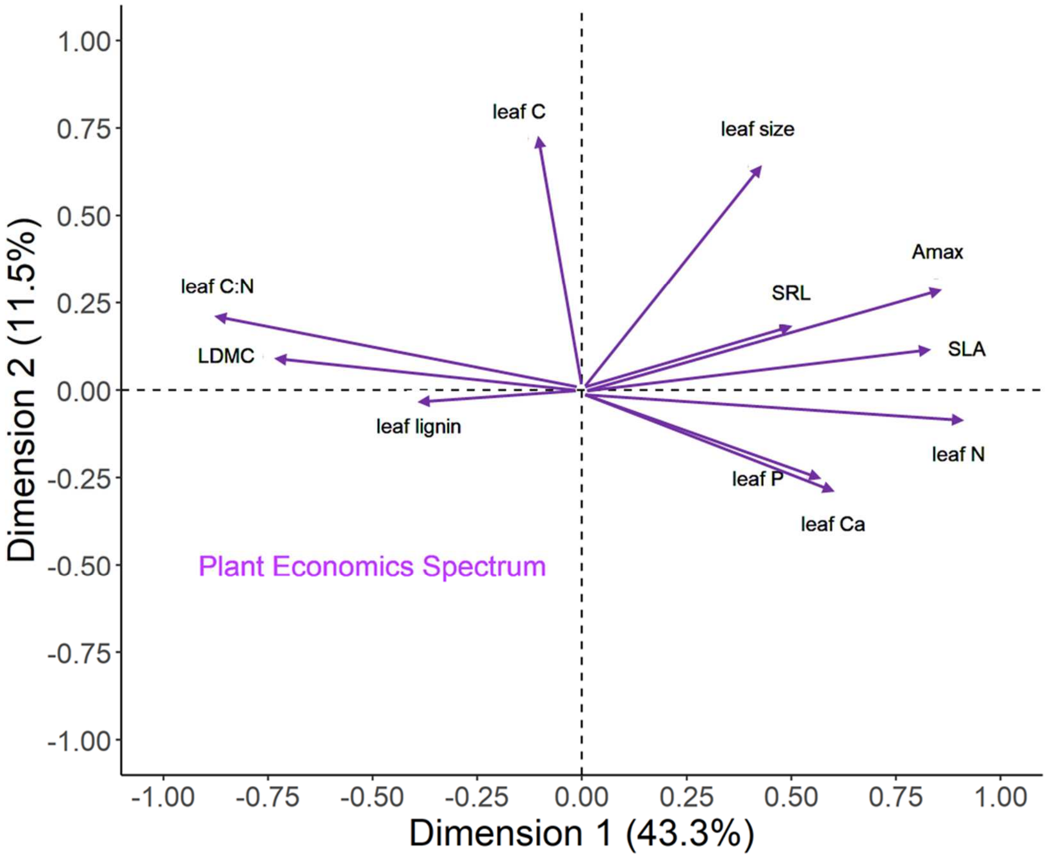
Supplementary Fig. S16 | Map of study site locations. A few sites had no geographical coordinates and are located approximately. The colours indicate the SOC pool size in the upper part of the soil mineral layer (for an Equivalent Soil Mass of 1,000 Mg of soil per hectare).



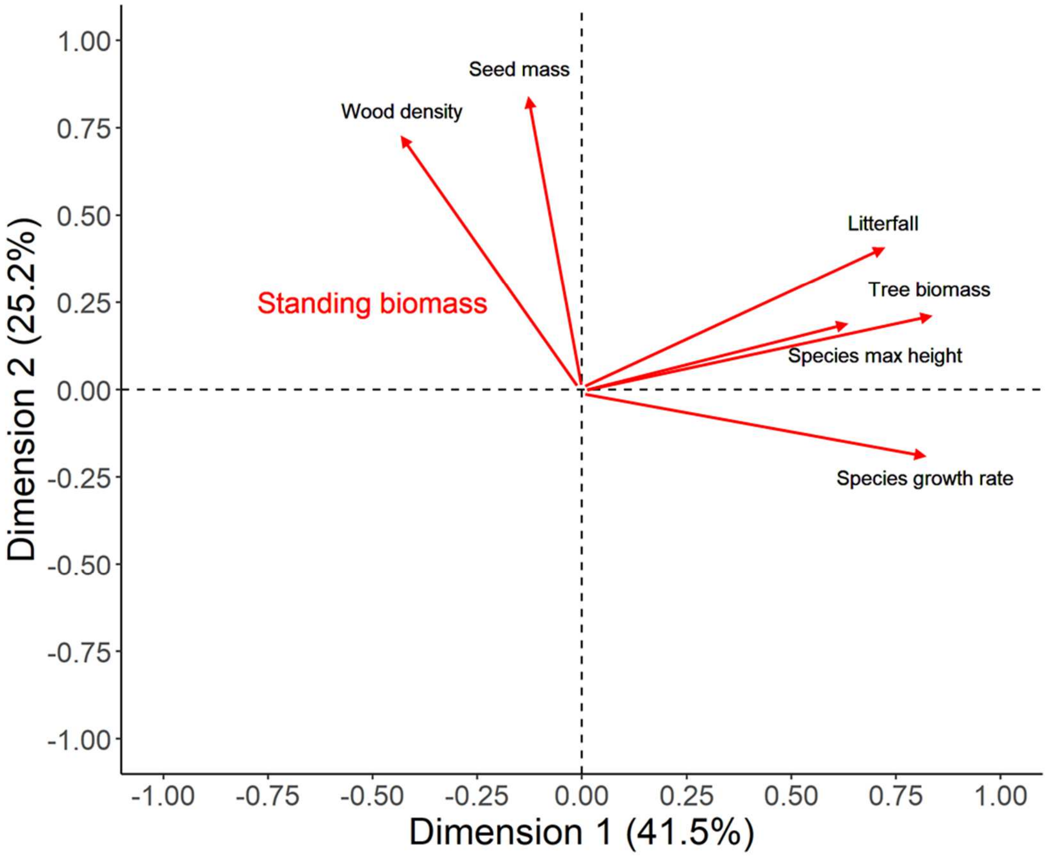
Supplementary Fig. S17 | Equivalent Soil Mass calculation. Fictive example of the way original SOC values were calculated in Equivalent Soil Mass (ESM) values. In the panel (A), a soil profile was sampled down to 50 cm and split in four layers (0-5 cm, 5-15 cm, 15-30 cm, and 30-50 cm; circles coloured from dark brown to light yellow). The right vertical axis indicated the cumulative soil mass of the profile (calculated based on volume and bulk density of the sampled layers). Having the mass and the SOC content value of the soil layers, it enabled to calculate the SOC pool of each layer. In the panel (B), the SOC pool values (*x* axis) were represented in a cumulative way (first the layer 0-5 cm [dark brown circle], then {layer 0-5 cm + layer 5-15 cm} [light brown circle], and so on), and plotted versus the cumulative soil mass (*y* axis). Then, a regression (cubic spline) was fit (red line). This regression was used to estimate the SOC pool of layers of equivalent soil mass (ESM, in Mg_{-soil} ha^{-1}): the topsoil layer of 1000 Mg_{-soil} ha^{-1} contained 69.3 Mg_{-SOC} ha^{-1}, the second layer of 1000 Mg_{-soil} ha^{-1} contained 22.5 Mg_{-SOC} ha^{-1}, the third layer of 1000 Mg_{-soil} ha^{-1} contained 12.7 Mg_{-SOC} ha^{-1}, and so on. The panel (C) indicated the final data. In our study, we retained as main studied soil layer the cumulated value of the three uppermost ESM individual layers (*i.e.* having an ESM of 3000 Mg_{-soil} ha^{-1}). In this example, this soil layer (named ESM.0000-3000) had a cumulative ESM SOC value of 104.5 Mg_{-SOC} ha^{-1}.



