Experimental evidence for diel variations of the carbon isotope composition in leaf, stem and phloem sap organic matter in *Ricinus communis*

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**ABSTRACT**

Carbon isotope fractionation in metabolic processes following carboxylation of ribulose-1,5-bisphosphate (RuBP) is not as well described as the discrimination during photosynthetic CO2 fixation. However, post-carboxylation fractionation can influence the diel variation of δ13C of leaf-exported organic matter and can cause inter-organ differences in δ13C. To obtain a more mechanistic understanding of post-carboxylation modification of the isotopic signal as governed by physiological and environmental controls, we combined the modelling approach of Tcherkez et al., which describes the isotopic fractionation in primary metabolism with the experimental determination of δ13C in leaf and phloem sap and root carbon pools during a full diel course. There was a strong diel variation of leaf water-soluble organic matter and phloem sap sugars with relatively 13C depleted carbon produced and exported during the day and enriched carbon during the night. The isotopic modelling approach reproduces the experimentally determined day–night differences in δ13C of leaf-exported carbon in *Ricinus communis*. These findings support the idea that patterns of transitory starch accumulation and remobilization govern the diel rhythm of δ13C in organic matter exported by leaves. Integrated over the whole 24 h day, leaf-exported carbon was enriched in 13C as compared with the primary assimilates. This may contribute to the well-known – yet poorly explained – relative 13C depletion of autotrophic organs compared with other plant parts. We thus emphasize the need to consider post-carboxylation fractionations for studies that use δ13C for assessing environmental effects like water availability on ratio of mole fractions of CO2 inside and outside the leaf (e.g. tree ring studies), or for partitioning of CO2 fluxes at the ecosystem level.

**Key-words:** isotope modelling; post-carboxylation fractionation; starch; transport.

**INTRODUCTION**

Whereas carbon isotope discrimination during photosynthetic CO2 fixation is a comparatively well-described and understood phenomenon (Farquhar, O’Leary & Berry 1982; Farquhar, Ehleringer & Hubick 1989), much less is known about the isotopic fractionation associated with the metabolic processes following carboxylation in leaf tissues (Hobbie & Werner 2004; Badeck et al. 2005; Brandes et al. 2006). However, fractionations because of equilibrium, kinetic and fragmentation (Tcherkez et al. 2004) isotope effects beyond CO2 diffusion and fixation by ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco) are of importance because they result in differences in isotopic signatures among metabolites and in non-statistical intramolecular isotope distributions (Schmidt & Gleixner 1998; Schmidt 2003; Tcherkez & Farquhar 2005).

Post-carboxylation carbon isotope fractionation might account for diel variations in the isotopic composition of carbon exported from the leaves to heterotrophic tissues...
(Tcherkez et al. 2004; Brandes et al. 2006). Transitory starch, the origin of phloem-loaded sugars during the night, can carry δ13C signatures up to about 4% greater than triose-P originating directly from the Calvin–Benson cycle (Gleixner et al. 1998).

The occurrence of diel variations and intra-plant gradients in δ13C of organic matter are directly relevant to approaches that use the isotopic signature of CO2 exchange fluxes at the ecosystem level for the reconstruction of individual sinks and sources (Yakir & Wang 1996; Bowling, Tans & Monson 2001; Pataki et al. 2003; Badeck et al. 2005) as the isotopic signature of the organic substrate for respiration is imprinted on the respired CO2 (Barbour et al. 2005; Knoll et al. 2005). In addition, the interpretation of δ13C in different plant materials as a time-integrating proxy for environmental effects on ratio of mole fractions of CO2 inside and outside the leaf (c/c0) may be complicated by post-carboxylation changes of δ13C (Gessler, Rennenberg & Keitel 2004; Helle & Schleser 2004).

At the leaf level, the impact of post-carboxylation isotope effects has been assessed using the modelling approach of Tcherkez et al. (2004). Those authors examined the origin of the non-statistical intramolecular distribution of 13C in hexoses by relating it to the reactions of plant primary carbon metabolism. The model takes into account C-C bond-breaking reactions of the Calvin cycle and gives a mathematical expression for the isotope ratios in hexoses. While the estimated fractionations associated with transketolase and aldolase enzymes are sensitive to the flux of starch synthesis parameterized in the model, it is unequivocally predicted that a day–night difference in carbon isotopic composition of leaf-exported carbon should occur, with a 13C enrichment in the dark period when starch is decomposed to give dark sucrose and a 13C depletion in the light because of the use of 12C-enriched triose phosphates from the chloroplast to produce day sucrose. If true, this prediction would be significant, because it would contribute to explaining the isotopic differences between organs outlined earlier. However, until now, there has been no direct experimental evidence showing such a diurnal oscillation of the δ13C of exported carbon.

In the present study, we therefore tested the 13C-cyclic prediction of Tcherkez et al. (2004) by analysing δ13C in different organic matter pools in leaves (non-exportable, exportable), stems (total organic matter and phloem sap organic matter) and roots (total organic matter) during a light–dark cycle in greenhouse-grown Ricinus communis plants. To further assess the cause of inter-organ differences in carbon isotope composition, we compared the δ13C of primary assimilates with the exportable and the non-exportable carbon from the leaves and with phloem sap organic matter transported along the stem axis to the roots. In addition, we combined the modelling of isotopic fractionation in primary metabolism with the experimental determination of δ13C in different plant carbon pools. An agreement between measured and predicted values has been observed, showing indeed that post-carboxylation fractionations have occurred and correlated with the δ13C circadian rhythm. Our findings may have pervasive implications, namely, for photosynthetic isotope discrimination models that aim to explain the δ13C value of plant organic matter.

