Supporting Information

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Dataset

The basic data gathering and processing methods are described in the main text. The purpose of this section is to outline differences in methods compared to other studies. Because Diefendorf et al. (1) presented superficially similar data and results, this comparison emphasizes their study's methods vs. the present one. Excepting points 1, 3, and 7 below, most differences probably have little effect on regression results. Nonetheless, all are listed for completeness and to help direct future data compilations. Note that regression results are provided with the dataset in a separate file. Specific differences in datasets and methods include:

1. A more comprehensive literature search identified about six times more sites than the largest previous study (1–65).
2. Nearly all climate data were taken directly from original publications. For North America, this contrasts with Diefendorf et al. (1), who used modeled MAP and MAT values. Although MAT values do not affect results of either this study or Diefendorf et al. (1), a few (<2%) MAT values for non-U.S. sites tabulated by Diefendorf et al. (1) did not correspond with published values. Published values were used for considering regression residuals vs. MAT in the present study.
3. Prior to regressions, data were averaged over all C3 plant species at an individual site. Excepting Stewart et al (4), this averaging approach differs from all other studies, which distinguished compositions of individual species within a site. Many studies have restricted consideration to woody plants (a subset of the global C3 dataset), and Diefendorf et al. (1) further distinguished differences in isotope fractionation among plant functional types. While their choice is crucial to a key goal of their study, it also emphasizes sites with analyses that span greater species diversity. For example, a single study (33) constitutes almost 30% of Diefendorf et al.'s entire dataset, potentially biasing regressions of global C3 δ^{13}C values vs. MAP. For the purposes of this study (evaluating correlations with MAP across all C3 plant types), averaging minimizes reporting bias and provides higher quality resolution of the correlation between MAP and δ^{13}C or Δ (4).
4. Several sources reported inaccurate $\delta^{13}C_{atm}$, typically rounding values to $-8‰$, rather than using actual values for $\delta^{13}C_{atm}$, typically between -7.7 and $-7.9‰$. This does not affect the conclusions of these studies, partly because data scatter exceeds any introduced error by a factor of 3–5, and also because these studies emphasize differences in Δ, rather than absolute values. Nonetheless, this error was corrected in the present study, although not in Diefendorf et al. (1).
5. Compositions for leaf litter and leaf cellulose, which are enriched in ^{13}C compared to whole fresh leaves (66), were reported in a few studies (44, 51, 67), and used without correction by Diefendorf et al. (1). Cellulose compositions were not used in the present study, and corrections for leaf litter vs. whole fresh leaves were based on Dawson et al. (66).
6. Data from gardens, plantations, and experimental plots were excluded. This differs from Diefendorf et al. (1), who included results from gardens and experimental plots. A comprehensive analysis of leaf compositions in natural vs. experimental settings has not been reported, and these choices might not influence regressions.
7. Most studies regressed data linearly, although simple logarithmic and polynomial functions have also been used. A linear model may be appropriate for a regional dataset, but clearly not for global data (Figs. 1 and 2). The simple logarithmic function used by Diefendorf et al. (1), while far superior to a linear model, seems inappropriate because $\log_{10}(\mathrm{MAP})$ approaches negative infinity (predicted δ^{13}C approaches infinity) as MAP approaches 0. Similarly, the polynomial functions proposed in other studies (9, 54) do not extrapolate realistically to high and low MAP. For logarithmic functions, the quality of fit is significantly improved if an offset to MAP is used, i.e., regressing δ^{13}C vs. $\log_{10}(\mathrm{MAP} + m_o)$, where m_o is solved for iteratively, maximizing either R^2 or F. Data at low MAP (as low as 1–10 mm/yr) have finite δ^{13}C values, which can be achieved in this functional form only with $m_o > 0$. For example, the preferred regression has $m_o =$ 300 mm/yr and an R^2 value of 0.594. Omitting m_o results in an R^2 value of 0.499 and unrealistic predicted compositions at low MAP.

