

# Global patterns in leaf $^{13}\text{C}$ discrimination and implications for studies of past and future climate

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Fractionation of carbon isotopes by plants during  $\text{CO}_2$  uptake and fixation ( $\Delta_{\text{leaf}}$ ) varies with environmental conditions, but quantitative patterns of  $\Delta_{\text{leaf}}$  across environmental gradients at the global scale are lacking. This impedes interpretation of variability in ancient terrestrial organic matter, which encodes climatic and ecological signals. To address this problem, we converted 3,310 published leaf  $\delta^{13}\text{C}$  values into mean  $\Delta_{\text{leaf}}$  values for 334 woody plant species at 105 locations (yielding 570 species-site combinations) representing a wide range of environmental conditions. Our analyses reveal a strong positive correlation between  $\Delta_{\text{leaf}}$  and mean annual precipitation (MAP;  $R^2 = 0.55$ ), mirroring global trends in gross primary production and indicating stomatal constraints on leaf gas-exchange, mediated by water supply, are the dominant control of  $\Delta_{\text{leaf}}$  at large spatial scales. Independent of MAP, we show a lesser, negative effect of altitude on  $\Delta_{\text{leaf}}$  and minor effects of temperature and latitude. After accounting for these factors, mean  $\Delta_{\text{leaf}}$  of evergreen gymnosperms is lower (by 1–2.7‰) than for other woody plant functional types (PFT), likely due to greater leaf-level water-use efficiency. Together, environmental and PFT effects contribute to differences in mean  $\Delta_{\text{leaf}}$  of up to 6‰ between biomes. Coupling geologic indicators of ancient precipitation and PFT (or biome) with modern  $\Delta_{\text{leaf}}$  patterns has potential to yield more robust reconstructions of atmospheric  $\delta^{13}\text{C}$  values, leading to better constraints on past greenhouse-gas perturbations. Accordingly, we estimate a 4.6‰ decline in the  $\delta^{13}\text{C}$  of atmospheric  $\text{CO}_2$  at the onset of the Paleocene-Eocene Thermal Maximum, an abrupt global warming event  $\sim 55.8$  Ma.

biogeochemistry | ecophysiology | fractionation | PETM

Human perturbation of the global carbon (C) cycle is potentially far greater in rate and magnitude than variations in the recent past, pushing predictions of future climate beyond the calibration range of models based on modern and near-modern observations. Robust predictions of future impacts of rising  $\text{CO}_2$  require not only extrapolation of ecological patterns along modern environmental gradients but also insights gained from changing ecological patterns at times of high  $\text{CO}_2$  and hot climate in the geologic past (1 and 2). Global patterns of variation in leaf carbon isotope ( $\delta^{13}\text{C}_{\text{leaf}}$ ) values potentially record climate-driven changes in modern plant physiology and biogeochemistry. An understanding of factors controlling plant fractionation ( $\Delta_{\text{leaf}}$ ) at the global scale will improve interpretations of past changes in climate and ecology recorded in ancient terrestrial sedimentary organic carbon (2). Patterns in  $\delta^{13}\text{C}_{\text{leaf}}$  of living plants at the global scale, however, are unresolved in spite of abundant published data at smaller spatial scales.

In living plants,  $\delta^{13}\text{C}_{\text{leaf}}$  values reflect the balance of photosynthesis and stomatal conductance and their coupled response to the environment (3). Edaphic factors (e.g., water availability, altitude, temperature) and plant attributes (e.g. phylogeny and leaf traits) can influence  $\delta^{13}\text{C}_{\text{leaf}}$  values (4–6). The relative importance of these factors at the global scale is not known, nor is it clear how they might drive the variations in ancient  $\delta^{13}\text{C}_{\text{leaf}}$  values

recorded in either terrestrial organic carbon ( $\delta^{13}\text{C}_{\text{TOC}}$ ) or  $\delta^{13}\text{C}$  values of plant biomarkers.

