Intramolecular carbon isotope signals reflect metabolite allocation in plants

Thomas Wieloch1*, Thomas David Sharkey2*, Roland Anton Werner3 and Jürgen Schleucher1

1 Department of Medical Biochemistry and Biophysics, Umeå University, 901 87 Umeå, Sweden
2 MSU-DOE Plant Research Laboratory, Plant Resilience Institute, and Department of Biochemistry and Molecular Biology, Michigan State University, East Lansing, MI 48824, USA
3 Department of Environmental Systems Science, ETH Zürich, Universitätstrasse 2, 8092 Zürich, Switzerland

* Correspondence: thomas.wieloch@umu.se

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Abstract

Stable isotopes at natural abundance are key tools to study physiological processes occurring outside the temporal scope of manipulation and monitoring experiments. Whole-molecule carbon isotope ratios (13C/12C) enable assessments of plant carbon uptake yet conceal information about carbon allocation. Here, we identify an intramolecular 13C/12C signal at tree-ring glucose C-5 and C-6 and develop experimentally testable theories on its origin. More specifically, we assess the potential of processes within C3 metabolism for signal introduction based (inter alia) on constraints on signal propagation posed by metabolic networks. We propose that the intramolecular signal reports carbon allocation into major metabolic pathways in actively photosynthesizing leaf cells including the anaplerotic, shikimate, and non-mevalonate pathway. We support our theoretical framework by linking it to previously reported whole-molecule 13C/12C increases in cellulose of ozone-treated Betula pendula and a highly significant relationship between the intramolecular signal and tropospheric ozone concentration. Our theory postulates a pronounced preference for leaf cytosolic triose-phosphate isomerase to catalyse the forward reaction (dihydroxyacetone phosphate to glyceraldehyde 3-phosphate). In conclusion, intramolecular 13C/12C analysis resolves information about carbon uptake and allocation enabling more comprehensive assessments of carbon metabolism than whole-molecule 13C/12C analysis.

Keywords: Carbon allocation, carbon stable isotopes, intramolecular isotope analysis, long time scales, ozone stress, primary carbon metabolism, triose-phosphate isomerase.

Introduction

Plant carbon metabolism is a central component of the global carbon cycle. It both depends on and affects environmental properties. Improved understanding of long-term plant–environment interactions relies on information from plant archives (such as tree rings) because manipulation and monitoring experiments can only cover short to medium time scales. Stable carbon isotope (13C/12C) analysis is among the most advanced tools to extract physiological and environmental information.
Intramolecular $^{13}$C signals reflect metabolite allocation

from plant archives. Conventionally, average $^{13}$C/$^{12}$C ratios of whole-plant metabolites are analysed. However, this approach neglects $^{13}$C/$^{12}$C differences known to occur among individual carbon positions of plant metabolites (Abelson and Hoering, 1961). In contrast, we recently analysed intramolecular $^{13}$C/$^{12}$C ratios in glucose extracted across an annually resolved *Pinus nigra* tree-ring time series (1961–1995) and reported intramolecular $^{13}$C signals (i.e. systematic $^{13}$C/$^{12}$C variation confined to individual glucose carbon positions; Wieloch *et al.*, 2018). Only after their ecophysiological origins have been elucidated can these archived signals become useful for applications within the plant and Earth sciences.

Based on our previous dataset (Wieloch *et al.*, 2018), we have already pinpointed a $^{13}$C signal at tree-ring glucose C-4 and proposed that it informs about carbon flux around leaf cytosolic glyceraldehyde–3-phosphate dehydrogenases and associated energy metabolism (Wieloch, 2021; Wieloch *et al.*, 2021). Here, we utilize the same dataset to isolate a $^{13}$C signal at tree-ring glucose C-5 and C-6. Since intramolecular $^{13}$C variation is governed (*inter alia*) by enzyme isotope effects and metabolite partitioning (Hayes, 2001), we hypothesize that the signal can be linked to shifts in carbon allocation and underlying environmental controls. Thus, we develop experimentally testable theories on ecophysiological mechanisms that can introduce the signal at glucose C-5 and C-6. To this end, we consider all enzyme reactions within central carbon metabolism of C$_3$ plants. This includes the Calvin–Benson cycle (CBC), the photosynthetic carbon oxidation (PCO) cycle, starch and sucrose synthesis and degradation, cellulose synthesis, the pentose phosphate pathway, glycolysis, and carbon metabolism downstream of phosphoenolpyruvate (PEP). Carbon exchange between other biochemical pathways and the pathway leading to the formation of tree-ring glucose are presumably small, particularly when integrated over the course of growing seasons, the time frame of tree-ring formation. Thus, these processes cannot introduce $^{13}$C signals of substantial size into tree-ring archives. Furthermore, we only consider primary isotope effects (which occur at atoms with altered binding after chemical reactions). Sizes of secondary isotope effects (which occur at atoms with unaltered binding after chemical reactions due to indirect involvement in reaction mechanisms) are usually small and therefore unlikely to introduce detectable $^{13}$C signals into tree-ring archives. Finally, we present evidence supporting our theory. For this part, we reanalyse our own tree-ring dataset (Wieloch *et al.*, 2018) in combination with publicly accessible climate data and $^{13}$C/$^{12}$C data from an ozone treatment experiment published by Saurer *et al.* (1995).

We distinguish two major types of $^{13}$C fractionation: diffusion–Rubisco fractionation, and post–Rubisco fractionation (Wieloch *et al.*, 2018). Diffusion–Rubisco fractionation accompanies CO$_2$ diffusion from ambient air into plant chloroplasts and subsequent carbon fixation by Rubisco (Figs 1, 2; Farquhar *et al.*, 1982). It affects all carbon positions of plant glucose equally (Wieloch *et al.*, 2018). In contrast, post-Rubisco fractionation results from metabolic processes downstream of Rubisco and is position specific (Figs 1–3). Deconvolution of the two fractionation types requires the intramolecular approach.

Our work makes several conceptual advances. (i) We show how constraints on signal propagation posed by metabolic networks can be used to narrow down signal origins. (ii) A conceptual model describes how the signal propagates from its origin to other glucose carbon positions and metabolite pools. Due to space restrictions, this model is presented in Supplementary Protocol S1. (iii) We revise current theory on plant isotope fractionation by ozone exposure. (iv) The present paper and a companion paper on the C-4 signal (Wieloch *et al.*, 2021) develop theories that consider all relevant parts of metabolism and link intramolecular $^{13}$C signals with specific shifts in carbon allocation and their environmental causes. For isotope signals generated within complex metabolic networks, such comprehensive theories are required as a starting point for subsequent tailored experimental tests.

