Atmospheric CO$_2$ effect on stable carbon isotope composition of terrestrial fossil archives

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The $^{13}$C/$^{12}$C ratio of C$_3$ plant matter is thought to be controlled by the isotopic composition of atmospheric CO$_2$ and stomatal response to environmental conditions, particularly mean annual precipitation (MAP). The effect of CO$_2$ concentration on $^{13}$C/$^{12}$C ratios is currently debated, yet crucial to reconstructing ancient environments and quantifying the carbon cycle. Here we compare high-resolution ice core measurements of atmospheric CO$_2$ with fossil plant and faunal isotope records. We show the effect of pCO$_2$ during the last deglaciation is stronger for gymnosperms ($-1.4 \pm 1.2 \, \permil$) than angiosperms/fauna ($-0.5 \pm 1.5 \, \permil$), while the contributions from changing MAP are $-0.3 \pm 0.6 \, \permil$ and $-0.4 \pm 0.4 \, \permil$, respectively. Previous studies have assumed that plant $^{13}$C/$^{12}$C ratios are mostly determined by MAP, an assumption which is sometimes incorrect in geological time. Atmospheric effects must be taken into account when interpreting terrestrial stable carbon isotopes, with important implications for past environments and climates, and understanding plant responses to climate change.
At present the global mean stable carbon isotope composition of C3 plants (δ\(^{13}\)C), most of Earth’s vegetation, is about −27% relative to VPDB, although δ\(^{13}\)C varies widely between about −22 and −36%\(^{3}\). Understanding the sources of this variation has been the major aim of stable isotope studies of plant physiology and ecology\(^{1,2,4}\). Studies of modern plants\(^{1,3}\) have found that although correlations exist with variables that include plant functional type and altitude, δ\(^{13}\)Cp is most strongly correlated with mean annual precipitation (MAP). Values more positive than about −22% are found in arid and hyperarid regions, whereas values more negative than −31.5% are restricted to closed-canopy tropical forests. However, there is currently no accurate understanding of how plant δ\(^{13}\)Cp varies with past atmospheric CO2 and climate. Nearly thirty years ago, a striking correspondence was first noted between a 4% change in the δ\(^{13}\)Cp of North American trees and the deglacial rise in atmospheric CO2 concentration\(^{6}\). The difference, also identified in fossilised Pinus flexilis needles\(^{2}\) and Japanese conifers\(^{3}\), has been explained by changes in leaf water-use efficiency and stomatal conductance under conditions of changing pCO2\(^{7,9,10}\), which are derived from classical models of photosynthetic fractionation\(^{11,12}\). The complexity of these models is seemingly at odds with experimental data from plant growth chambers obtained by Schubert and Jahren\(^{13}\), who propose a simple alternative model which depends on changes in only two atmospheric variables, i.e. pCO2 and the source isotopic composition of carbon (δ\(^{13}\)CO2). According to this simple model, most of the global change in δ\(^{13}\)Cp of fossil leaves and bulk terrestrial organic matter from the past 30 kyr\(^{14}\) can be explained by the deglacial rise in pCO2. This model has been disputed\(^{15}\) on two bases: first, that the change in δ\(^{13}\)Cp can be completely explained by an increase in MAP, differential organic degradation, and changes in δ\(^{13}\)CO2, and second, that fossil collagen and tooth enamel from the Eocene to the historical era apparently do not discern a pCO2 effect. On the other hand, globally averaged records of speleothem δ\(^{13}\)C appear to support a strong pCO2 dependence over the past 90 kyr\(^{16}\), and the issue is thus unresolved.

An accurate model of the factors which control δ\(^{13}\)Cp is of great importance for understanding CO2 exchange during glacial–interglacial cycles\(^{17}\), evaluation of palaeo-CO2 proxies for timescales beyond the ice-core record\(^{18}\), and investigating CO2 assimilation by the biosphere under future anthropogenic emissions\(^{19}\). There are also fundamental implications for palaeoecology. The average δ\(^{13}\)C of modern C3 plants is around −12.5%\(^{19}\) and the clear difference of −14% between this and the values of C3 plants gained early recognition as an effective method of distinguishing between the two photosynthetic pathways\(^{21,22}\). This difference is also passed onto animal tissues, forming the basis for reconstructions of the diets of ancient fauna and hominins\(^{20,23,24}\). Predictions from models of photosynthetic fractionation, however, suggest that C3 and C4 plants respond differently to changes in global pCO2, and the magnitude and timing of changes to δ\(^{13}\)Cp of each group will differ. Knowing the details of δ\(^{13}\)Cp response to changing atmospheric CO2 is therefore crucial in the interpretation of faunal stable isotope records as proxies of C3 and C4 vegetation cover in mixed environments in deep time\(^{25–27}\) as well as reconstructing environmental parameters such as MAP and/or forest cover in C3 settings\(^{28–30}\).