Alternative Regressions: Altitude and Latitude Corrections. Altitude and latitude corrections can be estimated in two different ways, either by directly regressing δ^{13}C vs. MAP, altitude, and latitude, as described in the text, or by assuming altitude and latitude coefficients, averaging over small MAP ranges (Table S1), and iteratively solving for best-fit coefficients that maximize R^2 or F in regressions of the averaged data. For a regression of δ^{13}C vs. $\log_{10}(\mathrm{MAP} + 300)$, the latter approach results in high R^2 (0.96), the same altitude coefficient (1.9e-4), and a larger latitude coefficient (0.028). The same method may be used to regress MAP as any function of δ^{13}C, including logarithmic or polynomial. Again, high R^2 results (0.96), but predictions are not substantially different from the regressions presented in the text.

Other Supporting Information Files

Dataset S1 (XLS)

1. Diefendorf AF, Mueller KE, Wing SL, Koch PL, & Freeman KH (2010) Global patterns in leaf ^{13}C discrimination and implications for studies of past and future climate. *Proc Natl Acad Sci USA* 107:5738–5743.
2. Medina E & Minchin P (1980) Stratification of δ^{13}C values of leaves in Amazonian rain forests. *Oecologia* 45:377–378.
3. Ehleringer JR & Cooper TA (1988) Correlations between carbon isotope ratio and microhabitat in desert plants. *Oecologia* 76:562–566.
4. Stewart GR, Turnbull MH, Schmidt S, & Erskine PD (1995) ^{13}C natural abundance in plant communities along a rainfall gradient: A biological integrator of water availability. *Aust J Plant Physiol* 22:51–55.
5. Damesin C, Rambal S, & Joffre R (1997) Between-tree variations in leaf δ^{13}C of Quercus pubescens and Quercus ilex among Mediterranean habitats with different water availability. *Oecologia* 111:26–35.
6. Schulze E-D, et al. (1998) Carbon and nitrogen isotope discrimination and nitrogen nutrition of trees along a rainfall gradient in northern Australia. *Aust J Plant Physiol* 25:413–425.
7. Cerling TE & Harris JM (1999) Carbon isotope fractionation between diet and bioapatite in ungulate mammals and implications for ecological and paleoecological studies. *Oecologia* 120:347–363.
8. Korol RL, Kirschbaum MUF, Farquhar GD, & Jeffreys M (1999) Effects of water status and soil fertility on the C-isotope signature in Pinus radiata. *Tree Physiol* 19:551–562.
9. Miller JM, Williams RJ, & Farquhar GD (2001) Carbon isotope discrimination by a sequence of Eucalyptus species along a subcontinental rainfall gradient in Australia. *Funct Ecol* 15:222–232.
10. Bowling DR, McDowell NG, Bond BJ, Law BE, & Ehleringer JR (2002) ^{13}C content of ecosystem respiration is linked to precipitation and vapor pressure deficit. *Oecologia* 131:113–124.
11. Macfarlane C, Adams MA, & White DA (2004) Productivity, carbon isotope discrimination an leaf traits of trees of Eucalyptus globulus Labill. in relation to water availability. *Plant Cell Environ* 27:1515–1524.