### Materials and methods

Intramolecular $^{13}$C/$^{12}$C ratios in tree-ring glucose of *P. nigra* from Vienna (Austria) were reported in Wieloch *et al.* (2018). They are expressed in terms of intramolecular $^{13}$C discrimination, $\Delta_i$, where $i$ denotes individual carbon positions in tree-ring glucose (Wieloch *et al.*, 2018; abbreviations and symbols are given in Table 1). In this notation, positive values denote discrimination against $^{13}$C. The prime denotes measurements subjected to a procedure that removes the $^{13}$C redistribution effect by triose phosphate cycling (Supplementary Protocol S2; Wieloch *et al.*, 2018). This correction restores leaf-level $^{13}$C signals. The dataset comprises six annually resolved time series (one per glucose carbon) each covering the period 1961–1995 and containing 31 time points ($n=6\times31=186$).

Additionally, we reanalysed published differences in intercellular CO$_2$ concentration, $\Delta C$, and whole-molecule $^{13}$C abundance, $\Delta \delta^{13}C_p$, between ozone-treated and control plants of *Betula pendula* grown in 1992 (Table 2; 90/40 nl O$_3$/l day/night versus <3 nl O$_3$/l; Saurer *et al.*, 1995). These authors used two different methods to determine $\Delta C$. Here, we calculated $\Delta C$. Corresponding differences in $^{13}$C discrimination by the diffusion–Rubisco interface were estimated as

$$\Delta \Delta_{\text{DR}} = (b - a) \Delta C_i / C_a$$

(1)

where $a$ and $b$ denote discrimination factors of CO$_2$ diffusion (4.4%) and Rubisco carboxylation (29%), respectively, and $C_a$ denotes atmospheric CO$_2$ concentration (356 ppm in 1992; Farquhar *et al.*, 1982). Reported $\Delta \delta^{13}C_p$ values (Table 2) were transformed to $\Delta \Delta$ values as

$$\Delta \Delta = \frac{R_s}{R_s + \Delta R_p} - 1$$

(2)

where $R_s$ denotes the $^{13}$C/$^{12}$C ratio of atmospheric CO$_2$, and $\Delta R_p$ denotes the difference in $^{13}$C/$^{12}$C ratios between ozone-treated and control plants. To utilize $\Delta \delta^{13}C_p$ values reported in per mill, we transformed Equation 2 as

$$\Delta \Delta = \frac{\delta^{13}C_p/1000 + 1}{\delta^{13}C_p/1000 + \Delta \delta^{13}C_p/1000 + 1} - 1$$

(3)
where $\delta^{13}C_1$ denotes the $^{13}C$ abundance of atmospheric $CO_2$ (−8‰ in 1992; Leuenberger, 2007).

For the regression analysis and linear modelling, we used $^{13}C/^{12}C$ data from Wieloch et al. (2018) and publicly accessible climate data. Data of sunshine duration (SD) and relative humidity ($rh$) were acquired from the climate station Hohe Warte in Vienna (Klein Tank et al., 2002). Tropospheric ozone concentrations, [O$_3$], were acquired from Stephansplatz, Laaer Berg, Hermannskogel, Hohe Warte, and Lobau (City of Vienna, Municipal Department 22).
Fig. 2. Formation and cleavage of bonds involving carbon atoms in central carbon metabolism. Carbon numbering is according to carbon positions in tree-ring glucose. Metabolites: 1,3BPGA, 1,3-bisphosphoglycerate; 3PGA, 3-phosphoglycerate; DHAP, dihydroxyacetone phosphate; FBP, fructose 1,6-bisphosphate; GAP, glyceraldehyde 3-phosphate; Pi, inorganic phosphate; RuBP, ribulose 1,5-bisphosphate. Numbers in parentheses denote enzymes: (1) Rubisco; (2) TPI, triose-phosphate isomerase; (3) aldolase, fructose-bisphosphate aldolase; (4) np-GAPDH, irreversible non-phosphorylating glyceraldehyde-3-phosphate dehydrogenase; (5) p-GAPDH, reversible phosphorylating glyceraldehyde-3-phosphate dehydrogenase; (6) PGK, phosphoglycerate kinase.
Results and discussion

Tree-ring glucose exhibits a post-Rubisco signal at C-5 and C-6

Figure 4 shows results of a hierarchical cluster analysis which groups $\Delta_i'$ time series according to co-variability (Wieloch et al., 2018); that is, $\Delta_i'$ time series carrying common $^{13}$C signals form clusters. Primary separation occurs between the $\Delta_i'$ to $\Delta_3'$ cluster and the $\Delta_4'$ to $\Delta_6'$ cluster. Average time series pertaining to these clusters are entirely uncorrelated ($r=0.08$, $P>0.65$, $n=31$). Thus, these clusters convey entirely different ecophysiological information. Wieloch et al. (2018) justified the use of air vapour pressure deficit (VPD) as a proxy of diffusion–Rubisco fractionation. While the average time series of the $\Delta_5'$ to $\Delta_9'$ cluster correlates highly significantly with VPD ($r=-0.70$, $P=0.00001$, $n=31$), the average time series of the $\Delta_3'$ to $\Delta_9'$ cluster is not significantly correlated ($r=-0.30$, $P>0.05$, $n=31$). This indicates...
that the diffusion–Rubisco signal is preserved at glucose C-1 to C-3 but not at C-4 to C-6. Among all Δᵢ, Δ₅ and Δ₆ exhibit the most significant correlation (r=0.61, P≤0.001, n=31). Since the diffusion–Rubisco signal is confined to glucose C-1 to C-3, we argue that C-5 and C-6 exhibit a strong post-Rubisco signal denoted the Δ₅-₆ signal.

**Exclusion of metabolic locations as origin of the Δ₅-₆ signal**

Much is known about plant carbon metabolism. Based on this knowledge, we can exclude several metabolic locations as the origin of the Δ₅-₆ signal as a first step in development of the
Significance levels of differences between ozone-treated and control plants: $P \leq 0.05$; $^* P \leq 0.01$; $^*^* P \leq 0.001$.

