Supporting Information Appendix

Diefendorf, Mueller, Wing, Koch and Freeman

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Dataset Description

Our data set, provided in Supporting Information (SI) Dataset, includes 334 species from 75 plant families (limited to woody trees and shrubs) present at 105 geographic sites distributed across 5 continents (representing 3,310 $\delta^{13}C_{leaf}$ measurements of individual plants). The result is 570 unique species-site combinations represented by a mean Δ_{leaf} value calculated from individuals of each species at a site. Sites are located within 8 biomes with mean annual temperature (MAT) ranging from -10 to 28°C and mean annual precipitation (MAP) from 147 to 3700 mm per year. $\delta^{13}C_{leaf}$ values were converted to $\Delta^{13}C_{leaf}$ using the equation $\Delta_{leaf} = (\delta^{13}C_{atm} - \delta^{13}C_{leaf})/(1+\delta^{13}C_{leaf}/10^3)$ with estimated or measured $\delta^{13}C_{atm}$ values (See SI Dataset). Δ_{leaf} values and latitude are approximately normally distributed. MAP and summer precipitation (P-JJA; June, July, August) were Log_{10}-normally distributed and transformed accordingly. Altitude was approximately normally distributed after square root transformation (Sqrt altitude). Species means were calculated for each geographic site to remove within-species variability. For a subset of sites where $\delta^{13}C_{leaf}$ values from multiple PFTs were reported (n=53), we calculated paired PFT differences at each site by averaging all species in each PFT and then calculating differences between PFT.

SI Data Analysis

Table 1) Linear regression of Δ_{leaf} with environmental variables at the global scale.

Environmental Variable	R^2	Slope	*p* value	n
$Log_{10}MAP^*$	0.55	+	<0.0001	506
Sqrt altitude	0.40	-	<0.0001	502
MAT	0.33	+	<0.0001	506

* $Log_{10}MAP$ is highly correlated with sqrt altitude (r = -0.59, p<0.0001, n = 501), MAT (r = 0.70, p<0.0001, n = 505), latitude (r = -0.78, p<0.0001, n = 505), and could be related to other environmental parameters not available in our global dataset. See Table 3, 4, and 5 (below) for multiple regression results.

Table 2) Linear regression of Δ_{leaf} with MAP, P-JJA, and altitude by geographic zone.

	$Log_{10}MAP$			$Log_{10}P\text{-}JJA^*$			Sqrt altitude		
Geographic zone	R^2	*p* value	n	R^2	*p* value	n	R^2	*p* value	n
Global†	0.548	<0.0001	506	0.24	<0.0001	194	0.403	<0.0001	502
Global (excluding Europe)	0.579	<0.0001	411	0.316	<0.0001	130	0.443	<0.0001	407
Asia	0.486	<0.0001	62	0.23	0.029	21	0.089	0.023	58
Europe	0.025	0.125	95	0.008	0.486	64	0.056	0.021	95
North America	0.42	<0.0001	177	0.332	<0.0001	109	0.452	<0.0001	171

Other continents in our database were excluded from these analyses due to small numbers of geographic sites (e.g. South America). *Summer precipitation in tropical sites was not included because precipitation is more evenly distributed during the year. †The global Δ_{leaf} relationship with MAP (mm/yr) is as follows (standard error shown in parentheses):

$$\Delta_{leaf} = 5.54(\pm 0.22) * \log_{10}(MAP) + 4.07(\pm 0.70)$$

Table 3) Multiple regression of Δ_{leaf} with MAP and altitude by geographic zone.