12. Swap RJ, Aranibar JN, Dowty PR, Gilhooly WP, & Macko SA (2004) Natural abundance of ^{13}C and ^{15}N in C3 and C4 vegetation of southern Africa: Patterns and implications. *Glob Change Biol* 10:350–358.
13. Codron J, et al. (2005) Taxonomic, anatomical, and spatio-temporal variations in the stable carbon and nitrogen isotopic compositions of plants from an African savanna. *J Archaeol Sci* 32:1757–1772.
14. Hemming D, et al. (2005) Pan-European δ^{13}C values of air and organic matter from forest ecosystems. *Glob Change Biol* 11:1065–1093.
15. Liu W, et al. (2005) δ^{13}C variation of C3 and C4 plants across an Asian monsoon rainfall gradient in arid northwestern China. *Glob Change Biol* 11:1094–1100.
16. Roden JS, Bowling DR, McDowell NG, Bond BJ, & Ehleringer JR (2005) Carbon and oxygen isotope ratios of tree ring cellulose along a precipitation transect in Oregon, United States. *J Geophys Res* doi:10.1029/2005JG000033.
17. Guo G & Xie G (2006) The relationship between plant stable carbon isotope composition, precipitation and satellite data, Tibet Plateau, China. *Quatern Int* 144:68–71.
18. Keitel C, Matzarakis A, Rennenberg H, & Gessler A (2006) Carbon isotopic composition and oxygen isotopic enrichment in phloem and total leaf organic matter of European beech (Fagus sylvatica L.) along a climate gradient. *Plant Cell Environ* 29:1492–1507.
19. Ometto JPHB, et al. (2006) The stable carbon and nitrogen isotopic composition of vegetation in tropic forests of the Amazon Basin, Brazil. *Biogeochemistry* 79:251–274.
20. Schulze E-D, Turner NC, Nicolle D, & Schumacher J (2006) Leaf and wood carbon isotope ratios, specific leaf areas and wood growth of Eucalyptus species across a rainfall gradient in Australia. *Tree Physiol* 26:479–492.
21. Feranec RS (2007) Stable carbon isotope values reveal evidence of resource partitioning among ungulates from modern C3-dominated ecosystems in North America. *Palaeogeogr Palaeocl* 252:575–585.
22. Drucker DG, Bridault A, Hobson KA, Szuma E, & Bocherens H (2008) Can carbon-13 in large herbivores reflect the canopy effect in temperate and boreal ecosystems? Evidence from modern and ancient ungulates. *Palaeogeogr Palaeocl* 266:69–82.
23. Song M, et al. (2008) Leaf δ^{13}C reflects ecosystem patterns and responses of alpine plants to the environments on the Tibetan Plateau. *Ecography* 31:499–508.
24. Wynn JG & Bird MI (2008) Environmental controls on the stable carbon isotopic composition of soil organic carbon: implications for modelling the distribution of C3 and C4 plants, Australia. *Tellus* 60B:604–621.
25. Gouveia AC & Freitas H (2009) Modulation of leaf attributes and water use efficiency in Quercus suber along a rainfall gradient. *Trees* 23:267–275.
26. 26.Pfautsch S, Gessler A, Rennenberg H, Weston CJ, & Adams MA (2010) Continental and local climatic influences on hydrology of eucalypt-Nothofagus ecosystems revealed by δ^{2}D, δ^{13}C, and δ^{18}O of ecosystem samples. *Water Resour Res* doi:10.1029/2009WR007807.
27. Buchmann J-M, Guehl JM, Barigah TS, & Ehleringer JR (1997) Interseasonal comparison of CO_2 concentrations, isotopic composition, and carbon dynamics in an Amazonian rainforest (French Guiana). *Oecologia* 110:120–131.
28. Buchmann N, Kao W-Y, & Ehleringer JR (1997) Influence of stand structure on carbon-13 of vegetation, soils, and canopy air within deciduous and evergreen forests in Utah, United States. *Oecologia* 110:109–119.
29. Ehleringer JR, Rundel PW, Palma B, & Mooney HA (1998) Carbon isotope ratios of Atacama Desert plants reflect hyperaridity of region in northern Chile. *Rev Chil Hist Nat* 71:79–86.
30. Hartman G & Danin A (2010) Isotopic values of plants in relation to water availability in the Eastern Mediterranean region. *Oecologia* 162:837–852.
