Is the Kok effect a respiratory phenomenon? Metabolic insight using $^{13}$C labeling in Helianthus annuus leaves

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Summary

- The Kok effect is a well-known phenomenon in which the quantum yield of photosynthesis changes abruptly at low light. This effect has often been interpreted as a shift in leaf respiratory metabolism and thus used widely to measure day respiration. However, there is still no formal evidence that the Kok effect has a respiratory origin.
- Here, both gas exchange and isotopic labeling were carried out on sunflower leaves, using glucose that was $^{13}$C-enriched at specific C-atom positions. Position-specific decarboxylation measurements and NMR analysis of metabolites were used to trace the fate of C-atoms in metabolism.
- Decarboxylation rates were significant at low light (including above the Kok break point) and increased with decreasing irradiance below 100 µmol photons m$^{-2}$ s$^{-1}$. The variation in several metabolite pools such as malate, fumarate or citrate, and flux calculations suggest the involvement of several decarboxylating pathways in the Kok effect, including the malic enzyme.
- Our results show that day respiratory CO$_2$ evolution plays an important role in the Kok effect. However, the increase in the apparent quantum yield of photosynthesis below the Kok break point is also probably related to malate metabolism, which participates in maintaining photosynthetic linear electron flow.

Introduction

Illuminated leaves not only assimilate CO$_2$ via photosynthesis but also produce CO$_2$ due to photorespiration and day respiration (denoted as $R_d$ hereafter). Here, the term day respiration encompasses all nonphotorespiratory CO$_2$-producing fluxes in catabolism (mostly pyruvate degradation, the TCA pathway and the oxidative pentose phosphate pathway). While the rate of photorespiration can be computed from Rubisco kinetics and oxygen response curves, fluorescence, or comparisons of O$_2$ and CO$_2$ fluxes, day respiration is a small flux that is technically difficult to measure (Tcherkez et al., 2017a,b). A popular technique widely used to estimate day respiration takes advantage of the ‘Kok effect’. The Kok effect was discovered decades ago (Kok, 1948, 1949). It is defined by the abrupt change in photosynthetic quantum yield occurring at very low light intensities, comparable to the light-compensation point. At such low light intensities (incident photosynthetically active radiation (iPAR) typically below 20 µmol photons m$^{-2}$ s$^{-1}$), photosynthesis increases linearly with irradiance and near the light-compensation point (~10 µmol photons m$^{-2}$ s$^{-1}$), there is usually an inflection in the response curve, referred to as the Kok effect. The slope of the light response is steeper (and thus the quantum yield is higher) below than above the inflection point (also referred to as the ‘break point’). The linear extrapolation of the intercept from the curve above the break point is believed to represent an estimate of $R_d$ (see Kok, 1949, and for recent examples Griffin & Turnbull, 2013; Crous et al., 2017). In mathematical terms, this effect can be simply formulated as follows:

$$A = k \cdot i\text{PAR} − i \cdot R_n$$

Eqn 1

where $A$ is the net CO$_2$ assimilation rate, $k$ is the apparent quantum yield of photosynthesis, $R_n$ is the respiration rate in darkness and $i$ the inhibition of respiration by light (so that $R_n = i \cdot R_d$). In the Kok effect, there is potentially a change in $k$ and/or $i$ as
light decreases. In the current understanding of the Kok effect based on a change in day respiration, it is assumed that \( i < 1 \) below the break point and \( i \) increases up to 1 above the break point. In fact, the change in quantum yield has been first attributed to the inhibition of mitochondrial respiration by light: below a certain light level (Kok break point), day respiration increases, causing lower assimilation values and thus a larger apparent quantum yield of net photosynthesis. However, its significance remains somewhat controversial, because alternative, nonrespiratory mechanisms have been proposed to explain the Kok effect, such as: a nonlinear response of photosrespiration to light (Cornic & Jarvis, 1972; Cornic, 1977); a drastic change in internal \( CO_2 \) mole fraction at very low light (proposed by Farquhar & Busch (2017) but dismissed by Buckley et al. (2017) and Gong et al. (2018)); a combination of both respiratory and internal \( CO_2 \) effects (Yin et al., 2020); or an increase in \( k \) below the break point, reflecting higher photochemical yield of photosystem II, \( \Phi_{PSII} \) (for a review, see Tcherkez et al., 2017a).

Understanding the origin of the Kok effect is of prime importance because estimating day respiration using this effect is common practice (including at the ecosystem level to compare the carbon balance of plant functional groups). Using the Kok effect, day respiration has been suggested to vary between species and also under relevant climatic conditions such as elevated \( CO_2 \) (Wang et al., 2001; Ayub et al., 2014) or high temperature (Sharp et al., 1984; Kroner & Way, 2016; Way et al., 2019) or drought (Ayub et al., 2011; Crous et al., 2012). Furthermore, the Kok effect has been observed at the ecosystem level using eddy covariance techniques (Bruhn et al., 2011; Wehr et al., 2016; Keenan et al., 2019). Nevertheless, we still do not know with certainty whether the technique based on the Kok effect gives valid estimates of day respiration.

From a metabolic point of view, the Kok effect could, in principle, be due to a change in catabolism, thereby altering the rate of \( CO_2 \) production. Monitoring \( O_2 \) exchange (with or without photosynthetic inhibitors) has shown that there is no Kok effect on gross \( O_2 \) production by photosynthesis while the effect is visible on net \( O_2 \) exchange, suggesting that photosrespiration or day respiration could be involved (Healey & Myers, 1971). As mentioned above, three major respiratory mechanisms can yield \( CO_2 \): pyruvate oxidative decarboxylation catalyzed by pyruvate dehydrogenases (PDHs), the TCA pathway (TCAP) and the oxidative pentose phosphate pathway (OPPP).