Here we address the issue by exploring the implications of changes in atmospheric δ\(^{13}\)CO2 and pCO2 for δ\(^{13}\)C proxies from terrestrial archives of carbon. We use recently published high-resolution data for δ\(^{13}\)CCO2 and pCO2 from Antarctic ice cores to compute predictions of δ\(^{13}\)Cp under four different models of photosynthetic fractionation over the past 155 kyr. We then compare model predictions with two high temporal resolution compilations of δ\(^{13}\)C from wood cellulose and faunal collagen which span the last deglaciation, to infer the relative magnitudes of changes due to MAP, pCO2 and δ\(^{13}\)CCO2.

**Results**

**Photosynthetic fractionation over the last glacial cycle.** First, we mathematically model the effects of shifts in pCO2 from 150 to 400 ppmv, over a range of relevant δ\(^{13}\)CCO2 (glacial maxima to present day) to demonstrate the potential magnitude and direction of changes in δ\(^{13}\)Cp. We consider four models which represent different scenarios of plant physiological control on isotope fractionation (Supplementary Fig. 1) in C3 land plants. The first three models are based on the expression developed by Farquhar et al.\(^{11,12}\), which combines fractionations associated with carboxylation and diffusion of CO2 into the leaf:

\[
\delta^{13}C_p = \delta^{13}C_{CO2} - a - (b - a) \frac{c_i}{c_a},
\]

where:

- a = constant
- b = constant
- c_i = constant
- c_a = constant
where \( a \) is the magnitude of fractionation during gaseous diffusion of CO\(_2\) through the lead boundary layer and stomata, and \( b \) is the magnitude of net discrimination during carboxylation in \( C_3\) plants. Both diffusion and carboxylation are dependent on the ratio of leaf intercellular to atmospheric partial pressures of CO\(_2\) (\( c_\text{i}/c_\text{a} \)).

Two of these models assume that \( c_\text{i}/c_\text{a} \) varies linearly with \( c_\text{a} \), but with different gradients for angiosperms and gymnosperms, which are called models “Voelker-2016a” and “Voelker-2016g” respectively (see Methods for details). Motivation for different leaf gas-exchange strategies in these two groups comes from analyses of modern experiments and fossil tree-ring data from the Last Glacial, as well angiosperm leaf waxes and terpenoids from the Paleogene, which consistently show a 2% depletion in \( ^{13}C \) relative to gymnosperm species. For comparison, another model (hereafter “Farquhar-1982”) assumes a leaf gas-exchange strategy where constant \( c_\text{i}/c_\text{a} \) is maintained across the entire range of pCO\(_2\), which is unlikely. Finally, we consider the hyperbolic model (SJ-2012) proposed by Schubert and Jäger, which is based on the expression

\[
\Delta^{13}C = [(A)(B)(pCO_2 + C)]/[A + (B)(pCO_2 + C)],
\]

where \( \Delta^{13}C = (\delta^{13}C_\text{\text{CO}_2} - \delta^{13}C_{\text{\text{p}}})/(1 + \delta^{13}C_{\text{\text{p}}}/1000) \), and \( A \), \( B \), and \( C \) are constants obtained by fitting Eq. (2) to data from modern growth chamber experiments conducted on *Raphanus sativus* and *Arabidopsis* plants, as well as fossil \( \delta^{13}C_{\text{p}} \) from the Last Glacial, which together provides a large range of pCO\(_2\) (180 to 4200 ppmv) and \( \delta^{13}C_{\text{CO}_2} \) (−6.4 to −18.0‰).