During extreme climate events in the past, changes in the isotope ratio of atmospheric  $\text{CO}_2$  ( $\delta^{13}\text{C}_{\text{atm}}$ ) reflect perturbations in atmospheric C fluxes, therefore accurate estimates of  $\delta^{13}\text{C}_{\text{atm}}$  are central to estimating past climate sensitivity to changes in  $p\text{CO}_2$  (7). Values of  $\delta^{13}\text{C}_{\text{TOC}}$  from sedimentary rocks are widely used to estimate  $\delta^{13}\text{C}_{\text{leaf}}$  of ancient plants and infer changes in  $\delta^{13}\text{C}_{\text{atm}}$  (8). However, the offset between  $\delta^{13}\text{C}_{\text{atm}}$  and  $\delta^{13}\text{C}_{\text{leaf}}$  (i.e.,  $\Delta_{\text{leaf}}$ ) varies with climate and plant characteristics and such variations must be accounted for when estimating atmospheric C isotope excursions (CIE) from ancient plant-derived C. For example, during the Paleocene-Eocene Thermal Maximum (PETM), a period of rapid global warming 55.8 million years ago (9), the CIEs in terrestrial organic carbon (TOC) and atmospheric  $\text{CO}_2$  likely differ because of changes in  $\Delta_{\text{leaf}}$  that accompanied plant community shifts, warming ( $\sim 5^\circ\text{C}$ ), decreasing precipitation and increases in atmospheric  $\text{CO}_2$  (2).

In this study, we provide predictive relationships for  $\Delta_{\text{leaf}}$  variability of woody  $\text{C}_3$  plants at the global scale from analysis of published  $\delta^{13}\text{C}_{\text{leaf}}$  values, plant functional types, biome, climate, and geography. We use these relationships to show how environmental and ecologic change during the PETM influenced plant fractionation and therefore the CIE recorded by fossil leaf waxes.

## Results and Discussion

**Leaf Carbon Isotope Fractionation.** We used  $\Delta_{\text{leaf}}$  in our analyses as it controls for variation in  $\delta^{13}\text{C}_{\text{atm}}$  (10).  $\Delta_{\text{leaf}}$  in  $\text{C}_3$  plants is a function of the fractionation associated with  $\text{CO}_2$  diffusion (4.4%) and photosynthetic fractionation by Rubisco (27%). For  $\text{C}_3$  plants, the concentration of  $\text{CO}_2$  in the substomatal cavities of leaves ( $c_i$ ) is directly proportional to  $\Delta_{\text{leaf}}$  when the atmospheric  $\text{CO}_2$  concentration ( $c_a$ ) is held constant (10) (but see ref. 11). In turn,  $c_i$  depends on the flux of  $\text{CO}_2$  into the leaf, which is largely regulated by stomatal conductance ( $g_s$ ) and the flux of  $\text{CO}_2$  removed from the leaf for C fixation by assimilation ( $A$ ) (10). Values of  $\Delta_{\text{leaf}}$  generally decrease with reductions in water availability, reflecting a down-regulation of  $g_s$  and increased water-use efficiency (WUE) (10, 12). Thus,  $\Delta_{\text{leaf}}$  is a time-integrated measure of WUE, although leaf temperature ( $T$ ), mesophyll conductance and differences in  $c_a$  are potential confounding factors (11 and 13). Confounding effects are reduced, however, because mesophyll conductance is correlated with  $A$  (and with  $g_s$ ) (11 and 14) and trees appear to maintain leaf

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$T$  within a narrow range ( $21.4 \pm 2.2^\circ\text{C}$ ) across a wide range of ambient  $T$  (15).  $A$  and  $g_s$  also vary with plant phylogeny, growth form and leaf traits, thus  $\Delta_{\text{leaf}}$  and its response to the environment may differ for plant functional types (PFTs) defined by these attributes (4).

**Data.** Our dataset, provided in [Dataset S1](#), includes 334 species from 75 woody plant families (including trees and shrubs) present at 105 geographic sites distributed across 5 continents (representing 3,310  $\delta^{13}\text{C}_{\text{leaf}}$  measurements of individual plants). The result is 570 unique species-site combinations represented by a mean  $\Delta_{\text{leaf}}$  value calculated from multiple individuals of each species at a site. These sites represent eight biomes with mean annual temperature ranging from  $-10^\circ$  to  $28^\circ\text{C}$  and mean annual precipitation (MAP) from 147 to 3,700 mm per year, capturing the broad range in which higher plants occur ([SI Appendix](#)).