### Table 2. Reanalysed data originally published by Saurer et al. (1995)

|          | C/LF     | O3/LF    | C/HF     | O3/HF    |
|----------|----------|----------|----------|----------|
| $\Delta C_{\text{p}}$ (ppm) | $0.008 \pm 0.002$ | $0.013 \pm 0.007^***$ | $0.014 \pm 0.005$ | $0.017 \pm 0.005^*$ |
| Steady state | $10 \pm 16^*$ | $5 \pm 28$ | $O_{3}/L_{F} \cdot C/L_{F}$ | $O_{3}/H_{F} \cdot C/H_{F}$ |
| Diurnal course | $1.1 \pm 0.7^*$ | $1.3 \pm 0.6^*$ | $0.4 \pm 0.9$ | $1.1 \pm 0.6^*$ |

Treatments: control group, C (<3 nl O$_3$ l$^{-1}$); ozone-treated group, O$_3$ (90/40 nl O$_3$ l$^{-1}$ day/night); low fertilization, LF; high fertilization, HF. $\beta$ denotes the carboxylation rate of phosphoenolpyruvate carboxylase relative to the total carboxylation rate of phosphoenolpyruvate carboxylase and Rubisco measured in vitro. $\Delta C_{\text{p}}$ denotes differences in leaf intercellular CO$_2$ concentrations between ozone-treated and control plants measured by two different methods (‘steady state’ and ‘diurnal course’). $\Delta \delta^{13} C_{\text{p}}$ denotes differences in carbon isotope ratios between ozone-treated and control plants in leaf and stem cellulose. Significance levels of differences between ozone-treated and control plants: $^* P \leq 0.05$; $^*^* P \leq 0.01$; $^*^*^* P \leq 0.001$.

**Fig. 4.** Clustering of $\Delta_i'$ time series due to co-variability. $\Delta_i'$ denotes time series of intramolecular $^{13}$C discrimination corrected for triose phosphate cycling (Wieloch et al., 2018). Red: time series discussed here. Data were measured on tree-ring glucose of Pinus nigra laid down from 1961 to 1995 at a dry site in the Vienna basin ($n=8 \times 31$). Members of clusters marked by asterisks are correlated at the following significance levels: $^* P \leq 0.05$; $^*^* P \leq 0.01$; and $^*^*^* P \leq 0.001$. Precursors of tree-ring glucose, dihydroxyacetone phosphate (DHAP), and glyceraldehyde 3-phosphate (GAP) are shown as molecular structures. Modified figure from Wieloch et al. (2018).

theory. Note that the $\Delta_{3-6}'$ signal is introduced at the level of three-carbon compounds because reactions at other levels do not modify carbon bonds that become glucose C-5 and C-6.

Exclusion of the tree-ring cell as origin of the $\Delta_{5-6}'$ signal

$^{13}$C labelling experiments provide compelling evidence for a complete or near-complete equilibration of triose phosphates in tree-ring cells of Quercus robur (Figs 1, 2; Hill et al., 1995). Numerous similar reports for other species and tissues suggest that triose phosphates in the cytosol of heterotrophic tissues are generally substantially equilibrated (Brown and Neish, 1954; Edelman et al., 1955; Neish, 1955, 1958; Shafizadeh and Wollfrom, 1955; Altermatt and Neish, 1956; Seegmüller et al., 1956; Shibko and Edelman, 1957; McConnell et al., 1958; Wollfrom et al., 1959; Keeling et al., 1988; Hatzfeld and Stitt, 1990; Viola et al., 1991). Only two $^{13}$C labelling studies report no evidence of substantial heterotrophic triose phosphate equilibration (Greathouse, 1953; Kikuta and Erickson, 1969). However, these authors analysed tissues during stages of exceptionally rapid fruit development with either high hexose phosphate flux into cotton-boll cellulose or high triose phosphate flux into avocado lipids (Greathouse, 1953; Brown and Neish, 1954; Kikuta and Erickson, 1969). Taken together, these reports suggest that heterotrophic triose phosphates are generally substantially equilibrated during normal growth.

The raw dataset of intramolecular $^{13}$C discrimination, $\Delta_i$, in tree-ring glucose (Wieloch et al., 2018) exhibits significant correlations among all pairs of symmetry-related time series (Table 3); that is, significant correlations occur between $\Delta_1$ and $\Delta_n$, $\Delta_2$ and $\Delta_n$, $\Delta_3$ and $\Delta_n$, and $\Delta_4$ and $\Delta_n$. These correlations probably result from carbon redistribution by triose phosphate cycling (TPC) which involves triose phosphate equilibration. Wieloch et al. (2018) describe this process mathematically and used the model to remove the TPC effect from $\Delta_i$, yielding a TPC-free dataset, $\Delta_i'$. In this latter dataset, significant correlations among pairs of symmetry-related time series are absent (Table 4). This provides strong evidence for the occurrence of substantial triose phosphate equilibration in tree-ring cells of the samples discussed here.

If a process in tree-ring cells had introduced a signal at carbon positions corresponding to glucose C-5 and C-6, triose phosphate equilibration would have transmitted it to carbon positions corresponding to glucose C-2 and C-1. The signal at C-5 would have had the same size as the signal at C-2, and the signal at C-6 would have had the same size as the signal at C-1. Please note that equally sized signals at symmetry-related glucose carbon positions are not removed by the method.
reaction is strongly on the side of pyruvate and considered nearly irreversible (Nageswara Rao et al., 1979; Tcherkez et al., 2011). In illuminated leaves of C₃ plants, PPDK activity is either very low or undetectable, except for orchids and grasses (Hocking and Anderson, 1986). In illuminated leaves of Xanthium strumarium, flux from pyruvate to PEP is very small at ~0.05% of net CO₂ assimilation (Tcherkez et al., 2011). In Arabidopsis thaliana, PPDK is up-regulated during leaf senescence which is believed to facilitate nitrogen remobilization (Taylor et al., 2010). This is of minor importance here because leaf senescence occurs during a short period relative to the multiyear life span of conifer needles. In Nicotiana tabacum, PPDK activity is increased up to 2.7-fold under strong drought (Doubnerová Hýsková et al., 2014). However, this should not result in significant flux in relation to fluxes in carbohydrate metabolism since basal PPDK activities in C₃ plants are generally low (Hocking and Anderson, 1986; Tcherkez et al., 2011). Thus, flux from pyruvate to PEP should be small, and transmission of ¹³C signals in pyruvate to cytosolic carbohydrates by the PK/PPDK interface should be negligible.

Phosphoenolpyruvate carboxylase (PEPC) and phosphoenolpyruvate carboxykinase (PEPCK) interconvert PEP and oxaloacetate (OAA). Conversion of PEP to OAA by PEPCK is irreversible (Chollet et al., 1996). To our knowledge, there are no reports of PEPCK activity in mesophyll cells where bulk carbohydrate synthesis takes place (Pyke, 2001). PEPCK RNA and protein were not detected in leaves of Solanum lycopersicum irrespective of their developmental stage (Bahrani et al., 2001; Famiani et al., 2016). PEPCK protein or activity were not detected in leaves of Hordeum vulgare (Chen et al., 2000). In mature leaves of A. thaliana, PEPCK protein amount and activity are low and probably confined to specific cell types (Malone et al., 2007). In leaves of N. tabacum, PEPCK occurs in trichomes and stomata (Leegood et al., 1999; Malone et al., 2007). In leaves of Cucumis sativus, PEPCK occurs in trichomes and phloem cells (Leegood et al., 1999; Chen et al., 2004). In leaves of Oryza sativa, PEPCK occurs in hydathodes, stomata, and the vascular parenchyma (Bailey and Leegood, 2016). Thus, transmission of ¹³C signals in OAA to cytosolic carbohydrates by the PEPC/PEPK interface should not occur.