To identify the timing and magnitude of expected shifts in \( \delta^{13}C_{\text{p}} \) over the past 155 kyr, we compute the predictions of the four models using Antarctic ice core records of \( \delta^{13}C_{\text{CO}_2} \) and \( \delta^{13}C_{\text{p}} \) (Supplementary Data 1). Our ice core compilation (Fig. 1) makes use of a recently published record \( ^{3} \) which significantly improves the temporal resolution of \( \delta^{13}C_{\text{CO}_2} \) measurements between Terminations I and II, which are already well-represented. These pCO\(_2\) and \( \delta^{13}C_{\text{CO}_2} \) measurements present a near-continuous record, apart from the period between 47–43 kyr BP, where there is disagreement between EPICA Dronning Maud Land and Talos Dome cores.

All models, with the exception of Farquhar-1982, resolve a ∼2.5‰ change in \( \delta^{13}C_{\text{p}} \) due to the anthropogenic isotope effect, and offer similar predictions for future \( \delta^{13}C_{\text{p}} \). However, it is important to note that the models diverge strongly under conditions of low pCO\(_2\). During the period between the Last Glacial and the beginning of the Holocene (11.4 kyr BP), ice cores document an 80 ppmv rise in pCO\(_2\), which is accompanied by fluctuations in \( \delta^{13}C_{\text{CO}_2} \) of up to 0.3‰ (Fig. 1). Over the same period, a change of similar magnitude (i.e. 0.3‰) is predicted in \( \delta^{13}C_{\text{p}} \), by Farquhar-1982, which assumes a negligible pCO\(_2\) effect. The Voelker-2016a and Voelker-2016g models predict a larger change in \( \delta^{13}C_{\text{p}} \) of ∼0.8‰ and ∼0.9‰, respectively. The largest change is predicted by SJ-2012 (∼2.0‰), which is comparable to the recent anthropogenic isotope effect. This is a significant change which is larger than that implied by an hypothetical doubling in MAP (1‰)\( ^{3} \), combined with any changes in \( \delta^{13}C_{\text{CO}_2} \), (<0.3‰) over the LGM/Holocene transition.

Furthermore, the SJ-2012 model predicts high amplitude changes (>1%) in \( \delta^{13}C_{\text{p}} \) during three periods over the past 155 kyr (12–18, 60–62.7, and 129.4–135 kyr). These changes occur at a rate which exceeds 0.25‰/kyr (Fig. 1), excluding the past 130 years, where the change in \( \delta^{13}C_{\text{p}} \) is two orders of magnitude greater (40‰/kyr). The durations of the three pre-Industrial high-amplitude episodes range from 2.7 to 5.6 kyr, and are therefore relatively brief on Quaternary timescales. Interestingly, while two of these episodes can be attributed to the rise in pCO\(_2\) during both glacial terminations, the 1‰ shift in \( \delta^{13}C_{\text{p}} \) predicted by this model between 60 and 62.7 kyr is mainly driven by a 0.5‰ decrease in \( \delta^{13}C_{\text{CO}_2} \), which is accompanied by an increase in CO\(_2\) concentration occurring during Marine Isotope Stage (MIS) 5.

The rates and timings of these predicted changes need to be considered when evaluating the pCO\(_2\) effect from fossil archives. Previous examination of faunal collagen and tooth enamel from the Eocene to the present appears to show no pCO\(_2\) effect\( ^{15} \). However, considering that our analysis shows that high amplitude changes in \( \delta^{13}C_{\text{p}} \) are predicted to occur during relatively brief periods (i.e. ∼2.7–5.6 kyr), and faunal data from previous studies are thinly represented across several million years, it is unlikely that they provide the necessary temporal resolution to discern a possible pCO\(_2\) effect. In other words, beyond the limit of radiocarbon dating (<50 kyr), fossil archives will have minimum age uncertainties of several thousand years, which makes evaluation of the pCO\(_2\) effect impossible. Our analysis reveals that the only period during which the effect would be statistically distinguishable is the last deglaciation, when radiocarbon methods offer sufficient dating precision (<50–300 yr. 1σ).