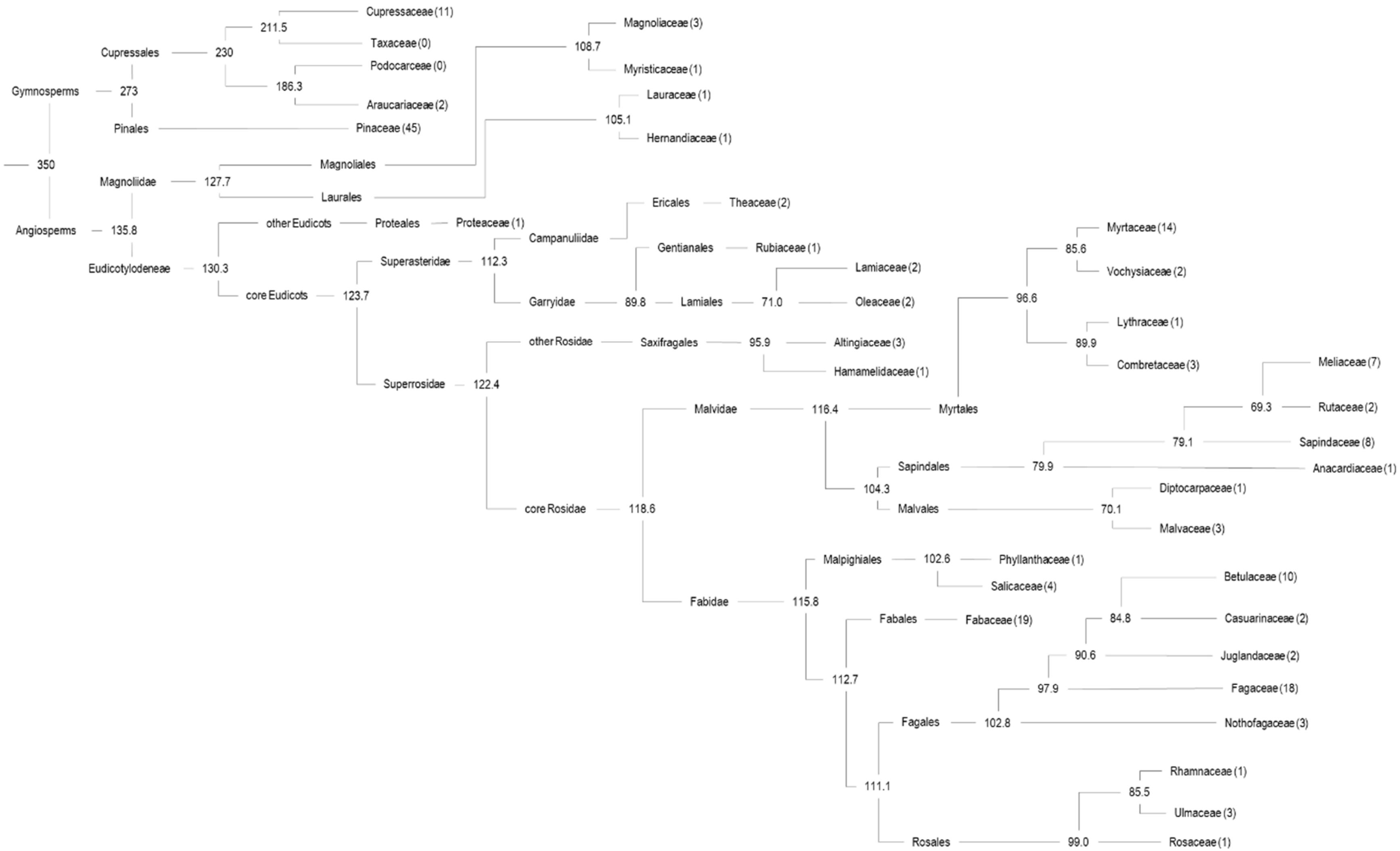
Supplementary Fig. S18 | Relationships among the site properties. Latitude (°); Climate = $f_{climate}$ (climate factor index; [0-1]; see Methods); N.dep = nitrogen atmospheric deposition (kg-N ha^{-1} yr^{-1}); Clay, Silt, and Sand = particle size fractions of soils (mg g^{-1}); pH = soil pH (unitless). The matrix shows the results of Spearman's rank correlation coefficients. The symbols *, **, and *** indicate correlations with P values respectively as follows: $P < 0.05$, $P < 0.01$, and $P < 0.001$.