3-Deoxy-d-arabino-heptulosonate 7-phosphate synthase (DAHS) catalyses the irreversible reaction from PEP and erythrose 4-phosphate (E4P) to 3-deoxy-d-arabino-heptulosononic acid 7-phosphate (DAHP; Herrmann, 1995). To our knowledge, there are no reports of enzymes catalysing the back reaction. Thus, transmission of ¹³C signals in DAHP to cytosolic carbohydrates should not occur.

Taken together, leaf-level carbon fluxes from OAA, pyruvate, and DAHP to PEP are negligible or absent (Figs 1, 3). Therefore, reactions downstream of OAA, pyruvate, and DAHP cannot feed significant amounts of carbon and associated ¹³C signals into carbohydrate metabolism.
Exclusion of starch, sucrose, and cellulose metabolism, and the pentose phosphate pathway as origin of the \( \Delta_5-6 \)' signal

Reactions leading directly from stromal GAP to the formation of starch, sucrose, and cellulose, reactions remobilizing starch, and reactions of the pentose phosphate pathway do not simultaneously modify carbon bonds that become glucose C-5 and C-6. This excludes these pathways for \( \Delta_5-6 \)' signal introduction.

Origin of the \( \Delta_5-6 \)' signal

After excluding several metabolic locations as the origin of the \( \Delta_5-6 \)' signal (see ‘Exclusion of metabolic locations as origin of the \( \Delta_5-6 \)' signal), the glycolytic pathway and PEP metabolism in leaves are left for consideration. Within this system, cytosolic GAP is used for PEP metabolism and sucrose synthesis (Fig. 1). Thus, GAP constitutes a central branch point in leaf carbon metabolism enabling isotope fractionation.

Leaf-level enolase, PEPC, PK, and/or DAHPS introduce the \( \Delta_5-6 \)' signal

Enolase, PEPC, PK, and DAHPS are the only enzymes which simultaneously modify carbon bonds that become glucose C-5 and C-6 (Figs 1–3). Reactions catalysed by these enzymes may be accompanied by \( ^{13} \text{C} \) effects of substantial size and may thus introduce the \( \Delta_5-6 \)' signal. Enolase interconverts 2-phosphoglycerate (2PGA) and PEP (Figs 1, 3). In vivo, the reaction operates close to equilibrium (Kubota and Ashihara, 1990) and might thus be accompanied by an equilibrium isotope effect. Formation of the C=C double bond in PEP probably favours turnover of \( ^{12} \text{C} \) isotopeologues of 2PGA, leading to \( ^{13} \text{C} \) enrichment in PEP. A \( ^{13} \text{C} \) signal might then arise from varying allocation of PEP to downstream processes (Fig. 1). Increased downstream consumption would remove more \( ^{13} \text{C} \)-enriched PEP and leave behind more \( ^{12} \text{C} \)-enriched 2PGA for glucose synthesis.

Kinetic isotope effects may accompany the unidirectional conversions of PEP to OAA by PEPC, PEP to pyruvate by PK, and PEP and E4P to DAHP by DAHPS (Figs 1, 3). These reactions break the C=C double bond in PEP and can therefore be expected to favour turnover of \( ^{12} \text{C} \)-isotopeologues of PEP, leaving behind \( ^{13} \text{C} \)-enriched PEP for glucose synthesis. Due to the usually larger size of kinetic isotope effects compared with equilibrium isotope effects, effects by PEPC, PK and DAHPS can be expected to outweigh any reciprocal effect by enolase. Thus, considering all four enzymes together, increasing turnover of PEP by PEPC, PK, and DAHPS can be expected to result in \( ^{13} \text{C} \)-enriched tree-ring glucose (i.e. \( \Delta_5-6 \) decreases).

Signal transmission to tree-ring glucose

Isotope signals generated at the level of leaf-cytosolic PEP or 2PGA need to be transmitted to GAP to then enter hexose phosphates and tree-ring glucose (Fig. 1). Transmission of a signal introduced by cytosolic enzymes is straightforward since the cytosolic glycolytic reactions between PEP and GAP are at equilibrium (Kubota and Ashihara, 1990). Transmission of a signal introduced by stromal enzymes is more intricate. First, it requires an incomplete or low–activity glycolytic pathway in leaf chloroplasts because signal equilibration with stromal triose phosphates would result in even signal distribution over all glucose carbon positions (Supplementary Protocol S1.6). An incomplete glycolytic pathway in leaf chloroplasts is supported by a reported lack of enolase in A. thaliana and O. sativa (van der Straeten et al., 1991; Prabhakar et al., 2009; Fukayama et al., 2015). Second, signal transmission from stromal PEP to C-5 and C-6 of cytosolic hexose phosphate requires chloroplast export of PEP. Transport of PEP across the chloroplasts’ inner membrane is mediated by the PEP/Pi translocator as counter-exchange with Pi, PEP, or 2PGA, and the putative in vivo preference for the transport of Pi and PEP (Fischer et al., 1997; Flügge et al., 2011). Numerous stromal processes, such as the shikimate pathway and fatty acid biosynthesis, rely on PEP import from the cytosol (Streatfield et al., 1999; Flügge et al., 2011). Therefore, a net flux of PEP from the cytosol to chloroplasts can be expected. However, members of the phosphate translocator family are believed to be highly inefficient. For instance, merely 10% of the activity of the triose phosphate translocator is used for net export of triose phosphate from chloroplasts; 90% is wasted on futile counter-exchanges (Flügge, 1987, 1999). In addition, low stromal and high cytosolic P levels (Sharkey and Vanderveer, 1989) can be expected to promote chloroplast export of PEP. Consequently, efficient equilibration of cytosolic and stromal PEP pools, and \( ^{13} \text{C} \) signals therein, can be expected. Thus, both cytosolic and stromal enzymes may contribute to the \( \Delta_5-6 \)' signal.

Signal introduction requires substantial carbon fluxes and flux variability

For the introduction of a \( ^{13} \text{C} \) signal, a substantial share of the photosynthetically fixed carbon must be directed towards enolase, PEPC, PK, and/or DAHPS and their downstream derivatives. This share must vary substantially; in the present case, on the interannual time scale. Therefore, we will now discuss carbon fluxes through enolase, PEPC, PK, and DAHPS.