Using mass-balance modeling, it has been suggested that the Kok effect comes from insufficient NADPH generation at low light, compensated for by an increased OPPP activity (Buckley & Adams, 2011). Such an effect could take place in the cytosol while chloroplastic OPPP is inhibited (even at very low light) to allow the activity of the Calvin cycle. It should nevertheless be noted that the Kok effect is observed with both \( CO_2 \) and \( O_2 \) net gas-exchange (Cornic & Jarvis, 1972; Sharp et al., 1984; Gauthier et al., 2018), suggesting that the \( CO_2/O_2 \) ratio does not change. This means that possible modifications in catabolism (\( CO_2 \) generation) during the Kok effect have to be compensated for by a comparable change in NAD(P)H re-oxidation by \( O_2 \). In the case of OPPP, NADPH can be used by anabolism (including malate synthesis) and it is unlikely to be quantitatively re-oxidized by \( O_2 \). Therefore, an increase in OPPP activity alone seems unlikely to explain the Kok effect. Mitochondrial PDH is regulated by phosphorylation and thus a dephosphorylation at low light could easily explain an increase in day respiration during the Kok effect. However, this has not yet been demonstrated experimentally. In addition, PDH phosphorylation decreases with the photosynthesis inhibitor 3-(3,4-dichlorophenyl)-1,1-dimethylurea (DCMU) (Budde & Randall, 1990), but DCMU suppresses the Kok effect (Healey & Myers, 1971). Also, the use of respiratory inhibitors (SHAM, antimycin A) does not change the Kok effect (Peltier & Sarrey, 1988; Padmavathi & Raghavendra, 2001), suggesting that respiration is not directly responsible for the Kok effect. Low oxygen tends to suppress the Kok effect but not high \( CO_2 \) (except super high \( CO_2 \geq 10 \, 000 \, \mu mol \, mol^{-1} \)) (Sharp et al., 1984), suggesting that the change in quantum yield is not caused by photosrespiration but rather by metabolic mechanisms sensitive to \( O_2 \) mole fraction, such as day respiration and/or the Mehler reaction. Monitoring \( O_2 \) uptake on isolated chloroplasts has indeed suggested that the Mehler reaction is proportionally higher at very low light (Malkin, 1968). While all of these studies provide separate insights into the origin of the Kok effect, a complete understanding remains elusive.

Taken as a whole, there are arguments both for and against a respiratory origin of the Kok effect, and the metabolic mechanisms involved are not known. Here, isotopic \( ^{13}C \) tracing was used to clarify the role played by metabolic reactions producing \( CO_2 \) in the Kok effect. Our working hypothesis was that if the break point visible in the \( A/iPAR \) curve (Kok break point) is associated with abrupt changes in catabolism, it must be reflected in position-specific decarboxylation rates and \( ^{13}C \)-enrichment in metabolites. We thus followed the position-specific decarboxylation of \([^{13}C]\)glucose in sunflower leaves and examined changes in metabolic pathways as a function of irradiance. This study relies on our understanding that PDH, TCAP and OPPP each lead to decarboxylation of C-atoms from characteristic positions in the parent glucose molecule (Fig. 1). We found that \([^{13}C]\)glucose decarboxylation progressively increased as irradiance decreased, but this increase in decarboxylation began at irradiances above the Kok break point. Metabolic changes further suggest a considerable enhancement of catabolic enzyme activities (PDH, TCAP) as well as a transient activation of the malic enzyme. While this profile suggests that augmented glucose degradation by catabolism per se cannot explain the Kok effect, it probably reflects a more general phenomenon whereby triose phosphate catabolism leads to decarboxylation and \( CO_2 \) release via multiple reactions, and sustains photosynthetic quantum yield.

**Materials and Methods**

**Plant material**

Sunflower seeds (Helianthus annuus var. Bashful), were planted in Jiffy peat soil pellets soaked with water and grown for 5–6 d in the laboratory under ambient light. Once first leaves appeared, plantlets were transferred to 10-l pots filled with potting mix...
(enriched with Miracle-Gro; The Scotts Company LLC, Marysville, WA, USA) and placed in a glasshouse. Photosynthetic photon flux density was maintained during the 16 h photoperiod above 500 $\mu$mol m$^{-2}$ s$^{-1}$ using supplemental lighting (high-pressure sodium lights). Air temperature was maintained at 23°C: 14°C, day : night. All pots were watered for 5–10 min two or three times a day depending on plant size using drip irrigation. Nutrient solution (Miracle-Gro enriched with Fe-EDTA) was applied twice a week. Mature green leaves (c. 3–4 wk old) were detached from the plants under water and used for experiments.

**Gas-exchange**

Position-specific glucose decarboxylation rates, net CO$_2$ assimilation rates and stomatal conductance were measured. In selected samples, gross O$_2$ production rate (rate of O$_2$ production from water splitting) was also measured, and used to compute internal conductance. These properties were measured using the gas-exchange cuvette and associated sensors described previously (Gaucher et al., 2018) and recalled in Supporting Information Notes (S1a). The leaf was first illuminated at moderate light
(iPAR = 600 µmol photons m\(^{-2}\) s\(^{-1}\)) and once the photosynthetic rate was stable, irradiance was decreased progressively in a stepwise manner. Each transition from one level to another was progressive and took c. 10 min. After photosynthetic stabilization, the decarboxylation rate was measured, and this took 30 min to complete. The leaf was then either sacrificed (snap frozen in liquid nitrogen for NMR analysis) or kept in the chamber to carry out decarboxylation measurements at the next light levels.