**MATERIALS AND METHODS**

**Plant material**

Seeds of Ricinus communis L. were germinated in vermiculite moistened with 0.5 mM CaSO4. After 13–15 d, the plants were transferred to 5 L pots with substrate consisting of commercial potting soil (two parts) (Floragard; Floragard GmbH, Oldenburg Germany) and Perlite (one part) (Perligran; G, Deutsche Perlite GmbH, Dortmund, Germany). Every third day, the pots were irrigated with tap water, and after 1 month on substrate, the plants were supplied with a commercial fertilizer (0.3% Hakaphos Blau; Compo GmbH, Münster, Germany).

The plants were cultivated for 35–40 d in a greenhouse (26 ± 5 °C) with a 16 h photoperiod provided by natural daylight plus mercury-vapour lamps (Osram HQL 400; Osram, Munich, Germany) supplying the plant with a minimum of 300–500 μmol photons m⁻² s⁻¹.

**Experimental design**

The δ13C of phloem sap-transported organic matter was determined at six different positions (a–f, Fig. 1) along the axis at six time points [four in the light [1030, 1200, 1630, 1900 h (±approx. 1 h)] and two in the dark period [2400, 0300 h (±approx. 1 h)]] during a diel course according to Gessler et al. (2007a). At each time point, three to four plants were harvested. Phloem sap was sampled by cutting the bark with a scalpel as described by Jeschke & Pate (1991). After sampling of the phloem sap, stem sections with a length of ca. 3 cm were collected from the same positions. In addition, all seven fully expanded leaves (L1–L7) and fine roots (diameter < 2 mm) were harvested at each time point for the analysis of carbon isotope composition and carbon content in total bulk, water-soluble organic matter (WSOM) and water-insoluble organic matter (IOM) (Fig. 1).

**Extraction of different carbon compounds**

All tissue samples (leaves, stem sections and roots) were homogenized in liquid nitrogen. For the extraction of WSOM and IOM, 1.5 mL of deionized water was added to 0.1 g aliquots of freshly frozen plant material. The mixture was agitated for 1 h at 4 °C, and then the extract was boiled at 100 °C for 1 min to precipitate proteins and was centrifuged (12 000 g for 5 min at 4 °C). The supernatant was considered to be the water-soluble (exportable) fraction consisting mainly of sugars but with some amino acids and organic acids, and the pellet to be the water-insoluble (non-exportable) fraction (Brandes et al. 2006).

δ13C in starch extracts was analysed in leaves L7, L5, L4 and L3 harvested at 1600 h and 0300 h. Determination of

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13C in starch was performed by modifying the method described by Wanek, Heintel & Richter (2001) and Göttlicher et al. (2006). One hundred milligrams of oven-dried leaves were incubated at 70 °C for 30 min in 1.5 mL of a methanol/chloroform/water solution (12:5:3 v:v:v) to completely remove soluble carbohydrates. This step was repeated three times, and the samples were kept at 60 °C overnight. The pellets were then incubated with 750 μL of demineralized water at 100 °C for 15 min to gelatinize the starch. Starch hydrolysis was performed by adding 250 μL (equivalent to 1200 U mL⁻¹ demineralized water) of a solution of heat-stable α-amylase from Bacillus licheniformis (Sigma Aldrich GmbH, Munich, Germany). The enzyme solution was cleaned by filtration with a Vivaspin 15 regenerated cellulose membrane with a 5000 Da molecular weight cut-off (Sartorius, Göttingen Germany) to remove stabilizers. After cooling, the solutions were centrifuged (12 000 g for 5 min) and 450 μL of supernatant was filtered with cleaned centrifugal ultrafilters (Vivaspin 500, regenerated cellulose membrane, 10 000 Da molecular weight cut-off; Sartorius). The filtered samples were used for stable carbon isotope analysis. Blanks without addition of plant material were treated in the same way as the samples. The samples were corrected for carbon content and Δ³¹C of the blanks.

Determination of phloem sap sugar concentrations

For the determination of soluble carbohydrates, 5–10 μL of phloem sap was diluted to 500 μL with demineralized water according to Keitel et al. (2003). One hundred microlitre aliquots were injected into a high-performance liquid chromatography system (Dionex DX 500; Dionex, Idstein, Germany). Separation of sugars was achieved on a CarboPac 1 separation column (250 × 4.1 mm, Dionex) with 36 mm NaOH as an eluent at a flow rate of 1 mL min⁻¹. Carbohydrates were measured by means of a pulsed amperometric detector equipped with a Au working electrode (Dionex DX 500, Dionex). Individual carbohydrates that eluted 8 to 16 min after injection were identified and quantified by internal and external standards. Sucrose was the dominant sugar in the phloem and made up >98% of the total phloem sap sugars. Sucrose carbon was related to total C in the phloem determined with an elemental analyser coupled to an isotope ratio mass spectrometer (IRMS) (see further) in order to check if the relative contribution of sucrose C changed over the diel course.

Gas exchange measurements

For all leaves at all time points, net CO₂ exchange (A) and cᵢ/cₐ (ratio of mole fractions of CO₂ inside and outside the leaf) were determined before harvest using a portable leaf gas exchange measurement system (LCA 4; ADC BioScientific Ltd., Hoddesdon, UK). Air temperature and relative air humidity varied between approximately 28.5 and 31.5 °C and 55 and 95%, respectively, during the diel course (Gessler et al. 2007a). During the light period, photosynthetically active radiation at the upper plant canopy level was between 320 and 600 μmol m⁻² s⁻¹.