Commonly, PEPC is localized in the cytosol both in dispersion and bound to the outer mitochondrial membrane (Figs 1, 3; O’Leary et al., 2011). In leaf mesophyll cells of O. sativa, a putatively rare additional isofrom occurs in chloroplasts (Masumoto et al., 2010; O’Leary et al., 2011). In C3 plants, PEPC provides OAA to replenish tricarboxylic acid cycle intermediates, and to support nitrogen assimilation and biosynthetic processes (O’Leary et al., 2011; O’Leary and Plaxton, 2017). On average, leaf carbon fixation by PEPC is believed to account for up to 5% of net CO2 assimilation (Melzer and O’Leary, 1987). Up-regulation of PEPC occurs (inter alia) with drought, salinity, ozone, nitrogen assimilation, and virus infections (see ‘Ecophysiological effects’; O’Leary et al., 2011). For instance, ozone triggers both an up-regulation of PEPC and
a down-regulation of Rubisco (Dizengremel, 2001). In forest trees, the Rubisco/PEPC activity ratio can change from up to 25 in ozone-free air to ~2 under realistic levels of ambient ozone, redirecting carbon flux to maintenance and repair processes (Dizengremel, 2001).

 Isoforms of PK are localized in both the cytosol and chloroplasts (Figs 1, 3; Ambasht and Kayastha, 2002). They provide pyruvate (inter alia) for mitochondrial respiration, fatty acid biosynthesis, and the non-mevalonate pathway (MEP). To our knowledge, estimates of the respiratory flux via PK in actively photosynthesizing leaves are unavailable. However, this flux may be substantial when photorespiration is low and thus co-occur with photorespiration and its environmental controls (Supplementary Protocol S3). In leaves, this flux is predominantly controlled at the level of acetyl-CoA carboxylase (Supplementary Protocol S4). In leaves, this flux is predominantly controlled at the level of acetyl-CoA carboxylase (Page et al., 1994; Harwood, 2005; Ohlrogge et al., 2015). It responds to the stromal redox state (energy status) and associated environmental controls (Rawsthorne, 2002; Harwood, 2005; Geigenberger and Fernie, 2014).

 The plastid-localized MEP pathway is yet another metabolic route carrying substantial flux. With isoprene as a major pathway product in some trees, it commonly consumes ~2% of net assimilated CO2 (Sharkey and Yeh, 2001). In forest trees, high temperature can enhance this fraction to up to 15% (Sharkey et al., 1996); a plant response believed to mitigate short-term high-temperature stress (Sharkey and Yeh, 2001).

 DAHPS, located in both chloroplasts and the cytosol, is the first enzyme of the shikimate pathway (Figs 1, 3; Maeda and Dudareva, 2012). In vascular plants, 20–50% of the photosynthetically fixed carbon enters the pathway (Tohge et al., 2013). In trees, most of the flux can be expected to occur in heterotrophic tissues supporting lignin biosynthesis. To our knowledge, flux estimates for actively photosynthesizing leaves are unavailable. However, the shikimate pathway provides precursors for (inter alia) the aromatic amino acids phenylalanine, tryptophan, tyrosine, and their numerous derivatives. Thus, the shikimate pathway is primarily exerted by gene expression and post-translational modification in response to developmental and environmental cues (Entus et al., 2002; Mir et al., 2015). Relative carbon flux through the shikimate pathway can be expected to (inter alia) vary with light (Henstrand et al., 1992; Logemann et al., 2000; Entus et al., 2002), ozone (Janzik et al., 2005; Betz et al., 2009), physical wounding (Dyer et al., 1989; Keith et al., 1991), bacterial infection (Keith et al., 1991; Truman et al., 2006), fungal infestation (McCue and Conn, 1989; Henstrand et al., 1992; Görlich et al., 1995; Bischoff et al., 1996, 2001; Ferrari et al., 2007), and nitrogen availability (Scheible et al., 2004). For instance, in leaves of N. tabacum, induction of DAHPS increased up to 5-fold under ozone fumigation (160 nl l⁻¹), and an increase in flux through the shikimate pathway was corroborated by increased levels of pathway products (Janzik et al., 2005). Performing an 83 d ozone fumigation experiment (160–190 nl l⁻¹, 8 h d⁻¹), Betz et al. (2009) reported evidence for increased carbon flux into the shikimate pathway in leaves of Fagus sylvatica.

 Since PEPC, PK, and DAHPS are located downstream of enolase (Figs 1, 3), all four enzymes may contribute to the Δ₅₋₆ signal. Based on arguments given above, associated carbon fluxes and their variability can be expected to be substantial. Other leaf-level pathways consuming PEP, such as the cytosolic mevalonate pathway, may exert additional control over the Δ₅₋₆ signal.

 Ecophysiological effects

 The Δ₅₋₆ signal is independent of the diffusion–Rubisco signal at C-1 and C-2 (Fig. 4). Since diffusion–Rubisco fractionation initially affects all carbon entering glucose synthesis equally (see the Introduction), we propose that the Δ₅₋₆ signal exhibits two components of variance. The first component is inversely correlated with diffusion–Rubisco fractionation and removes the diffusion–Rubisco signal from glucose C-5 and C-6. The second component constitutes systematic variation independent of diffusion–Rubisco fractionation. In the following, we propose ecophysiological mechanisms for the introduction of each component starting with the independent component. Please note that, in the present case, the Δ₅₋₆ signal can be expected to be under environmental rather than developmental control (Supplementary Protocol S5).

 Wieloch et al. (2018) studied effects of VPD, precipitation, soil moisture, temperature, and global radiation on the diffusion–Rubisco signal in their P nigra samples. These authors found that VPD, a measure of environmental drought, exerts predominant control and pointed out that this agrees with expectations for the generally dry study site. Thus, the independent component of the Δ₅₋₆ signal is governed by environmental factors other than VPD.

 The study site is ~10 km away from the city centre of Vienna and frequently exposed to substantial levels of tropospheric ozone (Oltmans et al., 1998; Ainsworth et al., 2012). Lefohn (1992) classified P nigra as an ozone-sensitive tree species. Radiation stimulates the photochemical reactions of ozone formation (Ainsworth et al., 2012). Ozone triggers relative flux increases through the anaplerotic and shikimate pathways via
PEPC and DAHPS, respectively (see ‘Signal introduction requires substantial carbon fluxes and flux variability’) and may thus cause $^{13}$C increases at PEP carbon positions that become glucose C-5 and C-6 (see ‘Leaf-level enolase, PEPC, PK, and/or DAHPS introduce the $\Delta_{5-6}'$ signal’). This may introduce an isotope signal independent of the diffusion–Rubisco signal due to independence at the level of environmental controls.