Comparison with plant and faunal isotope archives. To test each model we compile a record of \( \delta^{13}C_{\text{p}} \), which is based on 720 samples of radiocarbon-dated wood cellulose from the Northern Hemisphere, spanning the last deglaciation (Fig. 2). We also compile 521 \( ^{13}C \) values of well-dated herbivore collagen from predominantly \( C_3 \) locations in northwestern Europe and northern Eurasia. Since this compilation is biased towards these regions, and herbivore diets are selective, the faunal record will not always reflect the ‘average’ composition of plants in an ecosystem. Additionally, our cellulose data are over-represented by woody species from temperate northern latitudes. Therefore, to make these very widely dispersed samples comparable, we adopt a strategy of adjusting both cellulose and collagen \( ^{13}C \) records for geometrical variability in latitude, altitude and MAP (see Methods). When we adjust for geographical variability in this way (Fig. 2) the amplitude of changes across the LGM/Holocene transition is reduced from 1.41 to 0.93‰ (fauna) and 3.54 to 2.77‰ (plants). Therefore, the residual effect appears different for both cellulose and collagen. Note that our faunal data show greater scatter than our cellulose records, but the shift in \( ^{13}C \) between <10 and >20 kyr faunal data is statistically significant (one-sided paired sample t-test, \( t = -5.9, p = 5.2 \times 10^{-8}, \alpha = 0.05 \).

We hypothesise that the residual isotopic changes in adjusted cellulose and collagen records through time consist of two components: first, changing atmospheric chemistry, and second, changes in MAP, which are reasonably described by the regressions of Kohn\(^{1} \). Under this assumption we are able to constrain the pCO\(_2\) effect after correcting adjusted \( \delta^{13}C_{\text{p}} \) for the effect of changing MAP between <10 and >20 kyr, which we infer from an ensemble of coupled atmosphere-ocean general circulation models (GCMs, see Methods for further details). Note that these corrections are different from our adjustments for geographical variability; whilst the latter only adjust for geographical bias, the former correct for changes through time. We find that in most cases (~90% for fauna, ~95% for plants) the PMIP3-CMIP5 ensemble model predicts a change to wetter conditions during the Holocene. The average effect of MAP on the isotopic signal, constrained by GCMs, is therefore negative for both plants and fauna (Fig. 3b, c). The effect of faunal records, confined to Eurasia, is ~0.4 ± 0.88‰, which is larger than both gymnosperms (~0.27 ± 0.53‰) and all plants (~0.13 ± 0.74‰) but smaller than plants from North America (~0.46 ± 0.88‰).
Our corrections for changes in MAP imply a residual pCO2 effect during the deglacial rise in CO2 (~80.5 ppmv) of ~0.53‰ for fauna, or equivalently ~0.7 ± 1.9‰ per 100 ppmv (Fig. 3a). Only gymnosperm species are represented across our entire plant cellulose compilation, and these species distinguish a larger pCO2 effect changes in pCO2 (in addition to changing MAP), but with different magnitudes. Our fauna primarily reflect a dietary contribution from angiosperms, whereas our plant compilation is biased towards gymnosperm species at the LGM. We suggest that the disagreement between our plant and faunal records is likely caused by a genuine physiological difference in leaf gas-exchange strategy between angiosperm and gymnosperm plants.

The magnitudes of the pCO2 effect implied by our data are consistent with models of photosynthesis which predict a dynamic leaf gas-exchange strategy, and a variable ratio of intercellular to atmospheric pCO2 over the 180–400 ppmv range. This is less than that proposed by Breecker16 for speleothems, −1.6 ± 0.3‰ per 100 ppmv (1σ), but greater than that proposed by Kohn15 for fossil collagen, −0.03 ± 0.13‰ per 100 ppmv (2 s.e., see Fig. 3a). We suggest the latter discrepancy is due to the limited temporal resolution of that data set, which is neither large enough nor sufficiently well dated to resolve millennial-scale shifts in δ13C.