31. Schulze E-D, Ellis R, Schulze W, Trimborn P, & Ziegler H (1996) Diversity, metabolic types and δ^{13}C carbon isotope ratios in the grass flora of Namibia in relation to growth form, precipitation and habitat conditions. *Oecologia* 106:352–369.
32. Bai E, Boutton TW, Liu F, Wu XB, & Archer SR (2008) Variation in woody plant δ^{13}C along a topoedaphic gradient in a subtropical savanna parkland. *Oecologia* 156:479–489.
33. Bonal D, Sabatier D, Montpied P, Tremeaux D, & Guehl JM (2000) Iterspecific variability of δ^{13}C among trees in rainforests of French Guiana: Functional groups and canopy integration. *Oecologia* 124:454–468.
34. Brooks JR, Flanagan LB, Buchmann N, & Ehleringer JR (1997) Carbon isotope composition of boreal plants: Functional grouping of life forms. *Oecologia* 110:301–311.
35. Chevillat VS, Siegwolf RTW, Pepin S, & Körner C (2005) Tissue-specific variation of δ^{13}C in mature canopy trees in a temperate forest in central Europe. *Basic Appl Ecol* 6:519–534.
36. De Lillis M, Matteucci G, & Valentini R (2004) Carbon assimilation, nitrogen, and photochemical efficiency of different Himalayan tree species along an altitudinal gradient. *Photosynthetica* 42:597–605.
37. DeLucia EH & Schlesinger WH (1991) Resource-use efficiency and drought tolerance in adjcent Great Basin and Sierran plants. *Ecology* 72:51–58.
38. Dodd MB, Lauenroth WK, & Welker JM (1998) Differential water resource use by herbaceous and woody plant life-forms in a shortgrass steppe community. *Oecologia* 117:504–512.
39. Donovan LA & Ehleringer JR (1991) Ecophysiological differences among juvenile and reproductive plants of several woody species. *Oecologia* 86:594–597.
40. Dungait JAJ, Docherty G, Straker V, & Evershed RP (2008) Interspecific variation in bulk tissue, fatty acid and monosaccharide δ^{13}C values of leaves from a mesotrophic grassland plant community. *Phytochemistry* 69:2041–2051.
41. Ehleringer JR (1993) Variation in leaf carbon isotope discrimination in Encelia farinosa: Implications for growth, competition, and drought survival. *Oecologia* 95:340–346.
42. Ehleringer JR, Lin ZF, Field CR, Sun GC, & Kuo CY (1987) Leaf carbon isotope ratios of plants from a subtropical monsoon forest. *Oecologica* 72:109–114.
43. Ehleringer JR, Phillips SL, & Comstock JP (1992) Seasonal variation in the carbon isotopic composition of desert plants. *Funct Ecol* 6:396–404.
44. Escudero A, Mediavilla S, & Heilmeier H (2008) Leaf longevity and drought: Avoidance of the costs and risks of early leaf abscission as inferred from the leaf carbon isotopic composition. *Funct Plant Biol* 35:705–713.
45. Franco AC, et al. (2005) In situ measurements of carbon and nitrogen distribution and composition, photochemical efficiency and stable isotope ratios in Araucaria angustifolia. *Trees-Struct Funct* 19:422–430.
46. Garten CT & Taylor GE, Jr. (1992) Foliar δ^{13}C within a temperate deciduous forest: Spatial, temporal, and species sources of variation. *Oecologia* 90:1–7.
47. Gerdol R, Iacumin P, Marchesini R, & Bragazza L (2000) Water- and nutrient-use efficiency of a deciduous species, Vaccinium myrtillus, and an evergreen species, V. vitis-idaea, in a subalpine dwarf shrub heath in the southern Alps, Italy. *Oikos* 88:19–32.
48. Hanba YT, Mori S, Lei TT, Koiki T, & Wada E (1997) Variations in leaf δ^{13}C along a vertical profile of irradiance in a temperature Japanese forest. *Oecologia* 110:253–261.
49. He C-X, Li J-Y, Zhou P, Guo M, & Zheng Q-S (2008) Changes of leaf morphological, anatomical structure and carbon isotope ratio with the height of the Wangtian tree (Parashorea chinensis) in the Xishuangbanna, China. *J Integr Plant Biol* 50:168–173.
50. Holtum JAM & Winter K (2005) Carbon isotope composition of canopy leaves in a tropical forest in Panama throughout a seasonal cycle. *Trees* 19:545–551.