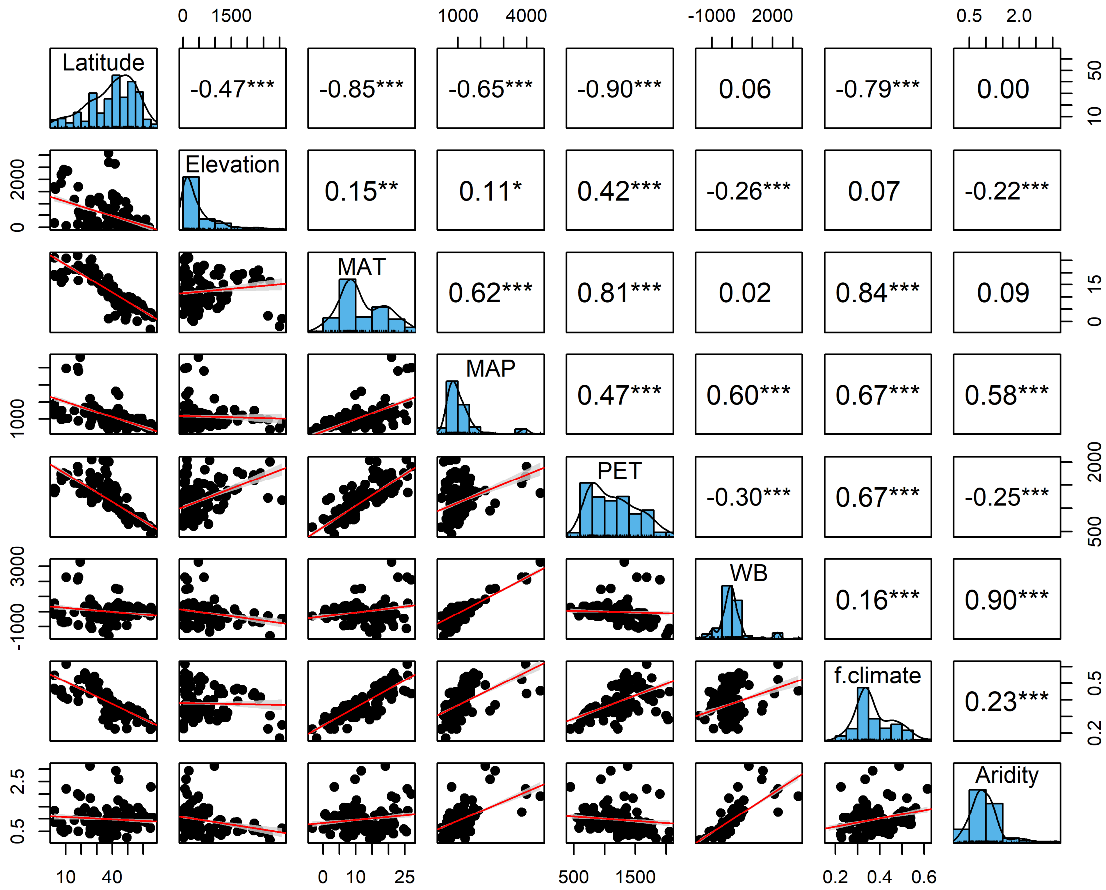
Supplementary Fig. S19 | Principal Component Analysis used to produce the index score of the Plant Economics Spectrum (PES). The functional traits of all the studied tree species were used to generate a Principal Component Analysis (PCA). For full explanation, see the section "*Data collection: plant functional traits*" in Methods. The final value of the index score of the PES was the coordinate value on the first axis ("Dimension 1").



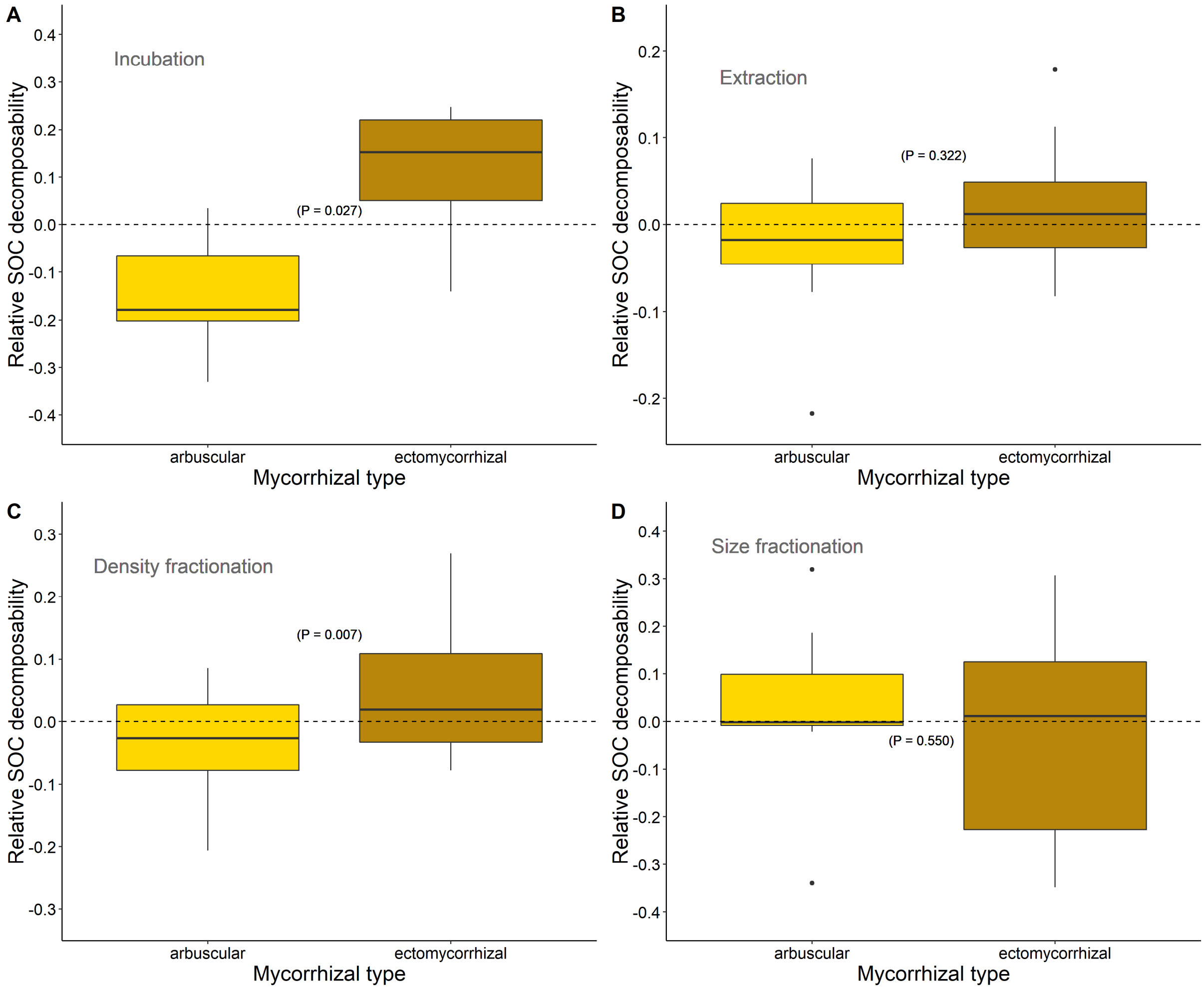
Supplementary Fig. S20 | Principal Component Analysis used to produce the index score of the forest standing biomass. The variables that were directly related to biomass ("litterfall" and "tree biomass"), and functional traits known to be related to biomass or growth ("max height", "growth rate", "seed mass", "wood density") were used to generate a Principal Component Analysis (PCA). For full explanation, see the section "*Data collection: plant functional traits*" in Methods. The final value of the index score of the standing biomass was the coordinate value on the first axis ("Dimension 1").