With respect to our gymnosperm cellulose record, we find that δ13C (adjusted for geographical variability) is best described by SJ-2012 and Voelker-2016g (SJ-2012; RMSE = 1.07, AIC = 25, BIC = 31; Voelker-2016g; RMSE = 1.04, AIC = 26, BIC = 34). This is not surprising because SJ-2012 is biased towards gymnosperm palaeo-data below ~350 ppmv. Our faunal analysis shows that the SJ-2012 model leads to an overestimation of the pCO2 effect for other plants and fauna, particularly at periods of low concentration. Therefore, although this model may be appropriate for gymnosperms, we suggest that SJ-2012 should not be used as a baseline to infer changes in angiosperm plants and hence the majority of ancient fauna. With respect to these records, the Voelker-2016a model best reproduces the magnitude of the deglacial shift observed in fauna (~0.53‰, Supplementary Table 4), but is offset from all cellulose records. The ~1.4‰ offset is probably related to our choice of a and b constants, and/or inaccuracies in the fitted relationship between cδ13C and cφ. Another alternative is some hitherto unknown subtlety of the isotopic relationship between fauna and bulk diet. This last scenario is unlikely because the difference between the cellulose and collagen records, averaged over the Holocene, imply an average collagen-diet enrichment factor consistent with the value of 5.1‰ determined from modern controlled-feeding studies35–37, after factoring in the ~1‰ isotopic offset between cellulose and bulk leaf tissue (faunal diet)38. Further chamber and palaeo-data from angiosperm plants, across a wider range of pCO2, might be needed to shed light on the other explanations.

Discussion
Faunal δ13C studies have been used to interpret changes in forest cover across Western Europe during the last deglaciation. For example, isotopic analysis of late Pleistocene roe deer in northern France show a range from ~19.0 to ~20.9‰, and a shift to values more negative than ~22.5‰ during the Holocene has been used to infer the presence of a ‘canopy effect’ on faunal δ13C during the deglaciation, considering only a correction for past changes in δ13C(CO2)39. This, if pCO2 effects are negligible. Although similar interpretations have been challenged28, 29, 40, presently the canopy effect and water availability are more frequently cited as the driving parameter behind δ13C trends of western European fauna during the late Pleistocene/Holocene transition30, 41.

Given the pCO2 effect displayed by our data, a cutoff of ~22.5‰ would overestimate the extent of the canopy effect on faunal δ13C. Values more negative than ~22.5‰ also reflect the postglacial rise in pCO2, via its effect on carbon isotope fractionation in C3 plants. The extent to which a genuine canopy effect is also reflected in our faunal record is difficult to determine. However, it is unlikely to be significant. First, there are no strong differences in δ13C across different species during the Holocene (species show similar means at approximately ~21.7‰, when adjusted for geographical variability). The opposite result would be expected from a canopy effect, as only some of our species are forest-dwelling. Second, modern studies from temperate woodlands show limited effects on faunal δ13C, even when a canopy effect is present in vegetation42. However, the possibility of some small contribution from changing canopy cover is difficult to fully exclude, therefore our pCO2 effect for fauna is a maximum estimate. Considering the multiple lines of evidence, including plant chamber experiments and the fossil record, it is now more plausible to believe that shifts in terrestrial δ13C during the last deglaciation primarily reflect changes in pCO2, along with smaller contributions from changing MAP and possibly increased canopy

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**Fig. 2** Stable carbon isotope composition of terrestrial fossil archives over the last deglaciation, from predominantly C3 ecosystems. a Faunal collagen from northwestern Europe and northern Eurasia from 33.4 kyr BP to early 20th century. Light red circles show δ13C before adjustment for MAP, altitude and latitude. Dark red circles show adjusted δ13C, based on the regressions of Kohn1. Dark black lines indicate adjusted means of faunal δ13C before 20 kyr and after 10 kyr, which are ~20.85‰ and ~21.78‰, respectively. b Plant cellulose δ13Cp records from the Northern Hemisphere, 40.5 kyr BP to early 20th century, with model curves. Colour codes match legend in Fig. 1: light green, SJ-2012; blue, Voelker-2016g; dashed yellow, Farquhar-1982. SJ-2012 model is shown with 1σ propagated uncertainties. Dark blue squares show gymnosperm data used for geographic variability in MAP, altitude, and latitude. Light blue squares show raw cellulose data before adjustment. Filled white circles and grey circles show mixed species (either angiosperm or unidentified) before and after adjustment for geographic variability, respectively.
cover. Our finding is supported by analysis of ancient and modern δ13C from wolves and bison bone collagen, which show strong correlations between pCO2 and δ13C.