**Precipitation.** MAP is positively correlated to global  $\Delta_{\text{leaf}}$  values ( $p < 0.0001$ ,  $R^2 = 0.55$ ; Fig. 1) and is the strongest predictor of  $\Delta_{\text{leaf}}$  among the environmental parameters in our dataset. To our knowledge this study represents the largest spatial scale at which this correlation has been documented, though it has been seen in some, but not all, regional studies and with considerably lower explanatory power (16–20). The strong correlation of MAP with  $\Delta_{\text{leaf}}$  suggests that as water availability increases, stomatal limitations on  $c_i$  and  $A$  relax and WUE declines (i.e.,  $g_s$  increases relative to  $A$ ), leading to greater absolute C fixation (3 and 10). These apparent stomatal limitations on leaf-level  $A$  likely scale up to the ecosystem level and help explain global variation in gross and net primary production, which also varies with MAP (21).

The relationship between MAP and  $\Delta_{\text{leaf}}$  is consistently strong within the continents of North America (NA) and Asia ([SI Appendix](#)), but not Europe (EU;  $R^2 = 0.025$ ,  $p = 0.125$ ). Extensive analysis of European data does not reveal any single

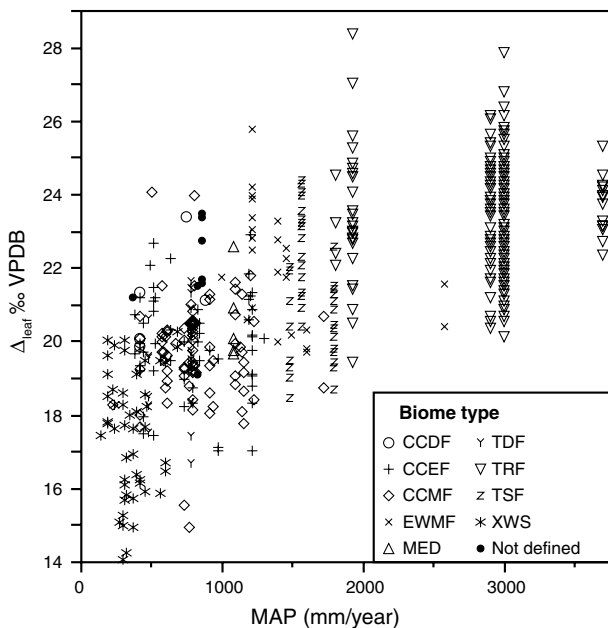
environmental variable (or simple combination of variables) that accounts for more than 20% of the variation in  $\Delta_{\text{leaf}}$  across all plant types. The lack of strong MAP effects on  $\Delta_{\text{leaf}}$  in EU (see also ref. 16) and elsewhere (17–19) may arise from heterogeneity in growing season water availability that is not captured by MAP, due to differences in the seasonality of rainfall across sites (i.e. EU includes areas with wet winters in the south and wet summers in the north) or the presence of sites where soil water does not come from local precipitation. Better measures of water availability during growth may yield different results. For example, in our NA dataset, summer precipitation (June to August) is a better estimate of water availability than MAP for deciduous angiosperms and is more strongly correlated with  $\Delta_{\text{leaf}}$  ( $R^2 = 0.83$  and  $0.57$  respectively,  $p < 0.0001$ ,  $n = 36$  species-site combinations, excluding tropical sites and one California site with a wet winter).

**Altitude and Other Factors.** We assessed the influence of other factors on  $\Delta_{\text{leaf}}$  using bivariate partial regression models that account for the covariance of MAP with other predictors ([SI Appendix](#)) and its correlation with  $\Delta_{\text{leaf}}$ . This approach is justified by our observation that MAP emerges as the strongest single predictor of  $\Delta_{\text{leaf}}$  and because the influence of MAP on  $\Delta_{\text{leaf}}$  is supported by theory and other observations. The partial regression model with altitude as a secondary predictor is the only model with notable explanatory power ( $R^2 = 0.13$ ,  $p < 0.0001$ ) indicating that altitude has a weak, negative influence on  $\Delta_{\text{leaf}}$  that is statistically independent of its covariance with MAP. The combination of MAP and altitude explains 61% of the global variability in  $\Delta_{\text{leaf}}$  in a multiple regression model ( $p < 0.0001$ ), and regression models for data-rich continents show similar results ([SI Appendix](#)). Elevation effects on  $\Delta_{\text{leaf}}$  have been observed previously (3 and 20), although altitude is rarely evaluated independently of MAP. The responsible mechanisms remain uncertain (3) and could be related to  $T$ , vapor pressure, oxygen partial pressure, irradiance, or other factors.