Geographic zone	R^2	*p* value	n	Log_{10}MAP SS* (partial R^2)	Sqrt altitude SS* (partial R^2)
Global[†]	0.607	<0.0001	502	646.2 (0.34)	187.9 (0.13)
Global (excluding Europe)	0.622	<0.0001	407	483.2 (0.32)	117.9 (0.10)
Asia	0.507	<0.0001	58	136.2 (0.46)	16.3 (0.09)
Europe	0.122	0.003	95	15.4 (0.07)	22.7 (0.10)
North America	0.534	<0.0001	177	78.6 (0.15)	108.8 (0.20)

Other continents in our database were excluded from these analyses due to small numbers of geographic sites (e.g. South America). *SS is the sum of squares. SS and partial R^2 values are listed only for parameters with significant effects in the model (alpha=0.05). [†]The global Δ_{leaf} relationship with MAP (mm/yr) and altitude (m) is as follows (standard error shown in parentheses):

$$\Delta_{leaf} = 4.20(\pm 0.26) * \log_{10}(MAP) - 0.06(\pm 0.01) * \sqrt{altitude} + 9.31(\pm 0.90)$$

We constrained multiple regression models of Δ_{leaf} variability to include both MAP and altitude, which were the strongest predictors of Δ_{leaf} variability in single factor regression models (excluding other measures of water availability that are highly correlated with MAP, but less well correlated with Δ_{leaf}). The inclusion of MAP in all models is also justified because the influence of MAP on Δ_{leaf} is well supported by theory and other observations. Since MAP is correlated with other potential predictor variables (Table 1 caption), care is required in evaluating these predictors for their additional influence on Δ_{leaf}. Therefore, we first assessed the influence of other factors on Δ_{leaf} using bivariate partial regression models that account for the covariance of MAP with secondary predictors (e.g. by plotting the residuals of Δ_{leaf} from its regression with MAP versus the residuals of altitude from its regression with MAP). The partial regression model with altitude as the secondary predictor was the only model with notable explanatory power (R^2=0.13, p<0.0001), indicating that altitude has a weak, negative influence on Δ_{leaf} that is statistically independent from MAP. In this manner altitude was determined to be the predictor with the second greatest explanatory power at the global scale. The regression models reported in Table 3 were then constrained to contain MAP and altitude for the purposes of evaluating the consistency of results within different geographic regions. Although these methods cannot determine how much of the variance explained by the regression between MAP and Δ_{leaf} is due to the covariance of MAP and altitude, they consistently show that altitude has an influence on MAP that cannot be explained by its correlation with MAP alone (see also Table 4 below).

The use of forward, backward, or mixed stepwise regression with additional predictors produces models with greater R^2 (up to 0.66 compared to 0.61 for the two factor model at the global scale) and with additional statistically significant predictors. However, the large number of factors required to achieve this minor R^2 improvement drastically reduces the utility and interpretability of the model. For global-scale analyses, three factor models (constrained to contain MAP and altitude, plus a third variable) do not yield an R^2 greater than 0.61, nor do they produce a third factor of statistical significance (p<0.05).

Table 4) Multiple regression of Δ_{leaf} with MAP and altitude for each plant functional type and well-represented genera.

PFT* or G*enera*[†]	R^2	*p* value	n	Log_{10}MAP SS (partial R^2) [‡]	Sqrt altitude SS (partial R^2) [‡]
EA	0.612	<0.0001	213	277.7 (0.39)	15.6 (0.03)
DG	0.281	0.037	23	ns	5.3
DA	0.327	<0.0001	175	50.8 (0.12)	33 (0.08)
EG	0.534	<0.0001	82	98.2 (0.37)	56.4 (0.25)
Acer	0.814	<0.001	12	6.9 (0.43)	20.7 (0.70)
Larix	0.307	0.031	22	2 (0.14) ms	5.7 (0.31)
Picea	0.094	ns	25	ns	ns
Pinus	0.702	<0.0001	36	64.2 (0.52)	32.8 (0.36)
Quercus	0.411	<0.001	32	4.6 (0.12) ms	5.7 (0.15)

*Plant functional types are as follows: Deciduous angiosperm (DA), deciduous gymnosperm (DG), evergreen angiosperm (EA), and evergreen gymnosperm (EG). [†]Only genera with at least 10 species-site combinations are included. [‡]SS is the sum of squares. SS and partial R^2 values are listed only for parameters with significant effects in the model (α=0.05). ns = not significant, ms = marginally significant (p<0.1). [§]The within PFT Δ_{leaf} relationship with MAP (mm/yr) and with MAP and altitude (m) are presented below (standard error shown in parentheses). Please see discussion in SI PETM (below) for application of these models.