Isotope measurements and isotopic calculations

Carbon isotope signatures and carbon contents of oven-dried bulk plant material and the different extracts were determined using a Delta Plus IRMS (ThermoFinnigan, Bremen, Germany) coupled to an elemental analyser (NA 2500; CE Instruments, Milan, Italy) as described in detail by Keitel et al. (2006) and Brandes et al. (2006). The samples which were combusted in tin capsules (IVA
Analsentechnik, Meerbusch, Germany) contained, on average, between 200 and 400 μg organic C. Precision of the measurements of the standard IAEA-CO-8 (International Atom Energy Agency, Vienna, Austria) was 0.11‰ (1 SD, n = 10). Carbon isotope signatures (δ13C in ‰) are presented as the ratios of 13C/12C of a sample relative to the Vienna Pee Dee belemnite standard.

Photosynthetic CO2 discrimination (Δ) was calculated from c1/c0 according to the following equation (Farquhar et al. 1982), which describes a two-stage model (diffusion through the stomata followed by carboxylation):

Δ = a + (b - a) \frac{c_1}{c_0}

(1)

where a is the fractionation (4.4‰) related to diffusion in air, and b is the net fractionation during CO2 fixation by Rubisco. The ordinary b value used to calculate Δ is 27‰, which has been obtained through best fits of experimental Δ response curves. Therefore, this value integrates the drawdown of the CO2 mole fraction from intercellular spaces to carboxylation sites. We thus used b = 27‰ with Eqn 1. In an additional approach, we applied the complete model for photosynthetic carbon isotope discrimination of Farquhar et al. (1982) according to the following equation:

Δ = \frac{eR_d}{k} + fI^* + (e_1 + a_1) \frac{c_1 - c_0}{c_0} + b \frac{c_0}{c_0} + \frac{c_2 - c_0}{c_0}

(2)

where c0 and c1 are the mole fractions of CO2 on the leaf surface and in the chloroplast, respectively; a0, e, and a1 are the fractionation factors associated with diffusion through the boundary layer (2.9%), with dissolution of CO2 (0.7‰) and with diffusion of CO2 in water (1.1‰), respectively. In Eqn 2, we used a fractionation factor b of 29.5‰ [pure ribulose-1,5-bisphosphate (RuBP) carboxylation fractionation]. The symbols e and f represent the fractionations associated with day respiration R_d and with photosynthesis; k is the carboxylation efficiency, and I^* is the CO2 compensation point in the absence of day respiration.

We estimated mesophyll conductance (g) from its relationship with assimilation rate as shown by von Caemmerer & Evans (1991) for various C3 species, and calculated c_i from the relation c_i = c_i - A/g. In order to account for the uncertainty of such an estimate, we calculated c_i not only for the g_i computed as described but also for g_i values 30% greater and less. Tcherkez (2006) gave a range for f from 7.0 to 13.7‰. Fractionation associated with glycine carboxylation amounts to 20‰, and is thought to roughly equal 2f, so a value of 10‰ for f seems reasonable, given that I^*c_i is approximately 0.1. The day respiratory fractionation, e, is thought to be less significant because the factor R_d/(kc_i) is so small (typically 0.02). Dark (as opposed to day) respiratory fractionation was shown to vary for several species under non-stressed condition between ~8.1 and ~0.1‰ (calculated from data in Duranceau et al. 1999; Ghashghaie et al. 2001). We used the value for dark respiratory fractionation in R. communis in Eqn 2, which was ~2‰ (Gessler et al., unpublished data) and was thus well within the range of the previously observed values.

We acknowledge that e might strongly change with environmental conditions and during the day–night cycle, and the assumption of a fixed value during the day might introduce some small error in the calculations of Δ. However, even if a variation of e between +10 and –10‰ is assumed (cf. Ghashghaie et al. 2003), the day respiration term will only vary between approximately +0.2 and –0.2‰.

To calculate δ13C values of newly produced organic matter (δ13Cp) from photosynthetic discrimination (Δ, or Δ), we applied the following equation:

δ13C_p = \frac{\delta^{13}C_{CO2} - \Delta}{1 + \Delta_i}

(3)

δ13C of CO2 (δ13C_{CO2}) from the greenhouse air was determined to be –8.0 ± 0.3‰ as the mean value during the diel course.

In order to calculate mean canopy δ13C values for a given time point, the carbon isotope compositions of different carbon fractions of single leaves were weighted for total leaf carbon content (mol leaf\(^{-1}\)). To calculate mean diurnal (daytime) or diel (day and night) δ13C values, carbon isotope composition was weighted according to Cernusak, Farquhar & Pate (2005) by photosynthesis or carbon content:

\text{weighted}δ13C = \frac{\int A \delta^{13}C \cdot dt}{\int A \cdot dt} \text{ or } \frac{\int C\% \delta^{13}C \cdot dt}{\int C\% \cdot dt}

(4)

where \int A \delta^{13}C \text{ is the light period and } \int C\% \delta^{13}C \cdot dt \text{ the light period or diel integral of the product of } A \text{ and } \delta^{13}C \text{, and } C\% \text{ and } \delta^{13}C \text{, respectively, and } \int A \cdot dt \text{ and } \int C\% \cdot dt \text{ are the light period or diel integrals of photosynthesis and carbon content.}