MAP and altitude effects on  $\Delta_{\text{leaf}}$  are evident when regressions are performed on data grouped by PFT ([SI Appendix](#)), indicating that their influence is independent of community changes along elevation or precipitation gradients. The effects of MAP and altitude are still apparent when regressions are performed separately for well represented genera in our database ([SI Appendix](#)). Phylogenetic variation is reduced within genera, making it unlikely that the global correlations of  $\Delta_{\text{leaf}}$  with MAP (Fig. 1) and altitude are driven exclusively by differences in the taxonomic composition of floras in different regions. Rather, we suggest  $\Delta_{\text{leaf}}$  is evolutionarily and physiologically plastic in response to changes in water availability.

Unexpectedly, other factors (e.g.  $T$ , latitude, evapotranspiration) were not significantly related to  $\Delta_{\text{leaf}}$  after controlling for MAP and altitude in regression models of the entire dataset. Negligible effects of these factors could indicate that  $A$  and  $g_s$  covary more tightly with  $T$  and other factors than with changes in MAP and altitude. Covariance of  $T$  with MAP, altitude, or PFT distribution may also mask its influence ([SI Appendix](#), see below).

**Plant Functional Types.** Despite the considerable variance in  $\Delta_{\text{leaf}}$  explained by MAP and altitude, much remains unexplained, as evident by the  $\sim 8\%$  range in  $\Delta_{\text{leaf}}$  at any given MAP value (Fig 1; [Dataset S1](#)). Microclimate, ecosystem structure, and differences in plant traits among the species and PFTs must explain some of this variability. Several studies have reported localized differences in  $\Delta_{\text{leaf}}$  among woody PFTs and similar results have been observed in metaanalyses of wood  $\delta^{13}\text{C}$  (6). Yet previous metaanalyses of  $\Delta_{\text{leaf}}$  of  $\text{C}_3$  plants have not found evidence of a PFT effect (22), with the exception that grasses differ from woody plants (4). This likely reflects inadequate control for environmental influences on  $\Delta_{\text{leaf}}$  that are independent of PFT. On the other



**Fig. 1.** Effect of mean annual precipitation (MAP) on  $\Delta_{\text{leaf}}$  ( $n = 506$ ). MAP accounts for 55% ( $p < 0.0001$ ) of the variability in  $\Delta_{\text{leaf}}$  in a linear regression model. Points are coded by biome: tropical rain forest (TRF), evergreen warm mixed forest (EWMF), tropical seasonal forest (TSF), cool-cold deciduous forest (CCDF), cool-cold evergreen forest (CCEF), cool-cold mixed forest (CCMF), tropical deciduous forest (TDF), xeric woodland scrubland (XWS). In a regression model using site-means ( $\Delta_{\text{leaf}}$  averaged by geographic location), MAP accounts for 52% ( $p < 0.0001$ ) of the variability in  $\Delta_{\text{leaf}}$  ([SI Appendix](#)).



There are uniformitarian assumptions in using  $\Delta_{\text{leaf}}$  patterns among extant plants to interpret the vegetation of the geological past, however two factors encourage us to proceed. First, the morphological and physiological responses of  $C_3$  plants to water stress are constrained by their fundamental anatomy and biochemistry (26), making it likely that the relationship of water availability and  $\Delta_{\text{leaf}}$  has been similar in direction and magnitude over geological time. MAP and altitude effects on  $\Delta_{\text{leaf}}$  are apparent within as well as among genera, implying that independent lineages respond similarly and quickly. Second, a recent study by Crisp et al. (27) shows that plant lineages rarely shift biomes during evolution, suggesting niche conservatism and supporting the careful use of biome type to constrain  $\Delta_{\text{leaf}}$  values. Nonetheless, applying modern correlations of  $\Delta_{\text{leaf}}$  with environment to the distant geological past may be problematic because of differences in major plant groups prior to the origin of angiosperms in the Cretaceous.