EA:

$$\Delta_{leaf} = 5.37(\pm 0.30) * \log_{10}(MAP) + 5.06(\pm 1.00)$$

$$\Delta_{leaf} = 4.64(\pm 0.40) * \log_{10}(MAP) - 0.04(\pm 0.01) * \sqrt{altitude} + 7.99(\pm 1.45)$$

DG: Based on the lack of significance of the regression model (see above), we do not report an equation for DG.

DA:

$$\Delta_{leaf} = 3.14(\pm 0.39) * \log_{10}(MAP) + 11.58(\pm 1.23)$$

$$\Delta_{leaf} = 2.18(\pm 0.45) * \log_{10}(MAP) - 0.04(\pm 0.01) * \sqrt{altitude} + 15.23(\pm 1.51)$$

EG:

$$\Delta_{leaf} = 5.38(\pm 0.76) * \log_{10}(MAP) + 3.16(\pm 2.18)$$

$$\Delta_{leaf} = 4.67(\pm 0.68) * \log_{10}(MAP) - 0.06(\pm 0.01) * \sqrt{altitude} + 7.07(\pm 2.05)$$

Table 5) Multiple regression of Δ_{leaf} with MAP, altitude and latitude or MAT for select plant functional types.

PFT*	R^2	*p* value	n	Log_{10}MAP SS† (partial R^2)	Sqrt altitude SS† (partial R^2)	Latitude SS† (partial R^2)	MAT SS† (partial R^2)
DA	0.378	<0.0001	175	77.4 (0.18)	37.5 (0.10)	28.5 (0.08)	na
DA	0.39	<0.0001	175	85.4 (0.20)	62.9 (0.15)	na	35.5 (0.09)
EG	0.572	<0.0001	82	109.5 (0.42)	30.4 (0.17)	13.6 (0.08)	na
EG	0.547	<0.0001	82	100.3	57.2	na	ns

*See Table 4 for PFT abbreviations. na = not applicable, ns = not significant. SS and partial R^2 values are listed only for parameters with significant effects in the model (α=0.05).

Table 6) Mean Δ_{leaf} and Δ_{leaf} residual values (corrected for MAP and altitude) for each plant functional type.

PFT*	Δ_{leaf}	Level†	n	Δ_{leaf} residuals‡	Level†	n
EA	22.6	A	225	0.4	A	213
DG	20.5	B	26	0.4	AB	23
DA	21.1	B	198	-0.1	B	175
EG	18.4	C	112	-1.1	C	82

*See Table 4 for PFT abbreviations. †Tukey-Kramer HSD levels comparison of mean Δ_{leaf} and mean residual Δ_{leaf} for each PFT; PFTs not connected by same letter are significantly different (p<0.05). ‡Δ_{leaf} residuals are the residuals of Δ_{leaf} after multiple regression with MAP and altitude.

Table 7) 'Paired-site' Δ_{leaf} PFT differences.*

Paired PFT†	Δ_{leaf} difference	Level‡	n
DA-EG	2.7	A	17
EA-EG	2.2	AB	12
DG-EG	1.5	B	21
DA-EA	0.2	C	16

*Paired-sites are sites that contain more than one PFT. Differences between PFTs at each site were calculated and then the mean difference was determined for all sites containing the relevant PFT pair. †See Table 4 for PFT abbreviations. ‡Tukey-Kramer HSD levels comparison of paired-PFTs mean Δ_{leaf} differences; paired-PFT differences not connected by same letter are significantly different (p<0.05) from each other.

Table 8) Mean Δ_{leaf} values for plant functional types within each geographic zone.