Isotope model

The modelling approach of Tcherkez et al. (2004), based on the fractionating enzymatic reactions of the primary carbon metabolism, is used here. A general scheme describing the main steps considered is given in Fig. 2. The carbon isotope composition of sucrose produced in the light or during the night is calculated with the steady-state equations (forward modelling) given in the Appendix of Tcherkez et al. (2004). Further details on the equations may be found in this reference. Briefly, the isotope ratios 13C/12C in all the C atom positions of carbohydrate molecules are expressed in the steady-state with mass balance equations. With a substitution procedure, we obtain linear functions of the isotope ratio in C-1 of chloroplastic 3-phosphoglyceraldehyde (further denoted as R_c). R_c is as follows:
Figure 2. Main steps and assumptions considered in the isotopic model of Tcherkez et al. (2004) used in the present paper. (a) shows a brief scheme of the steps of calculations leading to the modelled isotopic ratio $R$ of transitory starch and day sucrose. The model takes into account the fractionations of the chemical reactions that are involved in modifying C-C bonds: ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco), (trans)aldolase, transketolase and glycine decarboxylase. (b) shows the main carbon fluxes considered in the model and gives a comparison between measured (bold) and modelled (italics) isotopic values. The starch synthesis flux (in moles of hexoses per mole of CO$_2$ fixed) is $T$. Its average value is approximately 0.05 and has been determined from the rate of increase in leaf water-insoluble organic matter (IOM) during the day. Export from the chloroplast represents a flux $E$, from which $E/3$ is directed to glycolysis and $E/3$ to hoxose synthesis. $E$ ranges between approximately 0.12 and 0.16 (in moles of dihydroxyacetone phosphate per mole of CO$_2$ fixed) and is calculated from $v_r/v_c (= \Phi)$ and $T$ as follows (see Tcherkez et al. 2004 for details): $E = 1/3 - \Phi/6 - 2T$. In the cytoplasm, $2E/3$ is consumed for sucrose synthesis and $E/3$ for the production of other carbon compounds and for respiration. The fluxes denoted with solid arrows are day fluxes; those denoted with dotted arrows are night fluxes. Typical observed and calculated $\delta^{13}$C values for ratio of mole fractions of CO$_2$ inside and outside the leaf (denoted with solid arrows are day fluxes; those denoted with dotted arrows are night fluxes. Typical observed and calculated $\delta^{13}$C values are given in bold and italic, respectively. RuBP, ribulose-1,5-bisphosphate; G3P, 3-phosphoglyceraldehyde; DHAP, dihydroxyacetone phosphate; FBP, fructose bisphosphate; $v_r/v_c$, oxygenation-to-carboxylation ratio; $\Phi^*$, CO$_2$ compensation point in the absence of dark respiration; $\Delta$, photosynthetic carbon isotope discrimination; $R^*$, isotope ratio of the carbon input; $a_i$, isotope effects associated with the aldolase reaction; $t_i$, isotope effects of the transketolase reaction; $g$, carbon isotope fractionation associated with photorepository glycine decarboxylation; $R_{\text{chl}}$, isotope ratio in C-1 of chloroplastic 3-phosphoglyceraldehyde; $R_{\text{c}}$ and $R_{\text{t}}$, isotope ratios of chloroplastic and cytoplasmatic hexoses, respectively; OM, organic matter.

$$R_{\text{chl}} = R^*$$

$$R_{\text{c}} = R^*$$

$$R_{\text{t}} = R^*$$

where $\Phi^* = 1 + \Phi/2 - T^*$, $g = 1 + \Phi/2 - T^*$, $t_i = 1 + 3T^* - T^*$ for $i = 1, 2$ or 3, and $\varepsilon = a_i a_i$.

where $\Phi$ is the oxygenation-to-carboxylation ratio $v_r/v_c$, $g$ the isotope fractionation associated with CO$_2$ production from glycine (glycine decarboxylation), and $T$ the relative flux of starch synthesis. The isotope ratio of the carbon input ($R^*$) is calculated with the $c_i/c_i$ values obtained at different times (1000, 1200, 1600, 1900 h) weighted with assimilation of the leaves placed above the phloem sap collecting point. The use of the simplified model for photosynthetic carbon isotope discrimination seems justified as the application of the more complex approach (Eqn 2) did not result in different values for the isotopic composition of primary assimilates (see RESULTS section). The photosynthesis rate $\Phi$ is calculated with the $c_i$ value, assuming a Rubisco specificity factor of 90 and a CO$_2$ compensation point in the absence of dark respiration ($T^*$) of 40 mmol mol$^{-1}$ (c$_i$). This rate is within the range 0.46–0.61. The starch synthesis rate ($T$) is obtained, for each measurement time, using the rate of increase in leaf IOM during the day (source data not shown). The value obtained (in moles of hexoses directed to starch per moles of net fixed CO$_2$) is near 0.05. The inverse isotope effects associated with the
aldolase ($a_2$, $a_3$, $a_4$) and the transketolase ($t_1$, $t_2$) reactions are those found by Tcherkez et al. (2004) using the isotope ratios found in glucose in typical conditions (by reverse modelling): $a_2 = 1.0012$, $a_3 = 1.0058$, $a_4 = 1.0161$, $t_1 = 0.9924$, $t_2 = 1.0008$. The isotope effect associated with glycine decarboxylation was set to 1.020 as indicated by the latter authors and Tcherkez (2006). In such a framework, the average (whole molecule) isotope ratios are

$$R_{\text{at}} = \frac{1}{6} \left( 1 + \frac{a_2 a_3}{t_2} + \frac{a_2 t_2}{2} + \frac{a_3}{t_1} + \frac{a_4}{1} \right)$$

(6) in chloroplastic hexoses and transitory starch, and

$$R_{\text{sys}} = \frac{1}{6} \left( 2 + \frac{3(a_2 + 1)}{a_2 + 2} - \frac{3a_3}{2a_1} + \frac{3a_2}{2a_3} \left( a_3 + \frac{2a_4}{1 + a_4} \right) \right)$$

(7) in cytoplasmic hexoses (and thus in day sucrose).