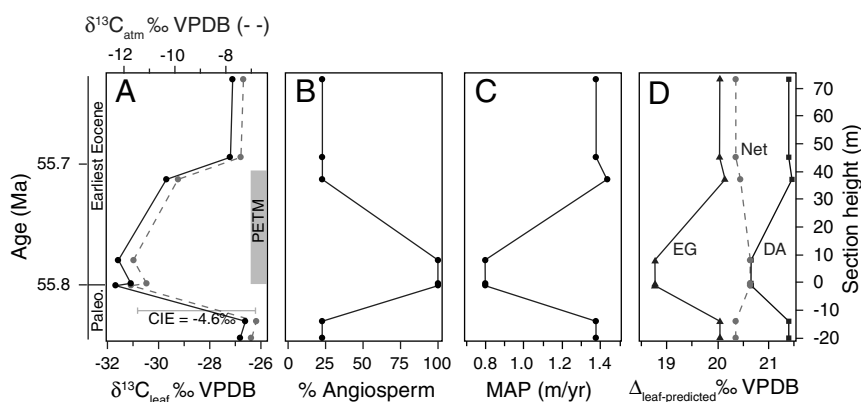
Pollen and leaf fossils document spatial and temporal changes in PFT as well as  $T$  and precipitation (9 and 28). Plant biomarkers (chemical fossils), such as  $n$ -alkanes (from leaf waxes) or terpenoids (defense compounds) are also preserved geologically (9) and have fewer diagenetic or source effects on their isotopic composition than  $\delta^{13}\text{C}_{\text{TOC}}$  (29). Plant waxes in ancient sediments reflect productivity-weighted inputs from all PFTs contributing to that deposit. The resulting mixed molecular signal can be used to estimate a  $\delta^{13}\text{C}_{\text{leaf}}$  value that integrates plant biomass within the catchment. In contrast, terpenoids provide PFT specificity because tricyclic diterpenoids are unique to woody gymnosperms and pentacyclic triterpenoids are unique to woody angiosperms. Therefore, ratios of these terpenoids, after accounting for production and preservational biases, may provide estimates of PFT (30). Also, terpenoid  $\delta^{13}\text{C}$  values can be used to calculate PFT-specific  $\Delta_{\text{leaf}}$  values (25).

Heterogeneity in rainfall and PFT dominance across ancient landscapes presumably created spatial patterns in  $\Delta_{\text{leaf}}$  just as they do now, even at small spatial scales. To understand differences in  $\delta^{13}\text{C}_{\text{TOC}}$ ,  $\delta^{13}\text{C}_{\text{biomarkers}}$  and the magnitude of CIEs recorded in different regions at the same time, and improve chemostratigraphic correlations using  $\delta^{13}\text{C}_{\text{TOC}}$ , we should account for biome (5), precipitation (9), and PFT (2 and 25) effects on  $\Delta_{\text{leaf}}$  values using relationships like those reported above.

An important goal in studies that document temporal variation in  $\delta^{13}\text{C}_{\text{atm}}$  is to reconstruct the sources and fluxes of C to the ancient atmosphere (7).  $\delta^{13}\text{C}_{\text{leaf}}$  and  $\delta^{13}\text{C}_{\text{TOC}}$  have been used to directly represent  $\delta^{13}\text{C}_{\text{atm}}$  (4 and 31), but this approach is

fraught with uncertainty (32). It has been suggested that using a simple numerical offset to convert  $\delta^{13}\text{C}_{\text{TOC}}$  to  $\delta^{13}\text{C}_{\text{atm}}$  under nonlimiting water conditions is sufficient to control for environmental impacts (4). To the contrary, we argue that secular changes in PFT and climate must also result in significant—but often unaccounted—effects on  $\Delta_{\text{leaf}}$ . Previous studies averaged multiple  $\delta^{13}\text{C}_{\text{TOC}}$  values to remove variation caused by environmental factors (4, 31, 32), ignoring insights about paleoecology and climate that might be inferred from  $\delta^{13}\text{C}_{\text{TOC}}$  variations.