Supplementary Fig. S21 | Phylogenetic tree of the species of the study. Values on the phylogenetic tree are the distances in millions of years (Myr). For the sake of clarity, the stem lengths are not proportional to the phylogenetic distances. Values in brackets next to family names are the number of species present in our dataset.



Supplementary Fig. S22 | Relationships among climatic descriptors. MAT = mean annual temperature (°C); MAP = mean annual precipitation (mm yr^{-1}); PET = potential evapotranspiration (mm yr^{-1}); WB = water balance (MAP-PET difference); f_{climate} (climate factor index; [0-1]; see Methods). The matrix shows the results of Spearman's rank correlation coefficients. The symbols *, **, and *** indicate correlations with P values respectively as follows: P < 0.05, P < 0.01, and P < 0.001.



Supplementary Fig. S23 | Differences of SOC decomposability between arbuscular mycorrhizal tree species and ectomycorrhizal tree species, as influenced by the method used to quantify the SOC decomposability. Values (n=20, 28, 36 and 27 pairs, for the panels A, B, C and D, respectively) show the SOC decomposability, which is the opposite of SOC stability. Values are normalised. Boxplots represent the median, the first and third quartiles, and 1.5 × the inter-quartile range. Significant differences were tested with pairwise t-test or Wilcoxon test (two-sided), depending on data structure.

Supplementary Table S1 | Influence of plant functional traits and stand properties on SOC pools. N = number of values; r = Spearman correlation coefficient; *P* value. Leaf A_{max}: leaf photosynthetic maximum capacity; LDMC: leaf dry matter content; SLA and SRL: specific leaf area and specific root length; Leaf C, lignin, N, P, and Ca: leaf content (mass basis). Correlations were tested with the Spearman's rank correlation coefficients.

Predictor	*Forest floor +Topsoil*			*Forest floor*			*Topsoil*		
	n	r	*P*	n	r	*P*	n	r	*P*
Leaf A_{max}	(75)	-0.65	<0.001	(139)	-0.67	<0.001	(107)	-0.25	0.009
LDMC	(33)	0.56	0.001	(58)	0.72	<0.001	(40)	n.s.	n.s.
SLA	(85)	-0.54	<0.001	(163)	-0.60	<0.001	(127)	n.s.	n.s.
SRL	(40)	-0.60	<0.001	(90)	-0.24	0.021	(53)	-0.25	0.067
Wood density	(149)	-0.30	<0.001	(227)	-0.35	<0.001	(256)	-0.11	0.087
Leaf C	(149)	0.16	0.057	(227)	0.22	0.001	(256)	n.s.	n.s.
Leaf lignin	(110)	n.s.	n.s.	(171)	0.18	0.020	(147)	n.s.	n.s.
Leaf N	(108)	-0.39	<0.001	(186)	-0.57	<0.001	(164)	n.s.	n.s.
Leaf C:N ratio	(108)	0.39	<0.001	(186)	0.54	<0.001	(164)	n.s.	n.s.
Leaf P	(103)	n.s.	n.s.	(166)	-0.23	0.002	(159)	n.s.	n.s.
Leaf Ca	(74)	-0.33	0.004	(126)	-0.46	<0.001	(125)	n.s.	n.s.
Leaf Size	(110)	-0.31	0.001	(175)	-0.34	<0.001	(148)	-0.13	0.113
Seed mass	(122)	-0.30	0.001	(200)	-0.29	<0.001	(209)	n.s.	n.s.
Tree max height	(145)	0.15	0.074	(223)	0.25	<0.001	(225)	n.s.	n.s.
Stand biomass	(113)	0.25	0.007	(160)	0.24	0.002	(164)	0.14	0.082
Stand litterfall	(51)	0.35	0.012	(81)	0.16	0.147	(78)	n.s.	n.s.

Supplementary Table S2 | Models predicting the SOC content. The tested models were all of the basic form:

SOC ~ (χ + Biomass) + { (χ + Biomass) : (Climate + Sand + pH + PLU) }

with:

":" indicates the tested interactions
SOC = soil content in organic carbon
χ = main predictor (A_{max} or PES, depending on the model)
A_{max} = Leaf maximum photosynthetic capacity (relative values)
PES = score value of the Plant Economics Spectrum (imputed values)
Biomass = stand biomass (relative values)
Climate = climatic descriptor of the sites ($f_{climate}$)
Sand = soil sand content
pH = soil pH value
PLU = site past land-use (used only in two of the four models)

Model χ	Model PLU	Retained predictors		AIC	r^2	Adj. r^2
A_{max}	yes	(n=2)	*A_{max} , Biomass*	-86.2	0.500	0.485
A_{max}	no	(n=2)	*A_{max} , Biomass*	-86.2	0.500	0.485
PES	yes	(n=5)	*PES , PES:Climate , PES:pH , PES:PLU , Biomass :Sand*	-130.4	0.207	0.180
PES	no	(n=4)	*PES , PES:Climate , PES:pH , Biomass :Sand*	-122.0	0.201	0.178

Supplementary Table S3 | Mean values of functional traits of several tree plant functional types. AM and EC: arbuscular mycorrhizal tree species and ectomycorrhizal tree species; leaf A_{max}: leaf photosynthetic maximum capacity; leaf N: leaf content in nitrogen; LDMC: leaf dry matter content; SLA and SRL: specific leaf area and specific root length; max height: tree maximum height. Values are means ± 1 standard error. Values followed by different letters are significantly different ($P < 0.05$; tested with Bonferroni test, Wilcoxon test, or Mann-Whitney, depending on data structure). Groups with less than 5 values were not included in the tests (¤). Groups with less than 3 values are not presented (n.p.).