In contrast, a process mitigating ozone entry into plant leaves may explain the component of the $\Delta_{5-6}'$ signal which is inversely correlated with the diffusion–Rubisco signal. Dizengremel (2001) proposed that drought and ozone combined is a main recurring stress factor in forest ecosystems. Isohydric plant species, such as P. nigra, respond to drought by closing their stomata (Sade et al., 2012). Reduced stomatal conductance impedes ozone uptake (Tingey and Hogsett, 1985; Dobson et al., 1990; Dizengremel, 2001). In needles of Pinus halepensis, PEPC activities in control plants and plants exposed to mild drought stress were similar, strongly increased under ozone stress, but significantly less so under combined ozone and drought stress (Fontaine et al., 2003). Thus, anaplerotic flux rates can be expected to be highest under ozone stress but lower when ozone stress is accompanied by drought. While drought causes $^{13}$C enrichments at all glucose carbon positions due to diffusion–Rubisco fractionation (Wieloch et al., 2018), it can be expected to reduce ozone-induced $^{13}$C enrichments at glucose C-5 and C-6. This drought component of the ozone response may remove the diffusion–Rubisco signal from glucose C-5 and C-6. In Supplementary Protocol S3, we discuss how changes in substrate supply to mitochondrial oxidative phosphorylation (glycolytic pyruvate versus photosynthetic glycine) may additionally contribute to the component of the $\Delta_{5-6}'$ signal that is inversely correlated with diffusion–Rubisco fractionation.

**Experimental evidence**

**Effects of tropospheric ozone on whole-molecule $^{13}$C/$^{12}$C composition of plant cellulose**

Growing B. pendula at increased ozone levels, several authors reported decreased $^{13}$C discrimination, $\Delta$, in leaf and stem cellulose (Matyssek et al., 1992; Saurer et al., 1995). Intriguingly, these $\Delta$ decreases coincided with increased ratios of intercellular to ambient CO$_2$ concentrations, $C_i/C_\infty$. As pointed out by Matyssek et al. (1992) and Saurer et al. (1995), this cannot be explained by the standard model of diffusion–Rubisco fractionation which predicts a positive correlation between $C_i/C_\infty$ and $\Delta$ (Farquhar et al., 1982). Thus, post–Rubisco fractionation can be expected to cause these ozone-related isotope effects.

Matyssek et al. (1992) and Saurer et al. (1995) proposed that increased relative carbon fixation by PEPC due to ozone explains the $\Delta$ decreases because carbon fixed by PEPC is strongly $^{13}$C enriched compared with carbon fixed by Rubisco (Melzer and O'Leary, 1987). While this proposal is in line with significantly increased relative PEPC activities observed under ozone (Table 2), it conflicts with the set-up of carbon metabolism. PEPC-fixed carbon supplies downstream metabolism, yet no pathway carrying substantial flux exists that could transfer it into carbohydrate metabolism (see ‘Exclusion of reactions downstream of OAA, pyruvate, and DAHPS as $\Delta_{5-6}'$ signal origin’). Above, we propose an ozone–dependent mechanism for the introduction of the $\Delta_{5-6}'$ signal which reconciles observations of Matyssek et al. (1992) and Saurer et al. (1995) with the set-up of carbon metabolism (see ‘Ecophysiological effects’).

Saurer et al. (1995) reported differences in intercellular CO$_2$ concentration, $\Delta C_{i}$, and whole-molecule $^{13}$C discrimination, $\Delta \delta$, between ozone-treated and control plants. Plants grown with lower amounts of fertilizer (LF) exhibited $\Delta C_{i}$=7.5 ± 2.6 SE ppm, while plants grown with higher amounts of fertilizer (HF) exhibited $\Delta C_{i}$=21.5 ± 4.5 SE ppm. This corresponds to estimated increases in $^{13}$C discrimination by the diffusion–Rubisco interface of $\Delta \delta_{DR}$=0.52 ± 0.18 SE ‰ and 1.49 ± 0.31 SE ‰, respectively (Fig. 5, dashed bars; Equation 1). However, Saurer et al. (1995) reported $\Delta \delta$ decreases in leaf and stem cellulose under both fertilization regimes (Fig. 5, solid bars; Equations 2, 3). With respect to $\Delta \delta_{DR}$, these decreases are statistically significant (one-tailed t-test: $P<0.05$) except for leaf cellulose synthesized under HF conditions which comes, however, close to being statistically significant ($P<0.08$).

In B. pendula, post–Rubisco fractionation causes average whole-molecule $\Delta \delta$ decreases of approximately $-1.98 \pm 0.58$ SE ‰ (Fig. 5). Below, we propose that a fraction of the $\Delta_{5-6}'$ signal enters glucose C-1 to C-4 through indirect signal propagation via chloroplast metabolism (see ‘Signal propagation to all glucose carbons via chloroplast metabolism’). We estimate that the signal at C-5 and C-6 is 6.625-fold larger than at C-1 to C-4 (Supplementary Protocol S1.8). Thus, an approximately $-1.98 \pm 0.58$ SE ‰ effect at the whole-molecule level scales to approximately $-4.56 \pm 1.34$ SE ‰ effects at cellulose glucose C-5 and C-6 and to approximately $-0.69 \pm 0.20$ SE ‰ effects at C-1 to C-4 (Supplementary Protocol S6). In P. nigra, measured $\Delta_{5-6}'$ values fall within a 5.80 ± 1.55 SE ‰ range (maximum=22.71 ± 0.99 SE ‰, minimum=16.91 ± 0.56 SE ‰). Wieloch et al. (2018) estimated that the $\Delta_{5-6}'$ time series contains 79% systematic and 21% error variance. Assuming the error is fully expressed in both the maximum and minimum value, we estimate a systematic time series range of $\sim 4.58 \pm 1.22$ SE ‰ ($5.80 \pm 1.55$ SE ‰ ×0.79). This largely equals the estimated effect at glucose C-5 and C-6 in ozone-treated B. pendula, corroborating the theory proposed above. Notably, occurrence of the post–Rubisco fractionation effect in leaf cellulose of B. pendula corroborates the proposed leaf-level origin of the $\Delta_{5-6}'$ signal.