	DA*			DG			EA			EG		
Geographic zone	Δ_{leaf} mean	n	Level†	Δ_{leaf} mean	n	Level	Δ_{leaf} mean	n	Level	Δ_{leaf} mean	n	Level
Global	21.1	198	B	20.5	26	B	22.5	225	A	18.4	112	C
Asia	20.4	6	B	20.2	4	B	23.5	40	A	19.6	12	B
Europe	20.4	49	A	20.7	11	A	19.9	27	AB	19.3	44	B
N. America	20.8	91	A	20.4	11	A	20.5	41	A	17.5	56	B

*See Table 4 for PFT abbreviations. †Tukey-Kramer HSD levels comparison of mean Δ_{leaf} values for each PFT, by geographic zone. Geographic zones not connected by same letter are significantly different (p<0.05) from other biomes.

Table 9) Mean Δ_{leaf} values by biome type.

Biome[*]	Δ_{leaf}	Level[†§]	n	Level[†] (with CCF)	n (with CCF)
TRF	23.4	A	206	A	206
EWMF	22.2	B	29	B	29
TSF	21.5	BC	47	B	47
CCDF	21.1	BCD	5	na	na
MED	20.6	CDE	5	BC	5
CCF[‡]	19.8	na	na	C	136
CCEF	19.9	DE	53	na	na
TDF	19.6	E	26	C	26
CCMF	19.6	E	78	na	na
XWS	17.3	F	59	D	59

[*]Biomes are as follows: tropical rain forest (TRF), evergreen warm mixed forest (EWMF), tropical seasonal forest (TSF), cool cold deciduous forest (CCDF), mediterranean (MED), cool cold evergreen forest (CCEF), cool cold mixed forest (CCMF), cool cold forest (CCF), tropical deciduous forests (TDF), and xeric woodland/scrubland (XWS) [†]Tukey-Kramer HSD levels comparison of mean Δ_{leaf} values for each biome. Biomes not connected by same letter are significantly different (p<0.05) from other biomes. [‡]CCF is a combined biome including CCDF, CCEF, and CCMF and is not included in the Tukey-Kramer HSD tests. [§]Biome accounts for 66% of the variability in Δ_{leaf} values (based on R^2 value from ANOVA; p<0.0001, n=508). na = not applicable.

Table 10) Mean Δ_{leaf} values for plant functional types within each biome.

	DA[†]			DG			EA			EG		
Biome[*]	Δ_{leaf}	n	Level[‡]	Δ_{leaf}	n	Level	Δ_{leaf}	n	Level	Δ_{leaf}	n	Level
CCF	20.5	43	A	20.3	24	A	19.5	14	AB	19.1	55	B
EWMF	22.5	19	A	20.9	1	A	21.9	4	A	21.3	5	A
TDF	20.0	19	A	na	na	na	18.7	7	B	na	na	na
MED	22.6	1	na	na	na	na	20.1	4	na	na	na	na
TRF	22.5	51	A	na	na	na	23.8	144	B	20.1	2	A
TSF	21.6	22	A	na	na	na	22.1	16	A	na	na	na
XWS	18.6	14	A	na	na	na	18.6	17	A	15.9	28	B

[*]See Table 9 for biome abbreviations. [†]See Table 5 for PFT abbreviations. [‡]Tukey-Kramer HSD levels comparison of PFT mean Δ_{leaf} values within each biome; PFTs not connected by the same letter are significantly different (p<0.05). na = not applicable.

Table 11) Linear regression of "site-mean[*]" Δ_{leaf} values with environmental variables at the global scale.

Environmental Variable	R^2	Slope	p value	n
Log_{10}MAP	0.52	+	<0.0001	70
Sqrt altitude	0.40	-	<0.0001	69
MAT	0.17	+	=0.0004	70

[*]Site-means are calculated by averaging all Δ_{leaf} values at a site, regardless of PFT. Sites with single species present are not included to avoid biasing the results by single species values.