Plant functional type	n	Leaf A_{max} (μmol g^{-1} s^{-1})	Leaf N (mg g^{-1})	LDMC (g g^{-1})	SLA (mm^{2} mg^{-1})	SRL (m g^{-1})	Wood density (kg L^{-1})	Max height (m)
Angiosperm - AM	21-65	0.15 ± 0.02^{b}	21.8 ± 1.3^{b}	0.36 ± 0.01^{ab}	17.5 ± 2.0^{c}	47.3 ± 7.0^{b}	0.54 ± 0.02^{b}	30.6 ± 1.8^{a}
Angiosperm - EC	14-34	0.15 ± 0.02^{b}	21.2 ± 1.0^{b}	0.35 ± 0.02^{a}	15.0 ± 1.0^{bc}	47.0 ± 5.2^{b}	0.62 ± 0.02^{c}	33.1 ± 2.5^{a}
Gymnosperm - AM	2-13	0.04 ± 0.01^{a}	12.2 ± 1.0^{a}	$0.37\pm0.04^{\text{¤}}$	5.8 ± 1.2^{a}	n.p.	0.47 ± 0.02^{a}	46.0 ± 5.7^{b}
Gymnosperm - EC	16-45	0.05 ± 0.01^{a}	12.6 ± 0.7^{a}	0.42 ± 0.02^{b}	7.6 ± 0.6^{ab}	24.0 ± 2.3^{a}	0.46 ± 0.01^{a}	49.1 ± 3.2^{b}
Broadleaf deciduous	32-68	0.17 ± 0.02^{b}	23.0 ± 0.7^{b}	0.35 ± 0.01^{a}	18.4 ± 1.6^{c}	48.3 ± 5.2^{b}	0.55 ± 0.02^{b}	33.7 ± 1.5^{a}
Broadleaf evergreen	10-50	0.17 ± 0.03^{b}	19.9 ± 1.9^{b}	0.36 ± 0.02^{a}	13.4 ± 1.1^{b}	63.8 ± 9.9^{b}	0.61 ± 0.02^{c}	35.0 ± 3.0^{a}
Needleleaf deciduous	1-4	$0.11\pm0.04^{\text{¤}}$	$22.1\pm2.1^{\text{¤}}$	n.p.	$11.7\pm1.5^{\text{¤}}$	n.p.	$0.46\pm0.02^{\text{¤}}$	$47.8\pm3.4^{\text{¤}}$
Needleleaf evergreen	19-55	0.05 ± 0.01^{a}	11.6 ± 0.4^{a}	0.42 ± 0.02^{b}	7.0 ± 0.6^{a}	23.7 ± 2.4^{a}	0.47 ± 0.01^{a}	46.8 ± 3.1^{b}
Angiosperm N fixer	5-26	0.20 ± 0.04^{a}	31.3 ± 2.5^{b}	0.35 ± 0.03^{a}	21.9 ± 4.7^{b}	68.1 ± 20.7^{a}	0.58 ± 0.03^{a}	23.4 ± 2.1^{a}
Angiosperm non-fixer	57-97	0.16 ± 0.02^{a}	19.3 ± 0.6^{a}	0.36 ± 0.01^{a}	15.1 ± 0.7^{a}	48.7 ± 4.0^{a}	0.58 ± 0.01^{a}	36.2 ± 1.7^{b}

Supplementary Table S4 | List of the variables used in the study.
H1, H2, H3 = hypotheses tested in the study (see main text); PES = Plant Economics Spectrum; SOC = Soil Organic Carbon;

Variable	Unit	Origin	Use	Hypothesis
Data weight (Wdata)	[0-1]	classified based on original publication (see Methods)	Used to give a statistical weight to SOC data (based on the strength of the study design)	H1, H2
Leaf C	mg/g	original publication, or trait database, or estimated (see Methods)	Trait of the PES, used as possible predictor of SOC	H1
Leaf C:N ratio	_	calculated		
Leaf N	mg/g	original publication, or trait database		
Leaf N:P ratio	_	calculated		
Leaf P	mg/g	original publication, or trait database		
Leaf K	mg/g	original publication, or trait database		
Leaf Ca	mg/g	original publication, or trait database		
Leaf Mg	mg/g	original publication, or trait database		
Leaf Mn	mg/g	original publication, or trait database		
Leaf Lignin	mg/g	original publication, or trait database		
Leaf Dry Matter Content (LDMC)	g/g	trait database		
Leaf area	mm2	trait database		
Specific Leaf Area (SLA)	mm2/mg	original publication, or trait database		
Leaf type (shape)	B=broadleaf, N=needleleaf	original publication, or trait database, or specialised websites		
Leaf phenology	D=deciduous, E=evergreen	original publication, or trait database, or specialised websites		
Leaf photosynthetic capacity (A_{max})	µmol/g/s	trait database		
Leaf stomatal conductance	mmol/m2/s	trait database	Initially used (1) to confirm that our dataset was consistent with the PES and (2) for the gap filling procedure (see Methods)	_
Leaf photosynthesis carboxylation capacity	µmol/g/s	trait database		
Litterfall C	mg/g	trait database		
Litterfall C:N ratio	_	calculated		
Litterfall N	mg/g	original publication, or trait database		
Litterfall P	mg/g	original publication, or trait database		

Litterfall K	mg/g	original publication, or trait database		
Litterfall Ca	mg/g	original publication, or trait database		
Litterfall Mg	mg/g	original publication, or trait database		
Litterfall Mn	mg/g	original publication, or trait database		
Fine root specific length (SRL)	m/g	trait database	Trait of the PES, used as possible predictor of SOC	H1
Fine root C	mg/g	original publication, or trait database	Initially used (1) to confirm that our dataset was consistent with the PES and (2) for the gap filling procedure (see Methods)	–
Fine root C:N ratio	_	calculated		
Fine root N	mg/g	original publication, or trait database		
Fine root P	mg/g	original publication, or trait database		
Fine root K	mg/g	original publication, or trait database		
Fine root Ca	mg/g	original publication, or trait database		
Fine root Mg	mg/g	original publication, or trait database		
Fine root diameter	mm	trait database		
Plant phylogenetic distance	Myr	calculated (see Methods)	Used as a possible proxy of functional distance between two species	H1
Plant phylogeny	spermaphyte, … , family, genus, species	wikispecies	Used as a categorical variable (e.g. angiosperms vs gymnosperms) that may explain SOC	H1
Plant mycorhizal type	AM=arbuscular, EC=ecto, MIX=mixed, NO=no symbiosis	trait database, or specialised publications (see Methods)	Used as a categorical variable that may explain SOC	H1
Plant N fixation	N=no, Y=yes	original publication, or determined based on species genus		
Plant growth rate	classes=1-3	original publication, or trait database, or specialised websites	Used as a proxy of the species ecological strategy	H1
Plant tolerance to drought	classes=1-5	trait database, or specialised publications, or specialised website (see Methods)		
Plant tolerance to waterlogging	classes=1-5	trait database, or specialised publications, or specialised website		
Plant xylem cavitation vulnerability (P50)	Mpa	trait database, or specialised publications, or specialised website		
Plant max height	m	original publication, or trait database, or specialised websites	Trait of the PES, used as possible predictor of SOC	H1
Plant seed mass	mg/seed	trait database, or specialised website		
Plant wood density	g/cm3	trait database, or specialised publications, or specialised website (see Methods)		