**Statistical approaches**

All statistical analyses were performed using NCSS 2004 (Number Cruncher Statistical Software, Kaysville, UT, USA). Differences in $\delta^{13}C$ between time points and/or different positions were determined using analysis of variance (ANOVA) (general linear model ANOVA). For variance analysis, the position was nested within a time point. Assimilation-weighted daily averages of $\delta^{13}C$ in primary assimilates were compared with other carbon pools by applying the two-sided Student’s $t$-test.

**RESULTS**

**Diel courses of net photosynthesis and c/c_a**

Net CO$_2$ exchange rate was not different among leaves L3–L7 (L7: youngest leaf at the top) during the whole diel course but was significantly lower in the youngest leaves L1 and L2 at the bottom of the canopy (Fig. 3). In the light, net assimilation of the upper five leaves (L3–L7) was between 6.2 and 10.6 μmol CO$_2$ m$^{-2}$ s$^{-1}$ with maxima during midday and during the late afternoon. Respiratory CO$_2$ emission in the dark ranged between 1.4 and 2.8 μmol CO$_2$ m$^{-2}$ s$^{-1}$. c/c$_a$ did not differ significantly among leaves L3–L7. Leaf area-weighted mean values of c/c$_a$ increased from 0.58 to 0.78 between 1030 and 1630 h and decreased again until 1900 h.

**$\delta^{13}C$ in different organic carbon pools of the leaves**

In the WSOM (exportable) fraction, there were only slight differences in $\delta^{13}C$ among leaves between 1030 and 1630 h (Fig. 4a). In the evening and during the dark period, however, a stronger gradient was observed within the canopy. The difference in $\delta^{13}C$ between the leaves of the upper canopy and L1/L2 was up to 2.2‰. During the diel course, weighted mean canopy $\delta^{13}C$ decreased from −26.1‰ at 1030 h to ca. −26.6‰ at 1200 h. Between 1630 and 1900 h, $\delta^{13}C$ increased by 1‰, and nocturnal values were between −24.8 and −25.0‰.

A significant increase in $\delta^{13}C$ from the lower to the upper part of the canopy was observed in IOM (non-exportable) of leaves during the whole diel course (Fig. 4b). Maximum differences between L1 and L7 observed at 1630 h were 4.2‰. The diel pattern was inverted compared with WSOM with maxima between 1200 and 1630 h and minima during the night.

The $\delta^{13}C$ values in the starch extracts were not significantly different among leaves L3, L4, L5 and L7 (ranging from −24.9 to −25.3‰, Table 1) and this is consistent with their similar c/c$_a$ values (Fig. 3). The $\delta^{13}C$ values of starch were similar in the light (mean value of leaves L3, L4, L5 and L7 at 1600 h: −25.0 ± 0.6‰) and in darkness (at 0300 h: −25.2 ± 0.7‰), and were comparable with mean canopy leaf WSOM in the night (Figs 2 & 4).

**$\delta^{13}C$ in organic carbon pools along the stem axis and in the roots**

Within the canopy, $\delta^{13}C$ of total organic matter (Fig. 5a) in stem sections decreased from the top (f) to the lower part (c). This gradient was most pronounced during the light period. In contrast, $\delta^{13}C$ did not differ significantly among
stem sections below the leaves (a–c). Total organic carbon of fine roots was, however, enriched in $^{13}$C by up to 1.6‰ as compared with the lowermost stem section. There was a distinct diel pattern in $\delta^{13}$C values of stem sections and roots with a minimum at 1900 h and a maximum during the night and a mean peak-to-peak variation of 0.6‰.

The diel amplitude was higher for $\delta^{13}$C in phloem sap organic matter (Fig. 5b). Minimum $\delta^{13}$C values between −28.3 and −29.9‰ were observed at midday, whereas lowest $^{13}$C depletion occurred during the night resulting in $\delta^{13}$C values of −23.7 to −24.9‰. In contrast to total organic matter in stem sections, there was no difference in $\delta^{13}$C of phloem sap organic matter among different sampling positions. There were slight variations in sucrose carbon and total carbon concentrations during the diel course, but the relative contribution of sucrose carbon was always around 90% (Table 2).

**Comparison of $\delta^{13}$C of leaf and leaf-exported carbon pools**

There was a highly significant negative regression relation between mean canopy-weighted $\delta^{13}$C of leaf IOM and (1) leaf WSOM [$\delta^{13}$C leaf WSOM (%) = −1.97$\times$$\delta^{13}$C leaf IOM (%) − 80.3 (%), $R^2 = 0.94$, $P = 0.0012$] and (2) phloem sap organic matter [[$\delta^{13}$C phloem (%) = −4.39$\times$$\delta^{13}$C leaf IOM (%) − 147.6 (%), $R^2 = 0.84$, $P = 0.01$, for phloem sap collected at position d directly below the canopy] during the whole diel course. This finding shows the close coupling between the water-insoluble and the two soluble pools, that is, any $^{13}$C enrichment in insoluble C is compensated by a $^{13}$C depletion in soluble C, and vice versa. In addition, the $\delta^{13}$C of mean canopy-weighted leaf WSOM was significantly correlated with phloem sap organic matter (at position d) [$\delta^{13}$C phloem (%) = 1.97$\times$$\delta^{13}$C leaf WSOM (%) + 24.6 (%), $R^2 = 0.84$, $P = 0.01$]. The nocturnal $\delta^{13}$C values in leaf WSOM and phloem sap organic matter were comparable to $\delta^{13}$C in starch (cf. Fig. 2) indicating this carbon pool to be the source for sugars exported from the leaves to the phloem in the dark.