Leaf labeling
The leaf was labeled in two ways: using H\(_2\)\(^{18}\)O for measurement of gross photosynthesis and mesophyll conductance as in Gauthier et al. (2018) – this technique takes advantage of on-line isotope ratio MS to measure \(^{18}\)O\(_2\) production by photosynthesis, compute the gross photosynthetic rate and therefore the carbonation-to-oxygenation ratio, which is in turn used to calculate internal conductance; or using 10% or 99% \(^{13}\)C-labeled glucose in positions C-1, C-2 and C-3, C-3,4 or uniformly labelled on the six positions. For each experiment, a fully expanded leaf was detached from a plant and the petiole was immediately immersed in tap water. After 30 min in darkness, the leaf area was reduced to c. 100 cm\(^2\) to fit into the chamber. The petiole was placed in the reservoir with 22 ml of \(^{18}\)O-labeled water (\(\delta^{18}\)O = 9000‰). Glucose concentration was 15 µmol L\(^{-1}\), and no glucose was added in negative control experiments. Two labeling conditions were used: unlabeled glucose (\(^{13}\)C natural abundance, 1.1%), or \([^{13}\text{C}]\)glucose (10% \(^{13}\)C). After having been placed in the reservoir, the petiole was recut under water to remove any potential embolism. The entire system (leaf + petiole + reservoir) was then sealed inside the chamber. In experiments that used \(^{18}\)O-water, the course of leaf water labeling was followed by measuring water transpired by the leaf using the cavity ring-down spectrometer. The leaf was considered to be fully labeled when the isotope concentration of outlet \(^{18}\)O\(_2\) changed by less than 1000‰ h\(^{-1}\) (compared to c. 2000‰ h\(^{-1}\) in the first minutes of \(^{18}\)O-labeling).

Calculations of photosynthesis, respiration and glucose decarboxylation
Day respiration (\(R_D\)) was measured with the Kok method (extrapolated intercept of the photosynthetic response curve to light), allowing us to verify that the Kok effect was manifested in our samples. Note that \(R_D\) does not enter into the calculation of position-specific glucose decarboxylation rates. The respiration rate in the dark was also measured after keeping leaves in darkness for 20 min. \(R_D\) was used to compute mesophyll conductance (\(g_m\)) and the CO\(_2\) mole fraction at carboxylation sites (\(e_c\)) as in Gauthier et al. (2018). [\(^{13}\)C]glucose decarboxylation was calculated by mass-balance from the observed difference in the isotope composition of outlet and inlet air, using a method similar to that given previously (Tcherkez et al., 2005, 2008). This calculation yields estimates of apparent decarboxylation, assuming that no respiratory CO\(_2\) is re-assimilated (the issue of refixation is addressed below). The \(\delta^{13}\)C of outlet CO\(_2\) was higher than that of inlet CO\(_2\) because of decarboxylation of [\(^{13}\)C]glucose, as well as the photosynthetic isotope fractionation against \(^{13}\)CO\(_2\). The mass-balance of CO\(_2\) fluxes in the leaf cuvette is such that:

\[
A = F_{in} - F_{out} + F_{Glc}
\]

Eqn 2

where \(A\) is net CO\(_2\) assimilation rate, \(F_{in}\) and \(F_{out}\) are inlet and outlet CO\(_2\) fluxes, respectively, and \(F_{Glc}\) is the decarboxylation flux. Note that \(F_{in}\) and \(F_{out}\) (in µmol m\(^{-2}\) s\(^{-1}\)) can be written as \(e_c\) \(D/S\) and \(e_o\) \(D/S\), respectively, where \(e_c\) and \(e_o\) are inlet and outlet CO\(_2\) mole fractions, and \(D\) and \(S\) are air flow (mol s\(^{-1}\)) and leaf surface area (m\(^2\)). In this equation, respiration of unlabeled glucose is included into \(F_{in} - F_{out}\), that is, the decarboxylation of \(^{13}\)C-glucose is assumed to be an additional, separate flux. Equations for mass-balance of \(^{12}\)C and \(^{13}\)C are as follows:

\[
^{12}A = (1 - p_{in})F_{in} - (1 - p_{out})F_{out} + (1 - p_{Glc})F_{Glc}
\]

Eqn 3

\[
^{13}A = p_{in}F_{in} - p_{out}F_{out} + p_{Glc}F_{Glc}
\]

Eqn 4

where \(p\) stands for the \(^{13}\)C mole fraction (= \(R/(1 + R)\), where \(R\) is the \(^{13}\)C/\(^{12}\)C isotope ratio). By definition, the \(^{12}\)C/\(^{13}\)C isotope effect is \(\alpha = 1 + \Delta\), where \(\Delta\) is the observed isotope discrimination associated with net photosynthesis. Therefore, the isotope ratio in net assimilated carbon (\(R_A\)) is:

\[
R_A = \frac{^{13}A}{^{12}A} = \frac{R_{out}}{\alpha}
\]