More generally, we propose that similarly rapid shifts in the carbon isotope baseline of C3 plants need to be considered throughout the Quaternary, particularly during periods of low pCO2, when atmospheric effects on photosynthetic fractionation are magnified. Faunal isotopes from predominantly C3 and mixed C3/C4 environments are routinely used to infer regional ecologies, under the assumption that δ13C mainly reflects growing season, mean annual temperature and MAP. We urge caution in this approach, since our analysis shows that shifts in terrestrial archives may simply reflect rapidly changing atmospheric chemistry, and not other environmental variables. Beyond the Quaternary, there is also evidence to suggest that other atmospheric variables may lead to significant changes in the carbon isotope baseline in deep time. Plant chamber experiments have revealed strong relationships between carbon isotope discrimination and changing pO2, since Rubisco also as an affinity for oxygen. Whilst potentially relevant to geological periods of subambient or elevated pO2, the influence of oxygen on plant δ13C is probably minimal during the Quaternary because pO2 levels remained relatively stable over much of this period. The short-term shifts we observe on millennial timescales are therefore more likely due to changes in pO2. In future, pCO2- and possibly O2-dependent models of carbon isotope fractionation should be used together with the regressions of Kohn to reconstruct changes in MAP or other atmospheric variables using ensembles of terrestrial archives. Rapid advancements in ice core measurements may help extend this approach further back in time, and offer more accurate tools for the reconstruction of ancient environments. Finally, there is now an intriguing body of evidence, which reveals strong phylogenetic differences in the carbon isotope response of plants to atmospheric extrema, but it is clear that several questions remain about the precise nature of these relationships. There is an urgent need for improved comprehensive models of photosynthetic fractionation, which are essential for pCO2 reconstruction beyond ice core records, as well as predicting uptake of future anthropogenic CO2 emissions by the terrestrial biosphere.

**Methods**

**Materials.** Plant δ13C records were compiled from previously published studies of tree wood and Pinus needles, which were all pretreated to α-cellulose, with the exception of more recent wood samples, which were pretreated using standard acid–base–acid (ABA) protocols. Radiocarbon dates of collagen and plants were calibrated using OxCal v. 4.2.44 using the IntCal13 calibration curve whenever raw radiocarbon determinations were reported, and reported in kyr BP (where BP = 1950 CE). Faunal collagen δ13C was compiled from the Oxford Radiocarbon Accelerator database as well as other previously published sources, are presented in Supplementary Data 1 (see also Supplementary Fig. 2). We selected herbivore cellulose from predominantly C3 environments (all >90%, most >99.5% according to ref. 55), excluding Reindeer (Rangifer tarandus) and other species known to consume large amounts of lichen. Over half our record comprises grazing and browsing ungulates (Supplementary Fig. 3), e.g. Cervus spp. (19%), Bos spp. (24%) and Equus spp. (17%).

![Fig. 3 Effect of atmospheric pCO2 on mean stable carbon isotope composition over the last deglaciation, determined from terrestrial records and from changes in MAP. a Magnitude of pCO2 effect predicted by models and palaeo-data. Error bars for models, fauna, and gymnosperms (all this study) and speleothems are 1σ propagated uncertainties, and 2 s.e. for fauna from Kohn. b Changes in MAP predicted by PMIP3-CMIP5 multi-model ensemble between the LGM and mid-Holocene, used to constrain the pCO2 effect on our data set. c Geographical distribution of our data, showing the magnitude of MAP changes predicted by the multi-model ensemble over the same time period.](image-url)
Adjustments for geographic variability. Collagen and cellulose δ13C values were adjusted to MAP = 1000 mm, altitude = 840 m, latitude = −50 °N, using Eq. (1) of Kohli et al.34. Following this, we corrected the altitude (m) for each location according to the GTOPO30 digital elevation model, available at https://lta.cr.usgs.gov/GTOPO30 (Accessed 13 Nov 2016). We also calculated modern globally averaged precipitation for each location according to the WorldClim v. 1.4 model35, averaged over the period 1960–1990 AD36. We calculated adjusted values according to

\[ \delta_{13C_{\text{adj}}} = \delta_{13C_{\text{p}}} + \Delta \left( \frac{\delta_{13C_{\text{p}}}}{C_{0}/C_{1}} \right) - \Delta \left( \frac{\delta_{13C_{\text{p}}}}{C_{0}/C_{1}} \right) \]