Table 12) Multiple regression of "site-mean[*]" Δ_{leaf} values by MAP and altitude by geographic zone.

Geographic zone	R^2	*p* value	n	Log_{10}MAP SS[†]	Sqrt altitude SS[†]
Global	0.725	<0.0001	69	76.9 (0.54)	49.0 (0.43)
Asia	0.833	0.0047	9	21.9 (0.83)	3.0 (0.39)
Europe	0.200	0.1	23	4.6 (0.15) ms	4.7 (0.16) ms
North America	0.749	<0.0001	32	12.8 (0.48)	30.8 (0.64)

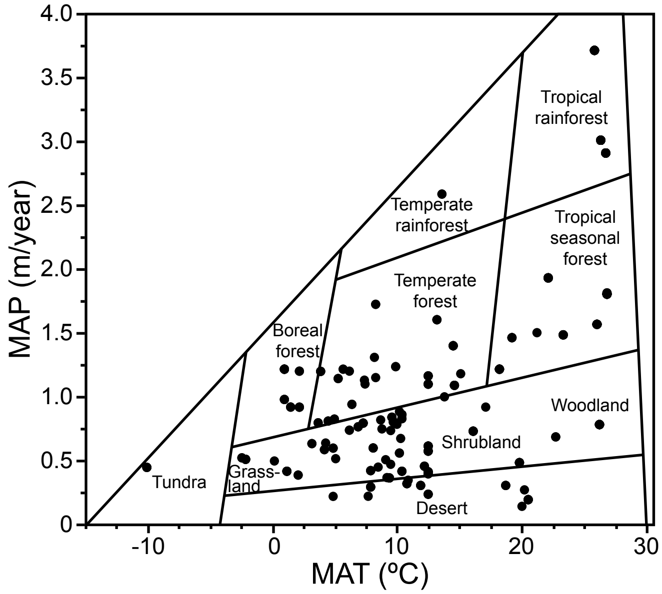
[*]Site-means are calculated by averaging all Δ_{leaf} values at a site, regardless of PFT. Sites with single species present are not included to avoid biasing the results by single species values. [†]SS is the sum of squares. SS and partial R^2 values are listed only for parameters with significant effects in the model (alpha=0.05). ms = marginally significant ($p<0.1$). Multiple regression analyses were performed as described in the caption of Table 3 (above).

Table 13) ANOVA of "site-mean[*]" Δ_{leaf} values by biome.

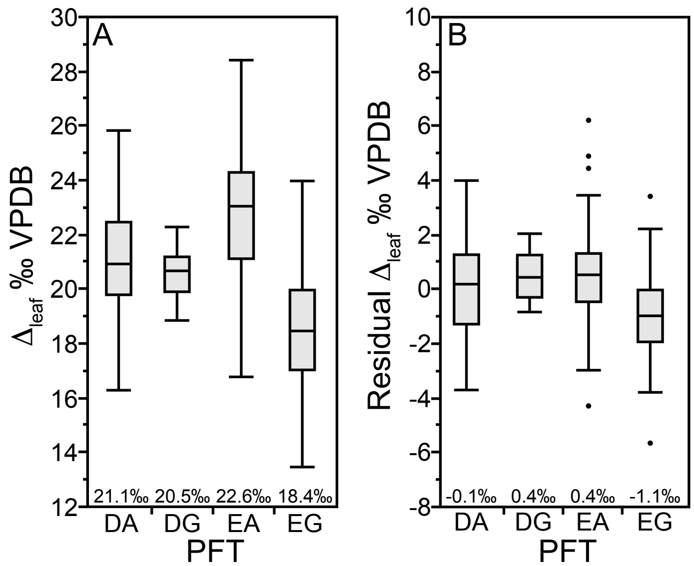
Biome[†‡]	Δ_{leaf} mean	n	Level[#]
TRF	23.4	6	A
EWMF	21.8	6	AB
TSF	21.0	3	BC
MED	20.6	1	
CCF[§]	19.7	39	C
TDF	19.4	2	CD
XWS	17.4	15	D