**Effect of tropospheric ozone on the $\Delta_{5-6}'$ signal in tree-ring glucose**

In Vienna, [O$_3$] is measured at five sites. Complete time series for all sites are available since 1992. Intra-annually, the highest [O$_3$]
occur during the period April to August (Fig. 6A) which can be expected to affect tree metabolism. Therefore, we calculated an April to August average time series for the Vienna region covering the period 1992–2020 (Fig. 6B, solid black line). We found that April to August SD and \( r_H \) explain 59% of the time series variability (Fig. 6B, dashed black line, \( P<0.00001, \ n=29 \)):

\[
[O_3] = 58.28 + 0.02951 SD - 0.3697 r_H
\]

Other studies report similar relationships (Felipe-Sotelo et al., 2006; Kovač-Andrić et al., 2009). Based on Equation 4, we reconstructed \([O_3]\) for the Vienna region over the period 1961–1991 (Fig. 6B, dashed red line). We found that April to August \([O_3]\) (reconstructed for 1961–1991 and measured for 1992–1995) explains 33% of the \( \Delta_{5-6} \) time series variability (Fig. 6C, \( P<0.0001, \ n=31 \)):

\[
\Delta_{5-6} = 35.24 - 0.2258[O_3]
\]

Accounting for measurement error, 75% of the variance in \( \Delta_{5-6} \) is explainable by modelling (cf. Nilsson et al., 1996). Thus, \([O_3]\) explains 44% of the explainable variability in \( \Delta_{5-6} \) (33%/75%×100). This is substantial considering that measured and modelled \([O_3]\) time series merely exhibit 59% co-variability (Fig. 6B, solid and dashed black line). In summary, these results corroborate the proposed negative relationship between ozone stress and the \( \Delta_{5-6} \) signal (see ‘Ecophysiological effects’), and, by extension, the theoretical framework developed above.

### Implications of the theory

**Signal propagation at the level of TPI in the cytosol of leaves**

The post-Rubisco signal at glucose C-5 and C-6 is independent of a signal at glucose C-1 and C-2 (Fig. 4; Wieloch et al., 2018); that is, substantial signal propagation from C-5 and C-6 to C-1 and C-2 is not supported by the data. This is surprising for the following reason: transmission of the \( \Delta_{5-6} \) signal from its origin, the lower end of the glycolytic pathway, into carbohydrate metabolism occurs via GAP (Fig. 1). Hence, signal independence requires negligible conversion of GAP (a precursor of glucose C-1 to C-3) to DHAP (a precursor of glucose C-1 to C-3) via leaf–cytosolic TPI (Figs 1, 2). Since TPI is often referred to as the prime example for the efficiency of enzyme catalysis, one would expect full equilibration of GAP and DHAP and inherent isotope signals. This view, however, is based on in vitro measurements of TPI kinetics. The following mechanisms may explain the apparent lack of equilibration and signal propagation in vivo.

In the light, chloroplast export of DHAP is favoured by the equilibrium position of stromal TPI, which is strongly on the side of DHAP (Walker, 1976; Knowles and Albery, 1977). Sharkey and Weise (2012) calculated that there should be >20 times more DHAP than GAP at equilibrium (Meyerhof and Junowicz-Kocholaty, 1943; Bassham and Krause, 1969). The substrate affinities of the triose phosphate translocator for DHAP and GAP are similar at \( K_m=0.13 \) mM and \( K_m=0.08 \) mM, respectively (Fliege et al., 1978). Thus, DHAP and GAP will be transported according to their concentrations; that is, 20 times more DHAP will be exported from chloroplasts to the cytosol. However, synthesis of fructose 1,6-bisphosphate uses DHAP and GAP at a 1:1 ratio. This may keep the concentration of leaf cytosolic GAP low. Flux of GAP into glycolysis and processes consuming glycolytic intermediates will additionally contribute to low cytosolic GAP concentrations. This may restrict the GAP to DHAP back-conversion. Furthermore, numerous common metabolites inhibit TPI competitively (Anderson, 1971; Grünig et al., 2014; Flügel et al., 2017; Li et al., 2019).

In addition, the activity of cytosolic TPI decreases significantly upon treatment with reactive oxygen species, especially \( \text{H}_2\text{O}_2 \) (Lopez-Castillo et al., 2016). Thus, during active photosynthesis, a lack of isomeric and isotopic equilibrium between leaf cytosolic GAP and DHAP is conceivable. This would block the propagation of \( ^{13}\text{C} \) signals in GAP to DHAP and enable independent \( ^{13}\text{C} \) signals in \( \Delta_{5-6} \) and \( \Delta_{1-2} \) as observed.
Signal propagation to all glucose carbons via chloroplast metabolism

Cytosolic PEP, 2PGA, 3-phosphoglycerate, 1,3-bisphosphoglycerate, and GAP carry the $\Delta^{5-6}_{\epsilon}$ signal from its putative origin (enolase, PEPC, PK, and DAHPS) directly into C-5 and C-6 of hexose phosphates (Figs 1–3). In addition, indirect signal propagation to C-1 to C-6 can be expected via import of 3-phosphoglycerate into chloroplasts (Supplementary Protocol S1.2). A model of signal propagation described in Supplementary Protocol S1 has several implications. First, observed $\Delta^{5-6}_{\epsilon}$ signals at C-5 and C-6 are 6.625-fold larger than at C-1 to C-4 (Supplementary Protocol S1.8). Second, the original signal as introduced at the level of enolase, PEPC, PK, and DAHPS is 1.4-fold larger than the signal observed at glucose C-5 and C-6 (Supplementary Protocol S1.9). Third, clustering of $\Delta^{5}_{\epsilon}$ with the $\Delta^{5-6}_{\epsilon}$ to $\Delta^{6}_{\epsilon}$ cluster (Fig. 4) can be explained by signal propagation via chloroplast metabolism (Supplementary Protocol S1.10).

Signal propagation to other plant metabolites

We propose that carbon flux changes around leaf cytosolic enolase, PEPC, PK, and DAHPS introduce the $\Delta^{5-6}_{\epsilon}$ signal. Hence, upstream derivatives of 2PGA carbons corresponding to glucose C-5 and C-6 will inherit the signal (Fig. 1). Compared with plant cellulose, the signal will be distinctly smaller in chloroplast derivatives, such as starch, and...
Intramolecular $^{13}$C signals reflect metabolite allocation

Distinctly larger in leaf sucrose synthesized during the photo-period (Supplementary Protocol S1). This latter metabolite may be used to follow the $\Delta_{5,6}'$ signal on an hourly basis. Downstream derivatives of PEP carbons corresponding to glucose C-5 and C-6 will obtain an inverse $\Delta_{5,6}'$ signal. These differences may help to test the theory.

Turnover by PEPC, PK, and DAHPS can be expected to result in $^{13}$C-enriched PEP (see ‘Leaf-level enolase, PEPC, PK, and/or DAHPS introduce the $\Delta_{5,6}'$ signal’). Thus, our theory can help to explain the $^{13}$C/$^{12}$C separation observed among plant compounds, specifically between $^{13}$C-enriched carbohydrates and $^{13}$C-depleted metabolites downstream of PK, PEPC, and DAHPS (Sharkey et al., 1991; Bathellier et al., 2017).