Eqn 5

Combining Eqns 3–5 gives the following:

\[
F_{Glc} = \frac{p_{out}F_{out}(1 - \frac{\alpha}{\Delta}) + F_{in}(1 - p_{in})\frac{p_{out}}{\Delta}p_{Glc}}{p_{Glc} - (1 - p_{Glc})\frac{1}{\Delta}p_{in}p_{out}}
\]

Eqn 6

which is identical to Eqn 4 in Tcherkez et al. (2005) by neglecting second-order terms and using the delta notation:

\[
F_{Glc} = \frac{\Delta F_{out} + (\delta_{out} - \delta_{in} - \Delta)F_{in}}{\delta_{Glc} - \delta_{out} + \Delta}
\]

Eqn 7

Further explanations on how Eqn 6 was implemented, calculations accounting for refixation and calculation of the photosynthetic isotope effect \(\alpha\) in Eqn 6 (fractionation \(\Delta\) in Eqn 7) are provided in Figs S1 and S2 and Notes S1(b–d).

NMR analyses and flux calculations
\(^{1}H\)-NMR analyses of absolute metabolite content were carried out on leaf extracts (10% D\(_2\)O) done with 21 mg lyophilized sample in powder extracted with 1 ml phosphate buffer pH 7 (15 mM), using a 700 MHz NMR spectrometer (Bruker Advance III) with water suppression by excitation sculpting. \(^{13}\)C-NMR analyses were carried out on leaf extracts with EDTA (12.5 mM) and maleate (standard; 125 µmol per sample) over 12 500 scans as in Abadie & Tcherkez (2019). Metabolic fluxes were estimated...
using a set of differential equations implemented across four steps of 1200 time increments, as in Cui et al. (2020). Here, the four steps of interest correspond to the four light transitions (in µmol photons m\(^{-2}\) s\(^{-1}\) iPAR): 80-to-60, 60-to-40, 40-to-20 and 20-to-darkness. Metabolic data presented here are mean ± SD of three replicates, or all three replicates are shown in the figures. Numerical data used as inputs were average values of pool sizes (determined by \(^1\)H-NMR) and \(^13\)C-enrichments (%\(^{13}\)C; determined by \(^13\)C-NMR). The contribution of OPPP to triose phosphate generation was calculated from the \(^13\)C-enrichment in C-atom positions of sugars (Notes S2). Calculation details and assumptions used to perform computations are detailed in Notes S3.

**Results**

**Photosynthesis response to light**

In this study, light response curves of both \(A\) and the decarboxylation rate of position-specific labeled glucose were measured. Fig. 2 shows net CO\(_2\) assimilation rate as a function of irradiance, with inlet CO\(_2\) kept at the ambient value. As photosynthesis increased, CO\(_2\) around the leaves \((c_\text{a})\) decreased, explaining why photosynthesis tended to saturate at \(c. 10\) µmol m\(^{-2}\) s\(^{-1}\) only at high light. Variations in \(c_\text{a}\) at low light were very small \((c_\text{a} \approx 400\) µmol mol\(^{-1}\)) because \(A\) was close to the compensation point. The Kok effect was clearly visible under our conditions, and linear regressions (continuous lines in Fig. 2) give a break point at 17 µmol photons m\(^{-2}\) s\(^{-1}\) (Fig. 2, inset), and an extrapolated day respiration rate of 0.48 µmol m\(^{-2}\) s\(^{-1}\). Average \(R_1/R_n\) was 0.44. The quantum yield of photosynthesis \((\Phi)\) was \(c. 7\%\) below the Kok break point and 3.6% above, corresponding to a relative change of 50%, consistent with values reported elsewhere (Tcherkez et al., 2017a).

**Decarboxylation rates**

Position-specific glucose decarboxylation rates \((F_{\text{Glc}})\) were measured at different irradiance and labeling conditions. Fig. 3 shows both absolute (in µmol m\(^{-2}\) s\(^{-1}\)) and rescaled rates (relative to that at iPAR = 600 µmol photons m\(^{-2}\) s\(^{-1}\)). Position-specific decarboxylation rates in the light were always of the order of 0.01–0.1 µmol m\(^{-2}\) s\(^{-1}\), that is, well below the rate of day respiration, simply reflecting the low entry of glucose into catabolism. Note that the average value of the mean decarboxylation rate with nonlabeled glucose was only 0.0002 ± 0.0001 µmol m\(^{-2}\) s\(^{-1}\), showing that the system used was associated with a very small uncertainty in measurements themselves. However, there was some variability in \(F_{\text{Glc}}\) between leaves (even under similar light conditions) because of slight differences in glucose incorporation due to differences in transpiration rate or leaf enzymatic capacities. Therefore, rescaled \(F_{\text{Glc}}\) values were computed to compare labeling conditions and to reduce variability unrelated to irradiance (for further details on rescaling, see Notes S1b).

There was a very clear increase in decarboxylation rates when irradiance decreased below 100 µmol photons m\(^{-2}\) s\(^{-1}\), with all relative \(F_{\text{Glc}}\) values being larger than 1, that is, larger than the rate observed at 600 µmol photons m\(^{-2}\) s\(^{-1}\) regardless of the labeled C-atom position. In other words, there was an increase in decarboxylation rates well above the Kok break point (here, 17 µmol photons m\(^{-2}\) s\(^{-1}\)). Despite some variability, there was a tendency for C-3 and C-4 atom positions in glucose to be decarboxylated at a higher rate than C-1 and C-2 atoms (compare black and blue symbols in Fig. 3). When C-atom positions were compared, there was a significant difference \((P < 0.05\) or \(\leq 0.07)\) between C-1/2 and C-3/4, suggesting that a fraction of labeled acetyl-CoA formed by pyruvate dehydrogenase was not decarboxylated. This was also the case in the dark, C-3/4 decarboxylation being \(c. 50\%\) larger than C-1/2 (Fig. 3). It is also worth noting that under our conditions, decarboxylation rates associated with C-1 were indistinguishable from those of C-2 (blue symbols in Fig. 3; see also Fig. S3).