[*]Site-means are calculated by averaging all Δ_{leaf} values at a given site, regardless of PFTs present. [†] See Table 9 for biome abbreviations. [‡]Biome accounts for 76% of the variability in site-mean Δ_{leaf} values (based on R^2 from ANOVA; $p<0.0001$, n=69). MED is excluded from ANOVA because the sample size is too small (n=1). [§]CCF includes CCDF, CCMF, and CCEF. [#]Tukey-Kramer HSD levels comparison of biomes within each PFT; Biomes not connected by the same letter are significantly different ($p<0.05$).

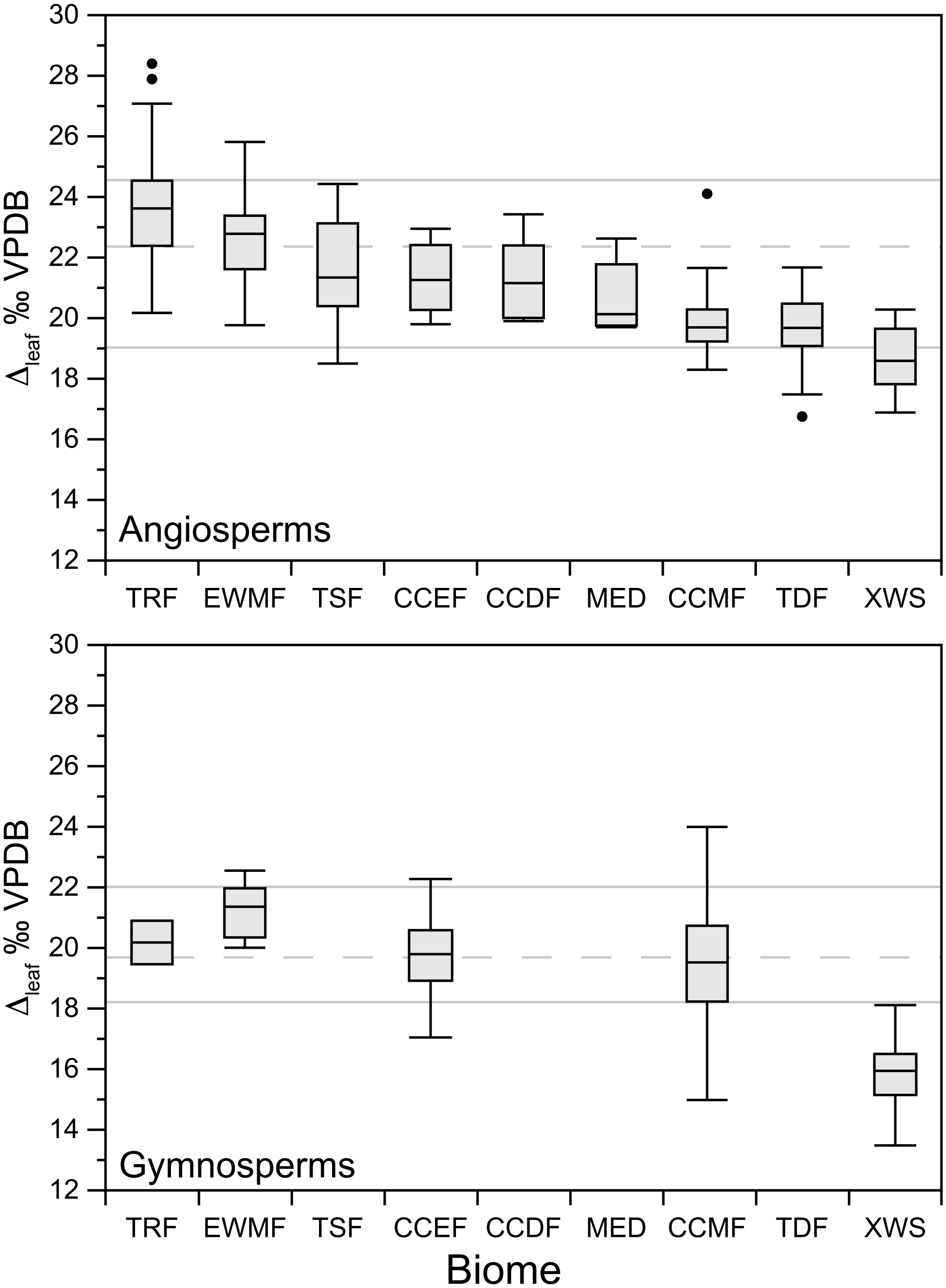
SI Figures



SI Figure 1. Mean annual temperature (MAT) and mean annual precipitation (MAP) for sites reported in text and S1 where environmental information was available. Biome types of Whitaker (1) are given for general reference and differ from the biome classification used within the text and data analysis (see methods section).



SI Figure 2. Box plots of A) Δ_{leaf} values by PFT (n: DA=198, DG=26, EA=225, EG=112) and B) Δ_{leaf} residuals (after constraining for MAP and altitude) by PFT (n: DA=175, DG=23, EA=213, EG=82). The box contains the interquartile range (50% of the central population). The median sample value is denoted by the line within the box. Vertical lines extend outward to the minimum and maximum values, except in the case of samples that fall outside 1.5 times the interquartile range (denoted with black dots). Statistical tests of means are sown in SI Data Analysis (above).



SI Figure 3. Biome-level Δ_{leaf} differences as a function of phylogeny. Biome-level box plots of Δ_{leaf} values separated by phylogeny. The box contains the interquartile range (50% of the central population). The median sample value is denoted by the line within the box. Vertical lines extend outward to the minimum and maximum values, except in the case of samples that fall outside 1.5 times the interquartile range (denoted with black dots). Dashed horizontal lines denote the grand means of the populations (excluding XWS; angiosperm=22.3‰ and gymnosperm=19.7‰). The 