Photosynthesis-weighted mean daily $\delta^{13}$C value for primary assimilates (calculated from $c_i/c_a$ according to Eqns 1, 3 & 4) was −26.3‰ (Fig. 6). When taking into account fractionation associated with photosynthesis and day respiration as well as estimated mesophyll conductance and $c_i$ for calculating photosynthetic discrimination, the $\delta^{13}$C for primary assimilates amounted to −25.9‰ and thus did not strongly differ from the $c_i/c_a$ derived value. The grey bar in Fig. 6 shows the range for $g_i$ values being 30% higher and lower than the one calculated according to von Caemmerer & Evans (1991). The value calculated from $c_i/c_a$ did not differ significantly from the $\delta^{13}$C of the leaf WSOM and the phloem sap carbon pool averaged over the light

| Table 1. Carbon isotope composition of starch extracted from different leaves at two time points |
|-----------------|-----------------|
|               | 1600 h (day)    | 0300 h (night) |
| L7             | −24.9 ± 0.3 a A | −25.1 ± 0.5 a A |
| L5             | −24.9 ± 0.3 a A | −25.2 ± 0.4 a A |
| L4             | −25.0 ± 1.0 a A | −25.2 ± 0.9 a A |
| L3             | −25.1 ± 0.9 a A | −25.3 ± 0.8 a A |
| Mean           | −25.0 ± 0.6 A   | −25.2 ± 0.7 A   |

The position of leaves L3, L4, L5 and L7 is given in Fig. 1. Data shown are mean values (± SD) in parts ‰ ($n = 4$). The mean value per time point is weighted for leaf area. Different leaves at a given time point that share the common lower case letter ‘a’ are not significantly different [one-way analysis of variance (ANOVA) with Tukey–Kramer post hoc test, $P < 0.05$] in $\delta^{13}$C. Leaves from the same position (and mean values) that share the common upper case letter ‘A’ are not different between the two different time points (Student’s $t$-test, $P < 0.05$).
whereas the leaf exportable and the phloem sap fraction were slightly albeit not significantly enriched.

Comparison of the $\delta^{13}C$ values with the predicted day/night oscillations

The $\delta^{13}C$ values of the organic matter transported in the phloem may be predicted, assuming that (1) during the light period, phloem sap organic matter essentially contains sucrose produced in the light through triose phosphates aldolization and sucrose synthesis, and (2) during the night, phloem sap organic matter comes from the degradation of transitory starch into sucrose (cf. Fig. 2). Using $c/c_i$ values to obtain the isotopic composition of photosynthetic CO$_2$ input, the $\delta^{13}C$ values of both day and night sucrose were calculated (see Materials and Methods). The results are shown as a function of time in Fig. 7a. The predicted values are very similar for all the a, d, e and f levels, and Fig. 7a shows the calculated time course associated with stem position f only. The model predicts a large oscillation of the phloem $\delta^{13}C$ value, and this is more or less consistent with the observed values.

Figure 7, inset in panel b gathers all the data points associated with the four different levels, a, d, e and f, into day and night values, and predicted values are plotted against the observed ones. It can be seen that the relationship is within the 1:1 neighbourhood. A linear regression analysis yielded an $R^2$ of 0.25 ($P = 0.017$). The remaining variability virtually disappears when average day and night values are used (Fig. 7b, $R^2 = 0.95$, $P < 0.001$). This indicates that the model satisfactorily accounts for the diel $\delta^{13}C$ oscillations, but this may be better demonstrated with average values, simply because phloem sap organic matter integrates the carbon input from leaves rather slowly (see DISCUSSION section).

Comparison between $\delta^{13}C$ of carbon pools along the axis

Mean diel $\delta^{13}C$ did not differ in the phloem sap organic matter among sampling positions but decreased in total organic carbon of stem sections in the basipetal direction along the stem (Table 3). These patterns resulted in total carbon of stem sections being significantly $^{13}C$ depleted as compared with phloem sap organic matter at the stem base (axis position a). The mean diel $\delta^{13}C$ in total carbon in fine roots (a) and in phloem sap organic matter (b) along the axis (a–f) of Ricinus communis during the diel course. Position a denotes the sampling position at the stem base; f is the uppermost stem position harvested (cf. Fig. 1; Materials and Methods). Data shown are mean values ($n = 3$–4). The average standard errors of the mean values for all tissue sections and time points are given as error bars. In addition, effects of position along the axis and time on $\delta^{13}C$ as calculated with the general linear model ANOVA procedure are given. n.s., not significant.

### Table 2. Sucrose carbon and total carbon concentration and relative contribution of sucrose carbon to total carbon in the phloem sap of Ricinus communis during the diel course

<table>
<thead>
<tr>
<th>Time of the day</th>
<th>Sucrose C concentration (M)</th>
<th>Total C concentration (M)</th>
<th>Sucrose C: total C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1030 h</td>
<td>3.46 ± 0.28</td>
<td>3.79 ± 0.45</td>
<td>0.91 ± 0.12</td>
</tr>
<tr>
<td>1200 h</td>
<td>3.66 ± 0.22</td>
<td>4.02 ± 0.33</td>
<td>0.91 ± 0.08</td>
</tr>
<tr>
<td>1630 h</td>
<td>3.58 ± 0.25</td>
<td>3.95 ± 0.43</td>
<td>0.91 ± 0.12</td>
</tr>
<tr>
<td>1900 h</td>
<td>3.59 ± 0.18</td>
<td>4.03 ± 0.39</td>
<td>0.89 ± 0.10</td>
</tr>
<tr>
<td>2400 h</td>
<td>3.46 ± 0.23</td>
<td>3.77 ± 0.25</td>
<td>0.92 ± 0.08</td>
</tr>
<tr>
<td>0300 h</td>
<td>3.30 ± 0.20</td>
<td>3.74 ± 0.32</td>
<td>0.88 ± 0.09</td>
</tr>
</tbody>
</table>

Data shown are mean values ± SE from phloem sampling position C (see Fig. 1). $n = 3$–4.
roots was more positive compared with total carbon at the stem base and was slightly – albeit not significantly – $^{13}$C enriched as compared with phloem sap organic matter.