The light-response curve of position-specific decarboxylation rates at low irradiance can be described in two ways. First, when values just above and just below (and at) the Kok break point were compared, there was no significant difference \((P = 0.24–0.91)\), indicating that the Kok break point was not associated with a sudden change in efflux of labeled CO\(_2\) (Table 1). Alternatively, position-specific decarboxylation rates increase by about a factor of 2 between 20 and 0 µmol photons m\(^{-2}\) s\(^{-1}\). This increase could be attributed to increased respiration rate associated with the Kok effect superimposed upon accelerating decarboxylations associated with diminished light inhibition of glycolysis.

**Variations in metabolite content**

Samples were also analyzed by \(^1\)H-NMR to quantify metabolic pool sizes (typical spectrum illustrated in Fig. S4). The content in sugars was rather variable but within the same order of magnitude regardless of irradiance, and amino acids such as alanine were always in relatively low abundance (Fig. 4a,b). By contrast, there were considerable changes in the content of metabolites involved in catabolism at low light, in particular an increase in malate from 60 to 40 µmol photons m\(^{-2}\) s\(^{-1}\) and then a strong decrease from 40 to 20 µmol photons m\(^{-2}\) s\(^{-1}\) (Fig. 4c), suggesting there was a transient synthesis of malate followed by an abrupt malate degradation. Variations in fumarate content were almost the opposite, showing that malate accumulation took place (at least partly) at the expense of fumarate production. However, citrate showed variations similar to malate, suggesting that changes in malate content were accompanied with citrate production and thus involved the TCAP at some point in metabolism, and not only anaplerosis via phosphoenolpyruvate carboxylase (PEPC). It is also worth noting that other metabolites were present in sunflower leaves, showing the involvement of alternative pathways such as the C\(_5\)-branched pathway (mesaconate) or leucine and valine synthesis (2-oxovalerate, isopropylmalate) (Figs 4d, S4). In particular, isopropylmalate was found to accumulate transiently as malate declined at 40 µmol photons m\(^{-2}\) s\(^{-1}\), suggesting that malate metabolism might have contributed to isopropylmalate synthesis via
pyruvate regeneration and thus the malic enzyme (also illustrated in Fig. S5).

13C-enrichment in metabolites

Samples associated with [13C-1]glucose labeling were analyzed by 13C-NMR to look at the 13C redistribution. Isotopic analysis by NMR is only possible for metabolites that are sufficiently concentrated to generate a 13C-signal. That is, minor compounds could not be analyzed. Here, our analysis was thus limited to sugars, malate, citrate, fumarate, succinate, alanine, glutamate and chlorogenate, the latter being a major secondary metabolite in sunflower (Fig. 5). There was considerable variation in the positional 13C-enrichment with light. In particular, the 13C-enrichment in malate followed the pattern seen in the malate pool size, showing that the increase in malate content at 40 \( \mu \text{mol photons m}^{-2} \text{s}^{-1} \) and its disappearance at 20 \( \mu \text{mol photons m}^{-2} \text{s}^{-1} \) were related to de novo synthesis and degradation, respectively. The same was true in citrate, where the 13C-enrichment followed changes in pool size. Succinate and fumarate showed little difference with 13C-natural abundance except at 60 \( \mu \text{mol photons m}^{-2} \text{s}^{-1} \). This means that whenever fumarate accumulated...
Table 1  Average decarboxylation rates of C-atoms in glucose in sunflower leaves at low light.

<table>
<thead>
<tr>
<th>Irradiance region</th>
<th>C-1 and C-2 atoms</th>
<th>C-3 and C-4 atoms</th>
<th>P-value (positions)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Absolute values</td>
<td>Rescaled rate</td>
<td>Absolute values</td>
</tr>
<tr>
<td>Just below and at the break point</td>
<td>(µmol m⁻² s⁻¹)</td>
<td>(µmol m⁻² s⁻¹)</td>
<td>(µmol m⁻² s⁻¹)</td>
</tr>
<tr>
<td>(10–20 µmol m⁻² s⁻¹)</td>
<td>0.0097 ± 0.0012</td>
<td>1.44 ± 0.13</td>
<td>0.0151 ± 0.0018</td>
</tr>
<tr>
<td></td>
<td>(+9%)</td>
<td>(+14%)</td>
<td>(+9%)</td>
</tr>
<tr>
<td>Just above the break point (40–60 µmol m⁻² s⁻¹)</td>
<td>0.0089 ± 0.0010</td>
<td>1.42 ± 0.05</td>
<td>0.0138 ± 0.0010</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P-value (below vs above)</td>
<td>0.59</td>
<td>0.91</td>
<td>0.53</td>
</tr>
</tbody>
</table>

Values shown here are mean ± SE (n = 7 to 13) near to and just above the Kok break point (17.5 µmol photons m⁻² s⁻¹). The P value corresponds to a test (Student-Welsh) made to compare values below (10–20 µmol photons m⁻² s⁻¹) and above (40 µmol photons m⁻² s⁻¹) the break point (bold) and between position types (italics). In parentheses: relative increase below the break point compared to the situation above the break point.