We use an example from the PETM to illustrate how our study of modern  $\Delta_{\text{leaf}}$  can improve interpretation of ancient  $\delta^{13}\text{C}_{\text{biomarkers}}$  and  $\delta^{13}\text{C}_{\text{atm}}$  (Fig. 4; see *SI Appendix*). Smith et al. (2) documented a shift from a mixed angiosperm-conifer flora (~25% angiosperm) in the late Paleocene to an angiosperm flora (~100%) at the onset of the CIE, and inferred that the 5% decrease in  $\delta^{13}\text{C}_{\text{leaf}}$  (estimated from  $n$ -alkanes) reflected both a decrease in  $\delta^{13}\text{C}_{\text{atm}}$  (3–4%) and an increase in  $\Delta_{\text{leaf}}$  caused by a shift from conifers to angiosperms (1–2%, (2, 9)). Although the dominant late Paleocene conifers in the Bighorn Basin (*Metasequoia* and *Glyptostrobus* (9 and 33)) were deciduous, they probably had low  $\Delta_{\text{leaf}}$ , as do their extant relatives (34 and 35) (Fig. 2). Yet the PETM in Wyoming is also marked by a change from wetter conditions (MAP ~ 1,380 mm/yr) in the late Paleocene (28) to drier conditions (MAP ~ 800 mm/yr) at the onset of the event (9), which should have decreased  $\Delta_{\text{leaf}}$ . When both PFT and MAP effects on  $\Delta_{\text{leaf}}$  are taken into account (Fig. 4; see *SI Appendix*), the decrease in  $\Delta_{\text{leaf}}$  from declining MAP is countered by the increase in angiosperms, resulting in a net  $\Delta_{\text{leaf}}$  increase of 0.2% and an estimated negative CIE in  $\delta^{13}\text{C}_{\text{atm}}$  of 4.6%. This estimate of the atmospheric CIE is larger than that calculated by Smith et al. (2), who argued the CIE in  $\delta^{13}\text{C}_{\text{alkanes}}$  was higher than the atmospheric CIE because of the loss of conifers, and that marine sediments recorded the true CIE. Our  $\Delta_{\text{leaf}}$  correction for both PFT and MAP effects on  $\delta^{13}\text{C}_{\text{alkanes}}$  suggests the relatively large CIE recorded in the Bighorn Basin and other terrestrial sites (36) may equal the atmospheric CIE. This larger CIE falls within the range recently reported from well-preserved shallow marine carbonate records (–3.5% to –5.0%) and supports the notion that –3.5% is too small (37). A larger atmospheric CIE implies the carbon released at the onset of the PETM was more depleted or greater in mass than presently thought. Adjusting other terrestrial CIE records for biome, MAP, and PFT effects should further refine and reconcile estimates of the magnitude of the CIE.



**Fig. 4.** Conceptual diagram of  $\delta^{13}\text{C}_{\text{atm}}$  reconstruction for latest Paleocene to earliest Eocene sediments in the Bighorn Basin (WY). The figures are constructed as follows: (A)  $\delta^{13}\text{C}_{\text{leaf}}$  values as inferred from  $\delta^{13}\text{C}$  values of  $n$ - $C_{31}$  alkanes (2), (B) percent of fossil leaves that are angiosperms, (C) mean annual precipitation (MAP) derived from fossil leaf metrics (9, 28), and (D) modeled net  $\Delta_{\text{leaf}}$  from our  $\Delta_{\text{leaf}}$ -MAP expressions for evergreen gymnosperm (EG; triangles) and deciduous angiosperm (DA; squares) PFTs (see *SI Appendix*). Each model was scaled by % angiosperm to derive a net  $\Delta_{\text{leaf}}$  (dashed line).  $\delta^{13}\text{C}_{\text{atm}}$  is denoted with a dashed line on A and is derived from the net  $\Delta_{\text{leaf}}$  and  $\delta^{13}\text{C}_{\text{leaf}}$  values. The negative CIE in  $\delta^{13}\text{C}_{\text{atm}}$  at the base of the Paleocene-Eocene Thermal Maximum (PETM) is 4.6% (difference between latest Paleocene value and average of initial PETM values). See *SI Appendix* for discussion of calculations and suggested use of these models.

Relationships based on modern plants may not fully quantify the response of  $\Delta_{\text{leaf}}$  to greenhouse climate conditions (high  $T$  and  $p\text{CO}_2$ ) such as those of the PETM (12, 13, 38). Given the multiple functions of stomata (water loss prevention,  $\text{CO}_2$  provision for  $A$ , evaporative cooling), it is unlikely that plants could simultaneously maintain homeostasis with respect to leaf  $T$  (15) and  $c_i$  or  $\Delta_{\text{leaf}}$  (12) during periods of rapid global change. Studies on  $\Delta_{\text{leaf}}$  of extant relatives of ancient plants under high temperature and  $p\text{CO}_2$  conditions and varying degrees of water stress are needed to better interpret changes in  $\delta^{13}\text{C}_{\text{TOC}}$  and  $\delta^{13}\text{C}_{\text{biomarkers}}$  during the PETM and other events.