2.6‰ difference between these grand Δ_{leaf} means reflects the PFT differences reported in the discussion section. Solid horizontal lines are shown to emphasize the Δ_{leaf} ranges observed in biomes between the phylogenies (excluding XWS). Number of samples per biome for angiosperms is as follows: CCDF=5, CCEF=8, CCMF=44, EWMF=23, MED=5, TDF=26, TRF=204, TSF=47, and XWS=31. For the gymnosperms: CCEF=45, CCMF=34, EWMF=6, TRF=2, and XWS=28.

SI PETM Discussion

Calculation of PETM Δ_{leaf} Values: The conceptual diagram of $\delta^{13}C_{atm}$ reconstruction for the Paleocene-Eocene Thermal Maximum (PETM) in Bighorn Basin (WY, USA) was determined from $\delta^{13}C_{leaf}$ values as inferred from $\delta^{13}C$ values of *n*-C_{31} alkanes (corrected for biosynthetic fractionation; (2)). The percent angiosperm and MAP values were derived from fossil leaf metrics (3, 4) and we make the assumption that *n*-alkane production in plants is similar across PFTs. We used Δ_{leaf}-MAP expressions for deciduous angiosperms (DA) and evergreen gymnosperms (EG; see SI Data Analysis Table 4 for determination of expressions):

$$\Delta_{leaf}(\mathrm{DA}) = 3.14(\pm 0.39) * \log_{10}(MAP) + 11.58(\pm 1.23)$$

$$\Delta_{leaf}(\mathrm{EG}) = 5.38(\pm 0.76) * \log_{10}(MAP) + 3.16(\pm 2.18)$$

To determine a net Δ_{leaf} value, we scaled the Δ_{leaf} values by the percentage of angiosperm and, by difference, conifer. $\delta^{13}C_{atm}$ was then calculated:

$$\delta^{13}\mathrm{C}_{\mathrm{atm}} = \Delta_{\mathrm{leaf}} * \left[1 + \frac{\delta^{13}\mathrm{C}_{\mathrm{leaf}}}{1000}\right] + \delta^{13}\mathrm{C}_{\mathrm{leaf}}$$

This results in minor changes to net Δ_{leaf} during the PETM (Fig. 4) because the MAP and PFT influences nearly cancel each other out. We note that this is likely not the case in other studies. For example, if MAP increases and there is a shift from conifers to angiosperms, Δ_{leaf} could change by several ‰ resulting in much larger corrections on $\delta^{13}C_{leaf}$ than in our example.