(such as in darkness, Fig. 4), it involved a carbon source weakly labeled by the C-1 atom of glucose, except at 60 µmol photons m⁻² s⁻¹. C-atom positions in glutamate were ¹³C-labeled but the labeling tended to decline at very low light (20 µmol photons m⁻² s⁻¹) and in darkness.

These ¹³C variations seen in metabolites (such as the decrease in %¹³C at very low light) were not due to changes in the isotopic dilution and thus in the ¹³C-enrichment in glucose, as both glucose and the glucosyl moiety of sucrose showed an increase at very low light and in darkness (Fig. 5d). Parenthetically, the present data show that the maximum %¹³C in metabolite C-atom positions was c. 5%, which matches the maximum enrichment in C-3 of triose phosphates (10% in C-1 of glucose). This shows that in sunflower leaves under our conditions, the metabolically active triose phosphates pool was relatively small and probably labeled maximally in C-3. This is in agreement with the ¹³C-labeling in C-3/7 in chlorogenate (which comes from C-3 of phosphoenolpyruvate) where, despite some variability, it was strongly labeled at 60 µmol photons m⁻² s⁻¹ (Fig. 5e).

Samples associated with [¹³C-3] or [¹³C₂-3] glucose labeling at 60 and 20 µmol photons m⁻² s⁻¹ and in darkness were also analyzed (Fig. 5f). As expected, the ¹³C-enrichment found in metabolites was much smaller than that observed with [¹³C-1] glucose labeling, reflecting the fact that ¹³C atoms were lost as CO₂ by the PDH (Fig. 1) and thus entered the TCAP to a much lower extent. Still, the %¹³C in succinate C-1/4 occasionally reached c. 2%, suggesting a contribution of the PEPC to feed the TCAP.

Estimation of metabolic fluxes

Pool sizes and %¹³C values were combined into a model based on differential equations to compute metabolic fluxes (described in Notes S3). The comparison of C-atom positions in sugars suggests strongly that the OPPP was associated with a rather small flux, explaining only c. 7.5% of the total triose phosphate produced by metabolism (Notes S2). The output of calculations is shown in Fig. 6. As expected, most changes in metabolic flux took place during the 40 to 20 µmol m⁻² s⁻¹ transition, that is, when the malate, citrate, fumarate and isopropylmaleate contents changed simultaneously. As a result, the transition to very low light was found to be associated with an increase in PDH, TCAP and PEPC activity (Fig. 6a). The OPPP activity was always very small. There was a transient flux through the malic enzyme, which explained the abrupt decrease in malate from 40 to 20 µmol photons m⁻² s⁻¹. Of course, depending on assumptions made to carry out calculations, there were substantial variations in absolute flux values (Fig. 6a) but the general increase of
pathway activities at low light and the transient malic enzyme activity seemed to be robust predictions. When compiled together to predict the CO₂ evolution rate (day respiration), there was a progressive increase in decarboxylation as irradiance declined, from c. \(1 \mu\text{mol m}^{-2} \text{s}^{-1}\) to \(2 \pm 1 \mu\text{mol m}^{-2} \text{s}^{-1}\) (Fig. 6b). Fluxes could also be used to predict \(^{13}\text{C-1}\)glucose decarboxylation rate so as to compare with experimental \(F_{\text{Cic}}\) values and therefore cross-validate the output of flux calculations. While assumption 1 (supposed low reversibility of fumarase and malate dehydrogenase) was clearly overestimating glucose decarboxylation (continuous line, Fig. 6c), the order of magnitude of predicted rates was in rather good agreement with observed values with the other two assumptions. In other words, flux values that best explained \(F_{\text{Cic}}\) were between those obtained under assumption 2 (high reversibility and alternative malate utilization) and assumption 3 (assumption 2 + no steady-state condition for 2-oxoglutarate).

**Discussion**

Possible causes of the Kok effect are numerous and have been recently reviewed (Tcherkez *et al.*, 2017a). Amongst them, a sudden increase in respiratory decarboxylation as light decreases is the mechanism by which the apparent change in quantum yield was originally explained by Kok (1948). This explains why the Kok effect has been widely used to estimate the rate of day respiration using linear extrapolation. Therefore, our working hypothesis was that the break point visible in the \(A_{\text{pp}}\) curve should be associated with abrupt changes in catabolism. Instead, the results presented here show that metabolic activities do not

![Fig. 5](image-url)
exhibit an abrupt change at the break point, but rather suggest that the enhancement of respiratory CO₂ evolution is progressive, showing that the increase in day respiration is an important component, but not the sole cause, of the Kok effect.

Catabolic CO₂ production does increase at low light

The results based on ¹³CO₂ evolution from [¹³C]-glucose show that there is a clear and significant increase in glucose catabolism when irradiance is low. In fact, [¹³C]-glucose degradation to CO₂ progressively increased as light decreased regardless of the ¹³C-labeled C-atom position (Fig. 3). This pattern was unlikely to be due to a side effect of low light on internal conductance, thereby decreasing refixation. The simplified one-box model calculations predict that accounting for refixation would change absolute rates but not the overall pattern of CO₂ evolution, and there was no relationship at all between position-specific decarboxylation rate and internal conductance (Figs S1, S2). Also, a third assumption is presented in which in addition to assumption 2, the TCAP is assumed to account for only one decarboxylation per cycle, a situation that may occur if 2-oxoglutarate is not in the steady-state (dash-dotted). (c) [¹³C-1]glucose decarboxylation computed with isofluxes obtained from panel (a), using the three same assumptions as in panel (b). The observed (experimental) average values (F_{Glc}) are shown in black (from Fig. 2). The dashed horizontal line is the average F_{Glc} at high light (200–600 µmol m⁻² s⁻¹). Note that under assumption 1, the predicted [¹³C-1]glucose decarboxylation rate is very large (c. 0.1 µmol m⁻² s⁻¹) at low light and thus beyond the frame of the graph. See also Supporting Information Notes S3 for calculation details.