**DISCUSSION**

In the present study, we aimed at characterizing post-carboxylation carbon isotope fractionation in leaves during the diel course and its effect on $\delta^{13}$C of carbon pools within and exported from leaves. For this purpose, we measured the carbon isotope composition of exportable and non-exportable leaf and phloem sap organic matter and compared the values with the ones calculated with a model, taking into account the carbon isotope fractionations in the reactions of the primary carbon metabolism (Tcherkez et al. 2004, Materials and Methods and Fig. 2). In order to assess potential fractionation in heterotrophic tissues, we characterized the $\delta^{13}$C of phloem sap organic matter along the axis and compared it with total organic matter in stem segments and fine roots of *R. communis*.

**The circadian rhythm of $\delta^{13}$C values in phloem organics**

Clearly, the present study shows that there is a circadian rhythm of the $^{13}$C abundance in leaf WSOM and in phloem sap, that is, in organic molecules exported by leaves (Figs 4b & 5b). This phenomenon was predicted by Tcherkez et al. (2004) on a metabolic basis. Briefly, during the light period, the production of sucrose in the cytoplasm involves $^{13}$C-depleted triose phosphates exported from the chloroplast. The $^{13}$C depletion is a consequence of transitory starch synthesis, which favours $^{13}$C during intra-chloroplastic fructose production by aldolase (Gleixner & Schmidt 1997). During the night, sucrose synthesis involves starch degradation and, so, uses $^{13}$C-enriched carbon. As a result, an oscillation between light- and dark-exported sucrose is expected (Fig. 2).

The comparison of the observed values of phloem sap organic matter to $\delta^{13}$C calculated using the model of Tcherkez et al. (2004) is shown in Fig. 7. While the model reproduces well the range in which day and night values vary, there are some discrepancies along the time course (Fig. 7a). As a result, there is some noise around the 1:1 relationship between observed and predicted values (Fig. 7b, inset). Nevertheless, we note that this is almost eliminated when day and night average values are used. This reflects the fact that the predicted values calculated with instantaneous $c/c_i$ measured values (photosynthesis weighted for several leaves) cannot fully account for the phloem sap organic matter $^{13}$C content. This effect might originate from (1) a lag phase
between the instantaneous production of photosynthates and phloem accumulation in the stem because of a turnover time of leaf sugars in *Ricinus* amounting to approximately 2 h (Gessler et al. 2007a) plus the time needed to transfer newly assimilated photosynthates from the leaf to the phloem cells (as observed by Barbour et al. 2000 and Keitel et al. 2003 with isotopic techniques), which the model does not account for, and (2) the probable heterogeneous export efficiency of the different leaves (Jeschke & Pate 1991). The prevalence of a given leaf in exported phloem material affects the overall $^{13}$C abundance, if its c/i/c value is not very close to the average c/i/c value. Another reason for our observation might be (3) the complexity of the phloem network, which may introduce carbon from leaves below the phloem collecting points (Turgeon 2006). As sucrose made up approximately 90% of the carbon transported in the phloem as also observed previously by Peuke et al. (2001) and the sucrose proportion did not change over the diel course, there is no reason to assume that changes in the chemical composition of the phloem sap are responsible for the variations observed in $\delta^{13}$C.

**The relationship with leaf carbohydrates**

There is also a (modest) circadian rhythm of the $\delta^{13}$C value of leaf IOM (Fig. 4b). This is likely the result of starch accumulation (increase of $\delta^{13}$C in the morning) and remobilization (slight decrease of $\delta^{13}$C at night). The inverse correlation between $\delta^{13}$C in leaf IOM and leaf WSOM or phloem sap organic matter (see Results) indeed reflects the influence of diel starch dynamics on $^{13}$C enrichment or depletion in phloem-transported sugars. This is consistent with the fact that the carbon isotope composition of phloem sap organic matter equals that of starch in the night-time (cf. Fig. 2). The present diel cycle of $\delta^{13}$C in phloem organic matter and its correlation with starch dynamics is in strong agreement with previous observations. In sunflower, Ghoshgaie et al. (2001) determined differences in the $\delta^{13}$C of foliar sucrose between light and dark periods of ca. 1‰, with $\delta^{13}$C values at night being close to those of starch. Brandes et al. (2006) report day–night differences in the $\delta^{13}$C of phloem exudates of >1‰ with *Pinus sylvestris*. The authors showed that the increase in the $\delta^{13}$C of phloem-transported organic matter during the night was associated with starch breakdown. Gessler et al. (2007b) observed that the $\delta^{13}$C signatures of phloem sap organic matter in *Eucalyptus delegatensis* followed the carbon isotope composition of carbon released from starch in the dark period.

Unsurprisingly, we note that the diel oscillation in $\delta^{13}$C was more pronounced in phloem sap than in leaf WSOM (Figs 4 & 5); this effect is simply the consequence of different compositions of the carbon pools: phloem-transported organic matter of many plant species including *R. communis* (Pate et al. 1998; Peuke et al. 2001; Keitel et al. 2003) mainly consists of sucrose (Table 2), while WSOM is more heterogeneous and contains various carbohydrates, organic acids, amino acids with potentially various turnover times (Brandes et al. 2006).