Site longitude	degrees	original publication	Used to extract data from global datasets	_
Site latitude	degrees	original publication	Used to evaluate the interactions between PES, SOC, and environmental conditions	H2
Site elevation	m above sea level	original publication, or global database (SRTM-NASA)		
Site mean annual precipitation (MAP)	mm/yr	original publication, or global database (WorldClim)		
Site mean annual temperature (MAT)	°C	original publication, or global database (WorldClim)		
Site Koppen climate	A=tropical, B=dry, C=temperate, D=snow, E=cold	global database (Kottet et al., 2006)		
Site aridity index	_	global database (WorldClim)		
Site potential evapotranspiration (PET)	mm/yr	global database (CGIAR)		
Site climatic conditions for biological activity ($f_{climate}$)	[0;1], From 0=unfavourable to 1=favourable	calculated based on latitude and mean monthly values of temperature and precipitation (Augusto et al., 2017)		
Site nitrogen atmospheric deposition	kg-N/ha/yr	global database (Vet et al., 2014)		
Site topography (class)	plain, hill, or mountain	original publication		
Site topography (value)	%	original publication		
Site past land-use	forest, grassland, savanna, tundra, wetland, other permanent vegetation, desert, cropland	original publication		
Site fertilisation history	N=no fertilisation, Y=at least one fertilisation application	original publication		
Site soil name	USDA soil classification	original publication		
Site soil parent material	acid, intermediate, mafic, calcareous (see Methods)	classified based on original publication (see Methods)		
Site mean value of topsoil texture (clay)	mg/g	calculated based on original publication (see Methods)		

Site mean value of topsoil texture (silt)	mg/g	calculated based on original publication		
Site mean value of topsoil texture (sand)	mg/g	calculated based on original publication		
Site mean value of topsoil SOC	mg/g	calculated based on original publication		
Site mean value of topsoil P-available content	µg/g	calculated based on original publication		
Site mean value of topsoil pH-water	–	calculated based on original publication		
Site mean value of topsoil base saturation	%	calculated based on original publication		
Stand age	yr	original publication	Used to evaluate the interactions between PES, SOC, and duration of the soil exposure to different tree species	H1
Stand aboveground biomass	Mg/ha	original publication, or calculated	Used a possible predictor of SOC	H1, H3
Stand aboveground growth	Mg/ha/yr	original publication		
Stand litterfall	Mg/ha/yr	original publication		
Stand fine root biomass	Mg/ha	original publication		
Stand fine root turnover	Mg/ha/yr	original publication		
Soil layer position (depth and thickness)	cm	original publication	Used to calculate SOC values following the Equivalent Soil Mass method	–
Soil bulk density	kg/dm3	original publication, or calculated		
Soil layer texture (clay)	mg/g	original publication, or estimated by global study (Hengl et al., 2017; Shangguan et al., 2014)	Used to (1) test the comparability among the stands of a given site, and (2) calculate the mean soil properties at the site scale	H2
Soil layer texture (silt)	mg/g	original publication, or estimated by global study (Hengl et al., 2017; Shangguan et al., 2014)		
Soil layer texture (sand)	mg/g	original publication, or estimated by global study (Hengl et al., 2017; Shangguan et al., 2014)		
Soil content in organic carbon (SOC)	mg/g	original publication, or calculated	Used to calculate the SOC values in ESM, which was the main studied variable	H1, H2, H3
Soil pool in organic carbon (SOC)	Mg/ha	original publication, or calculated		

Soil fraction of SOC stability	see Methods	original publication	Used as a proxy of the SOC stability	H1
Soil content in organic matter (SOM)	mg/g	original publication, or calculated	Used to calculate SOC values	–
Soil pool in organic matter (SOM)	Mg/ha	original publication, or calculated		
Soil content in total nitrogen (N-tot)	mg/g	original publication, or calculated	Used to calculate the mean soil properties at the site scale	H2
Soil pool in total nitrogen (N-tot)	Mg/ha	original publication, or calculated		
Soil C:N ratio	–	original publication, or calculated		
Soil content in P-available	µg/g	original publication		
Soil pH (water)	–	original publication, or estimated by global study (Hengl et al., 2017; Shangguan et al., 2014)		
Soil Cation Exchange Capacity (CEC)	cmol.c/kg	original publication		
Soil base saturation of the CEC	%	original publication, or estimated by global study (Hengl et al., 2017; Shangguan et al., 2014)		

Supplementary Table S5 | PRISMA abstract checklist.

Section and Topic	Item #	Checklist item	Reported (Yes/No)
TITLE			
Title	1	Identify the report as a systematic review.	Yes
BACKGROUND			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	Yes
METHODS			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	Yes
Information sources	4	Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched.	Yes
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	Yes
Synthesis of results	6	Specify the methods used to present and synthesise results.	Yes
RESULTS			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	Yes
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	Yes
DISCUSSION			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	Yes
Interpretation	10	Provide a general interpretation of the results and important implications.	Yes
OTHER			
Funding	11	Specify the primary source of funding for the review.	Yes
Registration	12	Provide the register name and registration number.	No

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71
For more information: http://www.prisma-statement.org/

Supplementary Table S6 | PRISMA checklist.

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Methods (Data collection: soil organic carbon): lines 224-226
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Dedicated file
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Introduction (lines 40-47)
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Introduction (lines 44-62)
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Methods (Data collection: soil organic carbon): lines 228-245
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Methods (Data collection: soil organic carbon): lines 223-228
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Idem
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Idem
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Methods (Data collection: soil organic carbon): lines 245-251
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	All details in Methods (Data collection: soil organic carbon; Data collection: auxiliary data; Data collection: plant functional traits; Dataset compilation: phylogenetic distance)
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Idem
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Data were extracted by both authors, working together. All studies and data were collegially evaluated to avoid inclusion/exclusion bias. See Methods
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Methods (Data handling and normalisation; Data analysis)
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	Methods (Data collection: soil organic carbon): lines 234-245
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary	Methods (Data handling)

Section and Topic	Item #	Checklist item	Location where item is reported
		statistics, or data conversions.	
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Not applicable
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Data were normalised to enable comparisons and synthesis of results (see Data handling and normalisation)
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	Heterogeneity was assessed by using climate, soil properties, past land-use, plant functional types, and stand biomass as factors (see for instance Figures 3-4)
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	Data were analysed using different methods, whose results were found to be consistent to each other (Methods: Data analysis)
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	Data were evaluated collegially evaluated to avoid inclusion/exclusion bias. For regions where data were scarce, we applied the selection criteria with flexibility to avoid having areas of the world severely under-represented in the dataset.
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	Methods: Data analysis
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Figure S15 in Supplementary Information
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Examples and criteria are given lines 236-241 (Data collection: soil organic carbon)
Study characteristics	17	Cite each included study and present its characteristics.	Supplementary References 1-3; Source Data
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Each included study received a score of confidence based on explicit criteria (Data handling and normalisation). This score was used to give to each study a statistical weight proportional to its robustness during data analyses
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	Not done because of the high number of original studies
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Not done because of the high number of original studies
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	Results and Supplementary Information
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	Results and Supplementary Information