Since it reproduced the modern globally averaged value of −27.1%o, it is unlikely that plants employ a strategy of constant c/ε or atmospheric δ13C as an intermediate control on δ13Cp. We have compared the four models with both our cellulose record and our faunal record. To model the carbon isotope discrimination and the intercellular carbon dioxide concentration from the Law Dome and South Pole70. Pre-industrial records were synchronised on the AICC2012 timescale. We obtained a Monte Carlo smoothing spline according to the procedure outlined in ref. 60. We performed 1000 replicate cubic spline fits to the entire data series, with input data picked randomly from the 1σ error range, and applied a 375 yr cutoff period to exclude high-frequency noise. Records for the anthropogenic era from the Law Dome and South Pole are presented on the age scale of ref. 70, cubic splined without a cutoff period, and then combined with the pre-industrial curve. The curve obtained for the pre-industrial δ13CCO2 records was taken from ref. 62. We used a similar procedure, synchronised on the AICC2012 timescale, as well as incorporating records from the Law Dome and South Pole.

Data availability. Model output and all data used in the current study are made available in the figshare repository, 10.6084/m9.figshare.5497918. Additionally, radiocarbon dates may be queried using the OxCal database, where appropriate: https://c14.arch.ox.ac.uk/database/db.php?page=oxaResult.

Received: 6 April 2017 Accepted: 19 December 2017 Published online: 17 January 2018

Models of photosynthetic fractionation. We computed four models as follows: model 1 (Farquhar-1982) was Eq. (1) with a constant c/ε ratio chosen of 0.6. Although it is unlikely that plants employ a strategy of constant c/ε or atmospheric δ13C as an intermediate control on δ13Cp, since it reproduced the modern globally averaged δ13CCO2 value from ref. 1 of −27.1‰. Model 2 (Voelker-2016) was calculated as Eq. (1) modified by a linear dependence of c/ε on δ, for 

\[ \delta_{13C_{\text{p}}} = \delta_{13C_{\text{p}}} + \Delta \left( \frac{\delta_{13C_{\text{p}}}}{C_{0}/C_{1}} \right) \]

For b, we used a value of 28.2‰, which also reasonably reproduces modern globally averaged δ13CCO2 using Voelker-2016. It should be noted that Eq. (1) is a simplification of an expanded and refined equation given in ref. 3, that incorporates dissolution of CO2 in solution, and diffusion inside the leaf, as well as discriminations associated with dark respiration and photorespiration. Surprisingly little discussion has been made as to the possible influence of the effects of photorespiration and dark respiration in deep time, which should also exhibit a strong dependence on C3/C4 (i.e. magnified at low C3). These components are intrinsically difficult to measure in modern plants. We assumed both effects were negligible. We think omission is justified, since these terms imply a shift in the carbon isotope composition of terrestrial C3 plants which is unreasonable in magnitude (−3−4‰), and in the wrong direction (i.e. a depletion in δ13C at the LGM relative to Holocene values). For all three of these models, we used a value of 0.00038 ± 0.00032, based on arguments of the diffusivity of atmospheric CO2, which is proportional to the square root of the reduced masses of the two isotopologues 13CO2 and 12CO2.

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Acknowledgements
We thank Sarah Eggleston, Ben Hmiel, Lee Murray, and Vinesh Rajpaul for their advice, and Patrick Roberts for his suggestions and critical reading. The manuscript was much improved by the constructive comments of the anonymous reviewers. V.J.H. and E.L. received support from the Clarendon Fund, University of Oxford. We acknowledge support from the UK Natural Environment Research Council (NERC) for the Oxford node of the national NERC Radiocarbon facility. Open access fees were kindly provided by Oxford University’s RCUK Open Access Block Grant. We also acknowledge the World Climate Research Programme’s Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output.

Author contributions
V.J.H. designed research, E.L., A.J. and C.B.R. assisted research. V.H. analysed the data and wrote the paper with input from all authors.

Additional information
Supplementary Information accompanies this paper at https://doi.org/10.1038/s41467-017-02691-x.

Competing interests: The authors declare no competing financial interests.

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