51. Inagaki Y, Miura S, & Kohzu A (2004) Effects of forest type and stand age on litterfall quality and soil N dynamics in Shikoku district, southern Japan. *Forest Ecol Manag* 202:107–117.
52. Kloeppel BD, Gower ST, Treichel IW, & Kharuk S (1998) Foliar carbon isotope discrimination in Larix species and sympatric evergreen conifers: A global comparison. *Oecologia* 114:153–159.
53. Kohorn LU, Goldstein G, & Rundel PW (1994) Morphological and isotopic indicators of growth environment: Variability in δ^{13}C in Simmondsia chinensis, a dioecious desert shrub. *J Exp Bot* 45:1817–1822.
54. Leffler AJ & Enquist BJ (2002) Carbon isotope composition of tree leaves from Guanacaste, Costa Rica: Comparison across tropical forests and tree life history. *J Trop Ecol* 18:151–159.
55. Lockheart MJ, Van Bergen PF, & Evershed RP (1997) Variations in the stable carbon isotope compositions of individual lipids from the leaves of modern angiosperms: Implications for the study of higher land plant-derived sedimentary matter. *Org Geochem* 26:137–153.
56. McArthur JV & Moorhead KK (1996) Characterization of riparian species and stream detritus using multiple stable isotopes. *Oecologia* 107:232–238.
57. Mooney HA, Bullock SH, & Ehleringer JR (1989) Carbon isotope ratios of plants of a tropical dry forest in Mexico. *Funct Ecol* 3:137–142.
58. Nagy L & Proctor J (2000) Leaf δ^{13}C signatures in heath and lowland evergreen rain forest species from Borneo. *J Trop Ecol* 16:757–761.
59. Sandquist DR & Cordell S (2007) Functional diversity of carbon-gain, water-use, and leaf-allocation traits in trees of a threatened lowland dry forest in Hawaii. *Am J Bot* 94:1459–1469.
60. Terwilliger VJ (1997) Changes in the δ^{13}C values of trees during a tropical rainy season: some effects in addition to diffusion and carboxylation by Rubisco? *Am J Bot* 84:1693–1700.
61. Toft NL, Anderson JE, & Nowak RS (1989) Water use efficiency and carbon isotope composition of plants in a cold desert environment. *Oecologia* 80:11–18.
62. Uemura A, Harayama H, Koike N, & Ishida A (2006) Coordination of crown structure, leaf plasticity and caarbon gain within the crowns of three winter-deciduous mature trees. *Tree Physiol* 26:633–641.
63. Valentini R, Anfodillo T, & Ehleringer JR (1994) Water sources and carbon-isotope composition (δ^{13}C) of selected tree species of the Italian Alps. *Can J Forest Res* 24:1575–1579.
64. Valentini R, Scarascia Mugnozza GE, & Ehleringer JR (1992) Hydrogen and carbon isotope ratios of selected species of a mediterranean macchia ecosystem. *Funct Ecol* 6:627–631.
65. Cerling TE, Hart JA, & Hart TB (2004) Stable isotope ecology in the Ituri Forest. *Oecologia* 138:5–12.
66. Dawson TE, Mambelli S, Plamboeck AH, Templer PH, & Tu KP (2002) Stable isotopes in plant ecology. *Annu Rev Ecol Sys* 33:507–559.
67. Van de Water PK, Leavitt SW, & Betancourt JL (2002) Leaf δ^{13}C variability with elevation, slope aspect, and precipitation in the southwest United States. *Oecologia* 132:332–343.

Table S1. Binned and averaged MAP and δ^{13}C values

Bin	0–100	100–200	200–250	250–300	300–350	350–400	400–450
MAP$_{ave}$	50	164	221	270	322	372	419
$\delta^{13}C_{Ave}$	−24.74	−25.05	−25.38	−25.24	−26.02	−25.88	−26.34
n	21	18	21	22	21	33	26
Bin	450–500	500–550	550–600	600–650	650–700	700–800	800–900
MAP$_{ave}$	471	515	575	623	671	750	838
$\delta^{13}C_{Ave}$	−26.63	−27.30	−27.06	−27.14	−26.60	−26.91	−27.33
n	48	28	18	22	21	27	28
Bin	900–1,100	1,100–1,300	1,300–1,600	1,600–2,000	>2,000		
MAP$_{ave}$	990	1,194	1,477	1,792	2,584		
$\delta^{13}C_{Ave}$	−27.64	−27.83	−28.63	−29.18	−29.51		
n	33	33	32	27	21		

Data are corrected for altitude (1.90e-4‰/m) and absolute latitude (0.0124‰/°).