Section and Topic	Item #	Checklist item	Location where item is reported
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	Not done
Reporting biases	21	Present assessments of risk of bias due to missing results for each synthesis assessed.	Not done
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	Main findings were analysed using a modelling approach, with a quantification of the level of explained variance (Results, Methods, Figure 4)
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Discussion
	23b	Discuss any limitations of the evidence included in the review.	Not done
	23c	Discuss any limitations of the review processes used.	Not done
	23d	Discuss implications of the results for practice, policy, and future research.	Final paragraph of the Discussion
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Not done
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	A protocol was initially prepared by the two authors to enable the collaborative work. This protocol was revised, when necessary, during the course of the systematic review. However, the protocol was neither register nor published
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Amendments were made when a case study presented a characteristic that was not yet taken into account in the protocol
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Described in the section Acknowledgements
Competing interests	26	Declare any competing interests of review authors.	Described in the section Competing interests
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Described in the dedicated sections (Data availability; Code availability)

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71; For more information: http://www.prisma-statement.org/

Supplementary Table S7 | Pedotransfer functions tested to estimate missing values of soil bulk density.

Four pedo-transfer functions were tested:

1. **Function A** [Augusto *et al*. Is 'grey literature' a reliable source of data to characterize soils at the scale of a region? *Eur. J. Soil Sci.* 61, 807–822 (2010)]: BD = soil bulk density (kg L^{-1}); SOC = soil organic carbon (mg g^{-1}); α, β, and γ = fitted parameters.
2. **Function D** [De Vos *et al*. Predictive quality of pedotransfer functions for estimating bulk density of forest soils. *Soil Sci. Soc. Am. J.* 69, 500–510 (2005)]: BD = soil bulk density (kg L^{-1}); LOI = lost on ignition (%); Sand and Clay = textural fractions (%); Depth = position in the soil profile (cm); α, β1, β2, β3, and β4 = fitted parameters. We tested the "CA" model of this publication.
3. **Function F** [Federer *et al*. The organic fraction - bulk density relationship and the expression of nutrient content in forest soils. *Can. J. For. Res.* 23, 1026–1032 (1993)]: BD = soil bulk density (kg L^{-1}); FO = fraction of organic matter [0-1; in mass]; α and β = fitted parameters.
4. **Function RK** [Ruehlmann & Korschens. Calculating the effect of soil organic matter concentration on soil bulk density. *Soil Sci. Soc. Am. J.* 73, 876–885 (2009)]: BD = soil bulk density (kg L^{-1}); SOC = soil organic carbon (mg g^{-1}); α, β, and γ = fitted parameters.

The validation dataset used to test the reliability of the functions was a compilation of measured values (soil bulk density, soil texture, soil organic carbon or soil organic matter, soil depth). This dataset consisted in 208 soils that are representative at the global scale of natural ecosystems (source: Augusto *et al*. Soil parent material - A major driver of plant nutrient limitations in terrestrial ecosystems. *Global Change Biology* 23, 3808–3824 (2017)). Estimated values were plotted versus measured values, and a linear regression was fitted (slope values, and adjusted r^2 values, are presented). Following the recommendation of Pineiro *et al.*, the linear regressions were of the form: $y = f(\hat{y})$, where y and ŷ are the measured value and the estimated value, respectively.

[Pineiro *et al*. How to evaluate models: Observed vs. predicted or predicted vs. observed? *Ecol. Model.* 216, 316–322 (2008)]

Pedotransfer function	Model	Reliability
A	$BD = \alpha + (\beta \times \exp^{(-\gamma \times SOC)})$	slope=0.94, r^2=0.66
D	$BD = (\alpha + \beta1 \times LOI + \beta2 \times Sand + \beta3 \times Clay + \beta4 \times Depth)^{-1}$	slope=0.95, r^2=0.64
F	$BD = (\alpha \times \beta) / ((FO \times \alpha) + ((1-FO) \times \beta))$	slope=1.12, r^2=0.57
RK	$BD = (\alpha - (\beta \times \gamma)) \times \exp^{(-\gamma \times SOC)}$	slope=0.90, r^2=0.68

Supplementary Table S8 | Comparisons between observed values and global values describing the site properties. When the descriptors of the sites were not provided in the original values (below referred to as *measured values*), we filled the data gaps with simulated values at the global scale in dedicated modelling studies (referred to as *estimated values*; for more details, see subsection *Data collection: auxiliary data* in Methods).

To test the reliability of the external datasets containing the estimated values, we compared them to our measured values (in the sites where the latter were available) by fitting linear regressions. Following the recommendation of Pineiro *et al.*, the linear regressions were of the form: $y = f(\hat{y})$, where y and ŷ are the measured value and the estimated value, respectively. Are presented only the variables for which estimated values were found as reliable enough: MAT = mean annual temperature (°C); MAP = mean annual precipitation (mm yr^{-1}); Elevation (m above sea level); soil texture (content in clay, content in sand, in mg g^{-1}); base saturation of the cation exchange capacity of the soil (%).

[Pineiro *et al.* How to evaluate models: Observed vs. predicted or predicted vs. observed? *Ecol. Model.* 216, 316–322 (2008)]

Variable tested	Results of the linear regression between measured values and estimated values			
MAT (°C)	n = 79	$P < 0.001$	slope = 1.02	$r^2 = 0.99$
MAP (mm/yr)	n = 110	$P < 0.001$	slope = 0.98	$r^2 = 0.90$
Elevation (m asl)	n = 91	$P < 0.001$	slope = 1.03	$r^2 = 0.95$
Soil clay (mg g^{-1})	n = 96	$P < 0.001$	slope = 0.98	$r^2 = 0.71$
Soil sand (mg g^{-1})	n = 91	$P < 0.001$	slope = 1.12	$r^2 = 0.86$
Soil pH	n = 102	$P < 0.001$	slope = 0.88	$r^2 = 0.98$
Soil BS (%)	n = 30	$P < 0.001$	slope = 0.75	$r^2 = 0.82$

Supplementary Table S9 | Regressions used for the gap filling procedure of the plant functional traits. Leaf A_{max}: leaf photosynthetic maximum capacity (µmol g^{-1} s^{-1}); Vc_{max}: leaf photosynthesis carboxylation capacity (µmol/g/s); Stomatal gs: leaf stomatal conductance (mmol m^{-2} s^{-1}); C, N, P, and Ca: content in carbon, nitrogen, phosphorus, or calcium (mg g^{-1}). The proportion of estimated values presents the number of tree species for which the trait value is estimated. Because the tree species were not equally present in the SOC database, and because the tree species that had estimated trait values differed from trait to trait, the percentage value was not proportional to the number of tree species involved in the gap filling procedure. Linear regressions were fitted.