**$^{12}$C/$^{13}$C distribution within the plant**

The diel rhythm of carbon accumulation in the light and remobilization in the dark period has a consequence for the...
The 13C value of the different leaf carbon pools, and, by integration over time, for the isotopic composition of leaf material compared with the exported material. The mean diurnal, nocturnal and diel 13C values of different carbon pools calculated according to Eqn 4 are shown in Fig. 6. Whereas during the light period 13C of exportable (leaf WSOM) and exported organic carbon (in the phloem sap) did not differ significantly from ‘primary assimilates’ (i.e. net assimilated carbon, calculated with c/c,, both exportable and phloem sap fractions were slightly isotopically heavier than net assimilated carbon when night values were included. On a mass balance basis, it means that, integrated over the whole day, an amount of lighter carbon remains in the leaves (IOM in Fig. 6). Taking into account photorespiration and day respiration as well as the drawdown of the CO2 concentration between the leaf intercellular spaces and the chloroplast for calculating photosynthetic fractionation did not change this picture (Fig. 6, left-hand side) as the simplified model used a lesser value for the effective fractionation by Rubisco.

In different plant species, post-carboxylation carbon isotope fractionation was also postulated to take place in the stem (Terwilliger et al. 2001; Helle & Schleser 2004). We observed a tendency for total carbon along the plant axis to be increasingly 13C depleted as compared with the respective carbon source (phloem sap organic matter) in the basipetal direction (Table 3). As lignonification is more pronounced at the stem base because of secondary thickening, a more intensive allocation of phloem-released carbon to this generally 13C depleted pool (Hobbie & Werner 2004) might explain the observed pattern.

<table>
<thead>
<tr>
<th>Axis position/tissue</th>
<th>δ13C (%) phloem sap organic matter</th>
<th>δ13C (%) total organic matter</th>
<th>Difference between pools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem f</td>
<td>−25.8 ± 0.6 a</td>
<td>−25.8 ± 0.5 b&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Stem c</td>
<td>−25.8 ± 0.7 a</td>
<td>−26.4 ± 0.4 b&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Stem a</td>
<td>−26.0 ± 0.5 a&lt;sup&gt;α&lt;/sup&gt;</td>
<td>−26.7 ± 0.4 b&lt;sup&gt;β&lt;/sup&gt;</td>
<td>*</td>
</tr>
<tr>
<td>Roots</td>
<td>−26.0 ± 0.5&lt;sup&gt;α&lt;/sup&gt;</td>
<td>−25.7 ± 0.3 b&lt;sup&gt;γ&lt;/sup&gt;</td>
<td></td>
</tr>
</tbody>
</table>

13C of phloem sap organic matter at stem position a. Phloem sap and stem total organic matter are compared at three positions along the stem (cf. Fig. 1, Materials and Methods). Position f is within the canopy, c directly below the canopy and a at the stem base. 13C of fine root total carbon is compared with the isotope composition of phloem sap organic matter at position a. 13C has been weighted for carbon content and time (Eqn 4). Greek letters indicate homogenous groups for phloem sap organic matter among different sample positions (general linear model ANOVA with a Tukey–Kramer post hoc test, P < 0.05). The asterisk in column four indicates significant differences (Student’s t-test, P < 0.05) between phloem sap and stem total organic matter at a given position.

Diel variations of the carbon isotope composition

<table>
<thead>
<tr>
<th>Table 3. Mean diel δ13C of phloem sap organic matter compared with total organic matter of stems and roots</th>
</tr>
</thead>
</table>

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Consequences for isotope ecology

The present study provides experimental evidence that the modelling approach developed by Tcherkez et al. (2004), which takes into account isotope fractionation of enzymatic reactions of the primary carbon metabolism, satisfactorily predicts the day–night differences in δ13C of leaf-exported carbon in *R. communis*. We have tested the modelling approach with one species, but there is evidence that comparable day–night variations related to the transitory starch metabolism occur with other species (e.g. Tcherkez et al.
Under the assumption that the cyclic nature is a general pattern in plants, it has important ramifications in isotopic ecophysiology.

Firstly, if such diel patterns were to occur in trees, the interpretation of tree ring isotope data would have to take post-carboxylation events into account (for a quantitative analysis, see Tcherkez, Ghashghaie & Griffiths 2007). For example, because phloem-transported sugars are the main C source for organic matter production in trunks, diel variations in δ13C may also affect the carbon isotope composition of whole wood or cellulose in tree rings. We know that there are indeed diel variations in the expression of key enzymes of lignin biosynthesis in herbaceous plants (Rogers et al. 2005). Even though uncertainty remains about such a circadian regulation of cellulose and lignin synthesis in trees, the cycling of ring deposition with phloem sap δ13C oscillations would affect the carbon isotope composition of tree rings and cause deviations from the values calculated from c/εc.

Secondly, diel variations in δ13C of phloem-transported organic matter, which serves as potential substrate for respiration in heterotrophic plant parts, may also have implications for the partitioning of ecosystem CO2 fluxes using isoflux approaches (Bowling et al. 2001). These approaches often assume δ13C of ecosystem-emitted CO2 to be constant over day–night cycles. Only recently, this prerequisite has been shown not always to be valid (Werner et al. 2006). A mechanistic understanding of variations in δ13C of assimilates as affected by post-carboxylation fractionation processes might at least partially help to explain temporal dynamics in the δ13C of respired CO2 and thus might help to improve measurement and sampling strategies for isoflux approaches.

Studies are thus needed to further specify carbon transport/flux pathways within different plant species including trees in order to build mechanistic models that are better representations of the carbon metabolism of these organisms.

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REFERENCES