Respiratory metabolism at low light

¹³CO₂ decarboxylation was higher when C-3 and C-4 positions were labeled compared to other positions (Table 1). That is, the prevalence of PDH over TCAP decarboxylation is reflected by 80 µmol photons m⁻² s⁻¹, including chlorogenate C-atoms 3/7, which come from phosphoenolpyruvate (PEP) (Fig. 5e). We note that, by contrast, NMR analysis indicates that the C-1 atom in glucose was between 2 and 4% ¹³C (Fig. 5f), suggesting an isotopic dilution by the pre-existing glucose pool. NMR analysis of glucose present in leaf extracts reflects total cellular glucose, not the metabolically active pool of glucose 6-phosphate directed to fructose 6-phosphate production. In effect, the corresponding C-atom position in the fructosyl moiety of sucrose appeared to be labeled to a larger extent than its glucosyl moiety (Fig. S6), suggesting that fructose 6-phosphate was indeed turned-over maximally and thus so were triose phosphates. Therefore, our data are consistent with a progressively relaxed inhibition of glycolysis (phosphofructokinase activity (Stitt, 1990)) and thus glucose degradation and CO₂ production via triose phosphate catabolism.
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The experimental results are broadly consistent with the decarboxylation pattern obtained upon pyruvate feeding of leaves, suggesting larger PDH activity relative to TCAP (Fig. 6a). Having said that, the predominance of decarboxylation of glucose C-3 compared to C-1 can be modulated by: the involvement of the malic enzyme, which liberates the C-4 atom of malate which can be labeled after [13C-3]glucose feeding due to equilibration by fumarase (Fig. 1); and the use of stored (non-labelled) citrate to feed the TCAP and the consumption of TCAP intermediates by N assimilation, which occurs under moderate light (Tcherkez et al., 2009; Gauthier et al., 2010; Abadie et al., 2017). The involvement of the malic enzyme is addressed below. Also, citrate concentrations paralleled those of malate (Fig. 4), suggesting that citrate production depended on malate metabolism – not the opposite. This interdependence of citrate and malate and the possible abstraction of 2-oxoglutarate to feed the synthesis of glutamate were included in flux calculations (Notes S1). Glutamate was visibly labeled (Fig. 5) showing that de novo synthesis of glutamate did not only involve reserves under our experimental conditions.

We further found that CO2 production by the OPPP was of little importance because C-1 and C-2 labeling led to similar decarboxylation rates (Fig. S3). In addition, direct estimation of OPPP contribution using the scrambling of 13C in sugars indicate that only 7.5% of fructose 6-phosphate molecules originated from the OPPP (Notes S2). For the plants studied here, this result is inconsistent with the hypothesis of Buckley & Adams (2011) that was based on steady-state calculations, in which OPPP was predicted to increase considerably at very low light (and caused the Kok effect) to compensate for the lack of redox power (i.e. NADPH). In addition, on purely biochemical grounds, a lack of redox power is unlikely. In fact, other mechanisms are more likely to meet the potential demand for NADPH at (very) low light, such as the decrease in cyclic electron flux around photosystem I (PSI) and a higher PSI photochemical yield (Oberhuber et al., 1993; Laisk et al., 2005; Kou et al., 2013; Yamori et al., 2016). Mutants affected in cyclic electron flux exhibit a normal electron transport rate and PSI oxidation state at low light (Munekage et al., 2004), and experiments on isolated chloroplasts have suggested that the stromal NADPH-to-NADP ratio is effectively high at very low light (Heber et al., 1982).

Note that in addition to the general involvement of PDH and TCAP (and the small contribution of OPPP) in decarboxylation across light levels, there were substantial variations in catabolic intermediates (Figs 4, 5) and flux rates (Fig. 6) when light progressively decreased. In particular, there was an enhancement of PDH and TCAP flux rates at very low light, and a transient activity of the malic enzyme. In fact, the peak in malate (both pool size and isotopic enrichment) indicates the probable involvement of enzymes of malate metabolism: malic enzyme and PEPC. Of course, the absolute value of the flux associated with the malic enzyme is rather uncertain, considering changes observed with different calculation assumptions. In particular, oxaloacetate formed by malate oxidation could be used by other pathways (aspartate and lysine synthesis, mesaconate production) and, in addition, mesaconate synthesis leads to 13CO2 production with a metabolic origin (C-4 of oxaloacetate + C-1 of pyruvate) identical to CO2 evolution by malic enzyme + PDH (Fig. S5). In other words, while the %13C and pool size analyses demonstrate important variations in organic acid metabolism, our flux values are just estimates because they could not incorporate alternative metabolic pathways. Also, other metabolites that cannot be easily seen by NMR (in particular C-OH groups that fall in the sugar region) such as tartarate could have contributed to changes in the malate pool.