**Conclusions.** We document global patterns in  $\Delta_{\text{leaf}}$  among woody plants, including: (i) a strong positive correlation with MAP ( $R^2 = 0.55$ ), (ii)  $\Delta_{\text{leaf}}$  values 1% to 2.7% lower for EGs than other woody PFTs, and (iii) differences up to 6% in  $\Delta_{\text{leaf}}$  among biomes ( $R^2 = 0.66$ ). The relationship of  $\Delta_{\text{leaf}}$  with MAP shows that the balance of leaf gas-exchange in modern plants is largely driven by water availability, consistent with the role of water in driving global trends in ecosystem-scale primary productivity. By revealing global-scale relationships of MAP, PFT, and biome with  $\Delta_{\text{leaf}}$ , our results uniquely enable applications of these patterns for understanding global-scale processes, such as extrapolation of the distribution of PFTs and leaf carbon and water fluxes under future climate scenarios. In geologic studies, our models of  $\Delta_{\text{leaf}}$  provide tools for interpreting spatial and temporal variation in  $\delta^{13}\text{C}_{\text{TOC}}$  and  $\delta^{13}\text{C}_{\text{biomarkers}}$ , leading to enhanced understanding of paleoecology and atmospheric  $\text{CO}_2$  during climate events that serve as analogs of the near future. Our results warn against the assumption in some geologic studies that  $\Delta_{\text{leaf}}$  is invariant in space and time and emphasize that estimating  $\delta^{13}\text{C}_{\text{atm}}$  from  $\delta^{13}\text{C}_{\text{TOC}}$  or  $\delta^{13}\text{C}_{\text{leaf}}$  requires information about biome, PFT, and paleoclimate. We use this approach to produce a refined estimate of the atmospheric CIE (−4.6%) during the PETM and suggest that it be extended to other PETM CIE records to better estimate  $T$  sensitivity to greenhouse gases. Such work will aid our

understanding of plant response to extreme climate change both in the geologic past and in the coming century.

## Methods

We extracted  $\delta^{13}\text{C}_{\text{leaf}}$  values for woody trees and shrubs from 45 publications and one new study (SI Appendix). We excluded  $\delta^{13}\text{C}_{\text{leaf}}$  values from juvenile, fertilized, or watered plants, immature or shaded leaves, and understory shrubs. All  $\delta^{13}\text{C}_{\text{leaf}}$  values were converted to  $\Delta^{13}\text{C}_{\text{leaf}}$  using the Farquhar et al. (10) equation ( $\Delta_{\text{leaf}} = (\delta^{13}\text{C}_{\text{atm}} - \delta^{13}\text{C}_{\text{leaf}}) / (1 + \delta^{13}\text{C}_{\text{leaf}}/10^3)$ ) and  $\delta^{13}\text{C}_{\text{atm}}$  values estimated for the year of sampling (39) unless reported. Estimating  $\delta^{13}\text{C}_{\text{atm}}$  may cause bias in  $\Delta_{\text{leaf}}$  due to seasonal and latitudinal gradients in  $\delta^{13}\text{C}_{\text{atm}}$ . However, this gradient is <0.5% during the growing season (40). Species means were calculated for each geographic site to remove within-species variability. For a subset of sites where  $\delta^{13}\text{C}_{\text{leaf}}$  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. For each geographic site, environmental factors were extracted from the publication or derived from global databases (SI Appendix) and biome classifications were assigned based on the BIOME4 model, descriptions in the original publication, and environmental factors. We analyzed the data using linear, least squares regression and ANOVA (SAS JMP 7.0).  $\Delta_{\text{leaf}}$  values and latitude are approximately normally distributed. MAP was  $\log_{10}$ -normally distributed and transformed accordingly. Altitude was approximately normally distributed after square root transformation. We performed pairwise comparisons of means using the Tukey-Kramer HSD. Statistics reported within the text and appendices were performed at the site-species combination level, unless otherwise noted ( $n = 570$  or less, depending on the model). Similar results were obtained from statistical models at the site level (SI Appendix) using means for all species at a site ( $n = 73$  or less).

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