Table of Δ_{leaf} and $\delta^{13}C_{atm}$ estimates for the PETM in the Bighorn Basin (WY, USA).

Age*	Meters*	$\delta^{13}C_{leaf}$*	% Angio.*	MAP (mm/yr)†	Δ_{leaf} (DA)‡	Δ_{leaf} (EG)‡	Net Δ_{leaf}‡	$\delta^{13}C_{atm}$‡
54.30	73.30	-27.1	23	1380	21.4	20.1	20.4	-7.3
54.80	45.30	-27.2	23	1380	21.4	20.1	20.4	-7.4
55.00	37.30	-29.7	23	1440	21.5	20.2	20.5	-9.9
55.65	8.20	-31.6	99	800	20.7	18.8	20.6	-11.6
55.75	-0.15	-31.1	99	800	20.7	18.8	20.6	-11.1
55.80	-0.85	-31.7	99	800	20.7	18.8	20.6	-11.7
56.00	-13.75	-26.6	23	1380	21.4	20.1	20.4	-6.8
56.20	-19.75	-26.8	23	1380	21.4	20.1	20.4	-7.0

*Age (Ma), section meters, $\delta^{13}C_{leaf}$ (‰ VPDB), and % Angiosperm (Angio) are from Smith et al. (2). †MAP is from Wing et al. (3) and Wilf (4). ‡Calculations are described above.

Suggested use of Δ_{leaf} models: We use Δ_{leaf} expressions calculated separately for each PFT as opposed to using the global Δ_{leaf} expression because the slope of the relationship between Δ_{leaf} and MAP differs according to PFT, and this allows us to account for MAP and PFT controls on Δ_{leaf} simultaneously. We caution that the magnitude of MAP and PFT corrections applied to terrestrial isotope records using this approach is sensitive to the slope and intercept estimated in our statistical models. Future additions to our global dataset will provide additional refinement of our models and enable further evaluation of our corrections to Δ_{leaf} and $\delta^{13}C_{atm}$. An assumption of this approach is that MAP is a reasonable estimate of water availability for the plants from which TOC or biomarker isotope records are derived.

SI Methods

Climate data. Mean annual precipitation (MAP) and mean summer (June, July, and August) precipitation (P-JJA) were derived from multiple sources due to differences in the quality of data available across sites. Summer precipitation was estimated using June, July and August only for sites in temperate or arctic latitudes. We did not have sites in these seasonal latitudes from the Southern hemisphere. Precipitation data were derived from the following three sources, listed in order of priority with respect to inclusion: 1) the 1971-2000 PRISM 800 meter resolution model (PRISM Group, Oregon State University, http://www.prismclimate.org, created Feb 17 2009), 2) values reported in the publication, or 3) the 1951-2000 0.5º x 0.5º GPCC normals data set (Global Precipitation Climate Center; http://gpcc.dwd.de). The PRISM model contained the highest geographic specificity, however is only available for the United States of America; it is highly correlated with GCCP values (R^2=0.80, p<0.0001) despite differences in resolution. Mean annual temperature (MAT) and mean summer temperature (T-JJA) were derived from the 1991-2000 0.5 X 0.5º CRU TS 2.1 data set (5). Additional climate parameters were also compiled from FAO gridded data sets (e.g., available soil moisture, vapor pressure, sunlight percentage, a continentality index, etc. see SI Dataset).

References

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