Implications for whole-molecule $^{13}$C/$^{12}$C analysis

The $\Delta_{5,6}'$ signal has two components of variance (see ‘Ecophysiological effects’). One is inversely correlated with diffusion–Rubisco fractionation, and the other is independent. Both components have implications for studies of plant carbon uptake and associated properties by whole-molecule $^{13}$C/$^{12}$C analysis. The inversely correlated component removes the diffusion–Rubisco signal from glucose C-5 and C-6. In addition, this signal is absent at glucose C-4 (Wieloch et al., 2018); that is, three out of six glucose carbon positions lack the diffusion–Rubisco signal. Thus, whole-molecule $^{13}$C/$^{12}$C analysis captures an attenuated diffusion–Rubisco signal and underestimates the variability of the original signal and associated physiological properties, such as $C_{i}/C_{a}$ and photosynthetic water use efficiency.

The independent component of the $\Delta_{5,6}'$ signal weakens signal extractions from whole-molecule $^{13}$C/$^{12}$C measurements because it constitutes pseudorandom noise with respect to diffusion–Rubisco fractionation. This may explain why models of whole-molecule diffusion–Rubisco fractionation as functions of environmental properties often suffer from low explanatory powers, $R^{2} \leq 0.5$ (Barbour and Song, 2014). In contrast, intramolecular $^{13}$C/$^{12}$C analysis resolves information about distinct ecophysiological processes; a fundamental conceptual advancement enabling more adequate modelling of the variability of plant carbon uptake and associated environmental/developmental controls.

Tracking carbon allocation in other biological organisms

Whole-molecule $^{13}$C/$^{12}$C analysis enables assessments of plant carbon uptake (Farquhar et al., 1982). According to theory reported here, intramolecular $^{13}$C/$^{12}$C analysis enables additional assessment of downstream carbon allocation in actively photosynthesizing leaves. This includes carbon flux into the anaplerotic, shikimate, MEP, and fatty acid biosynthesis pathways, and mitochondrial respiration (Fig. 1). Intramolecular $^{13}$C signals are governed by a small set of physicochemical principles that apply generally (Schmidt et al., 2015). Thus, intramolecular $^{13}$C/$^{12}$C analysis can be expected to enable retrospective assessment of carbon allocation in any biological organism including, for instance, disease-related shifts.

Utility of the $\Delta_{5,6}'$ signal

Laboratory experiments are limited to short time scales and in their capabilities to reproduce complex natural systems. Manipulation experiments on natural systems are limited to time scales of years and may suffer from spurious effects due to unnatural step changes in ambient conditions. In contrast, tree-ring analysis offers extensive temporal, spatial, species, and genotype coverage of natural systems that have not been subjected to unnatural step changes.

We propose that the $\Delta_{5,6}'$ signal reports flux into the anaplerotic pathway including CO$_2$ uptake by PEPC (Figs 1, 3, 5, 6). In addition, it may report flux into mitochondrial respiration (Supplementary Protocol S3). Thus, signal analysis may enable a better understanding of plant and ecosystem carbon balances including the so-called CO$_2$ fertilization effect.

Furthermore, intramolecular $^{13}$C/$^{12}$C analysis enables analysis not only of carbon uptake–environment relationships but also of carbon allocation–environment relationships (Figs 5, 6) and thus more comprehensive assessments of flux-level plant performance. For instance, atmospheric CO$_2$ and ozone concentrations have increased over recent years (Fig. 6B). Under business-as-usual scenarios, this will continue over the next decades (Turnock et al., 2018). While CO$_2$ promotes leaf photosynthesis and net primary productivity, ozone has the very opposite effect (Ainsworth et al., 2012; IPCC, 2014). When this highly reactive chemical enters plant leaves through stomata, it causes harm to structure and function, and leads to major rearrangements in carbon metabolism. While ozone decreases carbon fixation, it increases carbon allocation to costly maintenance and repair processes (Dizengremel, 2001; Ainsworth et al., 2012). This includes increased carbon flux into the anaplerotic and shikimate pathway, and this resource investment is likely to be recorded in the $\Delta_{5,6}'$ signal. Ozone tolerance varies among species, with metabolic changes depending on the duration of ozone exposure (Fontaine et al., 2003; Ainsworth et al., 2012). Thus, the $\Delta_{5,6}'$ signal may support flux-level screenings for species/genotypes with the capacity to optimally adjust to prolonged ozone exposure (requires further investigation).

While glucose positions C-1 to C-3 preserve the VPD-dependent carbon uptake signal (Wieloch et al., 2018), this signal was removed from glucose C-5 and C-6 and replaced by an independent ozone-sensitive carbon allocation signal (Figs 5, 6). Thus, intramolecular $^{13}$C/$^{12}$C analysis yields information about several environmental variables and may enable more powerful paleoenvironment reconstructions than whole-molecule analysis.
Lastly, sampling glucose at different developmental stages may enable the detection of shifts in carbon uptake and allocation over the life span of plants to better understand basic physiological processes such as plant senescence. In conclusion, intramolecular ¹³C/¹²C analysis opens up numerous new avenues of research within the plant and Earth sciences.

Supplementary data

The following supplementary data are available at JXB online.

Protocol S1. Signal propagation to all glucose carbons via chloroplast metabolism and implications.

Protocol S1.1. Signal propagation upon reimport of cytosolic metabolites into chloroplasts.

Protocol S1.2. Predominant import molecules.

Protocol S1.3. Predominant export molecules.

Protocol S1.4. Signal import into chloroplasts.

Protocol S1.5. Signal dilution and partial signal loss.

Protocol S1.6. Stromal signal redistribution

Protocol S1.7. Signal size in stromal triose phosphates.

Protocol S1.8. Signal size in cytosolic hexose phosphates.

Protocol S1.9. Original size of the Δ₁⁻Δ₅ signal.

Protocol S1.10. Signal propagation can explain the clustering of the Δ₁ signal.

Protocol S1.11. The role of chloroplast starch in signal propagation.

Protocol S1.12. Signal import into chloroplasts via cytosolic 1,3BPGA, 2PGA, and PEP.

Protocol S1.13. Assumptions.

Protocol S2. Correction for ¹³C signal redistribution by triose phosphate cycling in tree-ring cells.

Protocol S3. Alternating substrate supply to oxidative phosphorylation may contribute to the Δ₅ signal.

Protocol S4. Carbon flux into fatty acid biosynthesis in illuminated leaves.

Protocol S5. Potential influence of environmental and developmental variables on the Δ₅ signal.

Protocol S6. Intramolecular isotope effects in response to ozone.

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Author contributions

TW: conceptualization, devising the physiological and isotope parts, and writing with input from TDS, JS, and RAW; TW: leading the research; TW: data analysis with input from RAW.

Conflict of interest

The authors declare no conflict of interest.

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Data availability

The data that support the findings of this study have been published previously by Wieloch et al. (2018) and Sauer et al. (1995).

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