Estimated trait	Predictor	Linear model	Regression performance			Proportion of estimated values	
Leaf A_{max}	Vcmax	$y = 0.187x + 0.003$	$P < 0.001$	$r^2 = 0.49$	n = 34	n = 4	1.5%
Leaf A_{max}	Stomatal gs	$y = 0.00032x + 0.034$	$P < 0.001$	$r^2 = 0.44$	n = 43	n = 2	
Leaf C	Litterfall C	$y = 0.978x$	$P < 0.001$	$r^2 = 0.99$	n = 43	n = 17	13.4%
Leaf C	Fine root C	$y = 1.027x$	$P < 0.001$	$r^2 = 0.99$	n = 54	n = 13	
Leaf N	Litterfall N	$y = 1.433x$	$P < 0.001$	$r^2 = 0.86$	n = 68	n = 6	2.6%
Leaf N	Fine root N	$y = 1.436x$	$P < 0.001$	$r^2 = 0.84$	n = 87	n = 4	
Leaf P	Litterfall P	$y = 1.582x$	$P < 0.001$	$r^2 = 0.87$	n = 49	n = 7	3.1%
Leaf P	Fine root P	$y = 1.412x$	$P < 0.001$	$r^2 = 0.83$	n = 47	n = 4	
Leaf Ca	Litterfall Ca	$y = 0.716x$	$P < 0.001$	$r^2 = 0.78$	n = 34	n = 25	13.7%
Leaf Ca	Fine root Ca	$y = 1.386x$	$P < 0.001$	$r^2 = 0.77$	n = 40	n = 6	

Supplementary Table S10 | Data availability for the main functional traits used in the study. Leaf A_{max}: leaf photosynthetic maximum capacity (µmol g^{-1} s^{-1}); LDMC: leaf dry matter content (g g^{-1}); SLA: specific leaf area (mm^2 mg^{-1}); SRL: specific root length (m g^{-1}); Wood density (kg L^{-1}); Leaf C, lignin, N, P, and Ca: content in carbon, lignin, nitrogen, phosphorus, or calcium (mg g^{-1}); Seed mass (mg $seed^{-1}$); Tree max height: maximum height observed for the tree species (m). The number of values from TRY, or other sources, represents the total data availability before applying the procedures of curation, homogenisation, and averaging (see Methods); After having calculating the mean values per each tree species, we calculated the proportion of the tree species having a non-missing measured value, and the proportion of tree species having an estimated value.

Studied traits	Values from TRY	Values from other sources	Proportion of non-missing values	Proportion of estimated values	Range of values
Leaf Amax	1 000	1 964	50%	1.5%	0.012–0.583
LDMC	8 734	3 905	36%	0.0%	0.25–0.55
SLA	2 790	9 925	75%	0.0%	1.2–97.0
SRL	186	251	37%	0.0%	1.9–142.4
Wood density	1 149	863	99%	0.0%	0.28–0.91
Leaf C	2 295	63	100%	13.4%	272–589
Leaf lignin	72	408	65%	0.0%	38–455
Leaf N	5 339	1 855	76%	2.6%	6.5–54.4
Leaf P	1 422	647	64%	3.1%	0.35–3.31
Leaf Ca	312	91	51%	13.7%	1.4–23.1
Seed mass	2 524	2 647	92%	0.0%	0.1–17696
Tree max height	24 919	387	96%	0.0%	2–120

Supplementary Table S11 | Fictive example of the values available in supplementary information and the values used during data analysis to test a possible relationship between two variables. SLA: specific leaf area; RR: relative value (see above); SOC: soil organic carbon; SI: supplementary information containing the final dataset (Appendix 1); NA: non-available value. In this example, RR.SLA was not presented in the final dataset for the site B because one tree species had a missing-value, disabling any relevant comparison with the RR.SOC (calculated based on all tree species).

Site	Species	SLA (mm^2 mg)	RR.SLA (in SI)	RR.SLA (recalculated)	SOC (kg m^2)	RR.SOC (in SI)	RR.SOC (recalculated)
A	*Abies a.*	5.6	-0.62	-0.62	8.5	0.00	0.00
A	*Fagus s.*	18.2	0.56	0.56	7.9	-0.07	-0.07
A	*Picea a.*	7.4	-0.34	-0.34	9.1	0.07	0.07
B	*Acer p.*	20.1	NA	0.57	4.4	-0.11	-0.10
B	*Cupressus m.*	NA	NA	NA	5.1	0.03	NA
B	*Picea a.*	7.4	NA	-0.43	5.3	0.07	0.09
B	*Pinus p.*	6.5	NA	-0.56	4.9	-0.01	0.01

For example, in the site B, the absolute SOC values are 4.4, 5.1, 5.3, and 4.1 for the stands *Acer*, *Cupressus*, *Picea*, and *Pinus*, respectively. The "site value" is calculated as the mean values of its stands:

$$SOC.Site = mean(SOC.Acer, SOC.Cupressus, SOC.Picea, SOC.Pinus) = \frac{4.4 + 5.1 + 5.3 + 4.1}{4} = 4.925$$

Then, the relative values of SOC are calculated as the ratio of the stand value per the site value, with a log function to reduce the statistical weight of outliers. For the Acer stand:

$$RR.Acer = log\left(\frac{SOC.Acer}{SOC.Site}\right) = log\left(\frac{4.4}{4.925}\right) = -0.113$$

The negative relative ratio value for the *Acer* stand indicates that the SOC pool was lower than the mean SOC pool of the site.

In our study, we sometimes calculated the effect of plant functional types (*e.g.* angiosperms *versus* gymnosperms, or arbuscular mycorrhizal tree species *versus* ectomycorrhizal tree species). Still using the B site as an example, the effect of the spermatophyte type was calculated as follows:

$$RR = log\left(\frac{SOC.angiosperms}{SOC.gymnosperms}\right) = log\left(\frac{mean\{SOC.Acer\}}{mean\{SOC.Cupressus, SOC.Picea, SOC.Pinus\}}\right)$$

which is

$$RR = log\left(\frac{4.4}{mean\{5.1, 5.3, 4.9\}}\right) = log\left(\frac{4.4}{5.1}\right) = -0.148$$

The negative relative ratio value indicates that the SOC pool under the angiosperm species was on average lower than under the gymnosperm species.

Supplementary References

Supplementary Reference 1 – List of references used to build the Soil Organic Carbon dataset

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Supplementary Reference 2 – List of references used to complement the Plant Functional Traits dataset

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Supplementary Reference 3 – List of references used to build the mixed forests dataset and the SOC stability dataset

Supplementary Reference 3a – Mixed forests dataset

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Supplementary Reference 3b – SOC stability dataset

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