The transient involvement of the malic enzyme is reminiscent of light-enhanced dark respiration (LEDR), a respiratory transient in darkness where leaf respiration rates are higher after the light has been switched off (for a recent review, see Gessler et al., 2017). In effect, LEDR has been shown to be mostly related to the decarboxylation of malate by the malic enzyme (Gessler et al., 2009), leading to naturally 13C-enriched evolved CO2 (Barbour et al., 2007). This raises the question of whether the transient increase in malate decarboxylation found here could reflect the beginning of the LEDR phenomenon. In other words, the LEDR observed in the dark might simply be the continuation of malate catabolism started at very low light. Our flux values nevertheless suggest that malic enzyme activity is small during the transition from 20 µmol photons m−2 s−1 to darkness. At this stage, it is important to remember that the flux values obtained here from samples collected in darkness reflected metabolic events that took place during the transition from 20 µmol photons m−2 s−1 to darkness plus stabilization in darkness (representing a total of 40 min). Therefore, LEDR was probably finished when the samples were collected, explaining why malic enzyme activity found by flux calculation was small. Further experiments with a much higher time resolution would be required to definitely establish the role of LEDR and the malic enzyme in the Kok effect.

Is the Kok effect caused by day respiration?

A common interpretation of the Kok effect is that day respiration increases when light decreases below the observed break point, and then continues to increase linearly up to night respiration when iPAR equals zero. The results presented here shed light on
metabolic fluxes, but also demonstrate that there are pros and cons for considering a purely respiratory origin of the Kok effect.

On the one hand, it is clear that glucose catabolism increases as irradiance decreases (Fig. 3; see also the section ‘Catabolic CO₂ production does increase at low light’ above). In addition, at very low light, there is a transient activation of malic enzyme and an enhancement of PDH- and TCAP-catalyzed decarboxylation (Fig. 6a). In other words, there is a progressive increase in day respiration as irradiance drops below 40 µmol photons m⁻² s⁻¹ (Fig. 6b), which affects net photosynthetic assimilation and thereby increases the apparent slope of the photosynthetic light response curve. In that sense, therefore, respiratory metabolism does participate in the Kok effect.

On the other hand, it seems unlikely that day respiratory CO₂ production is the sole actor responsible for the Kok effect. The increase in glucose decarboxylation rate (either observed (Fig. 3) or reconstituted from calculated fluxes (Fig. 6c)) and thus the up-regulation of catabolism was progressive rather than abrupt (i.e. did not generate a ‘break’ point), and began significantly above the measured Kok break point. Accordingly, if observed positional decarboxylation rates were used to calculate the potential CO₂ evolution from catabolism of the entire glucose molecule (i.e. 4 × C-1/2 decarboxylation + 2 × C3/4 decarboxylation), the shape of the curve obtained therefrom would not perfectly match what would be expected to explain the Kok effect (Fig. S7a,b). Of course, it can be argued that although the increase in day respiration is nonabrupt, it progresses linearly, thereby mimicking a change in quantum yield (while the latter would then remain constant). The predicted shape of day respiration indeed suggests that it could progress sublinearly (calculation assumption 3, Fig. 6). However, when predicted Rₘ is used in Eqn 1 with a constant quantum yield of 0.036 (found at high light, Fig. 2), the general shape of the curve is relatively close to that of the observed AᵢPAR curve, but does not perfectly match observed assimilation rates (Fig. S7c) – regardless of the offset of c. 0.5 µmol m⁻² s⁻¹.

Although the change in CO₂ production itself from respiratory metabolism affects the intercept and the slope (k and i in Eqn 1) insufficiently to explain the Kok break point satisfactorily, this does not mean that the break is unrelated to catabolism. Our metabolic analysis confirms that triose phosphates can be catabolized at very low light (see the Results section). Adenylate and pH monitoring experiments have shown that when stromal NADPH but not ATP is high, typically at low light, triose phosphate production and export from the chloroplast to the cytosol increases (Heber et al., 1982). In this context, glycolysis and the activity of the mitochondrial electron transfer chain could be of importance at low light to: oxidize triose phosphates and maintain linear electron flux in the chloroplast while the Calvin cycle is slow; and favor stromal alkalization and thus ATP synthesis. Here, the chloroplast itself could in principle participate in this process via chloroplastic glycolysis (and pyruvate decarboxylation by chloroplastic PDH) and export of reducing power to the mitochondrial via the malate–oxaloacetate shuttle. The exchange of metabolites between cellular compartments would thus sustain both mitochondrial metabolism and photosynthetic maintenance. In other words, the Kok effect could be indirectly explained by catabolism via its support to the Calvin cycle. This mechanism contributes to the maintenance of linear electron flux in the chloroplast, and thus tends to increase the quantum yield of photosynthesis (and ΦPSII). This hypothesis was originally formulated by Ulrich Heber in the 1970s (Heber, 1974). A possible scenario would thus be that: just above the ‘break point’, the stimulation of triose phosphate catabolism leads to an increase in both organic acid pools and the rate of day respiration, with limited impact on maintaining the linear electron flux in the chloroplast; at and below the ‘break point’, the effect on linear electron flux becomes significant and this makes the Kok effect apparent. For example, the break point could coincide with a critical malate-to-oxaloacetate ratio that allows facile export of redox power from the chloroplast. If true, this scenario would also explain the importance of the transient role of the malic enzyme to regulate the pool of malate at very low light.

Perspectives

To our knowledge, the present study is the first to directly address the metabolic origin of decarboxylated CO₂ in the irradiance region where the Kok effect occurs. It required very challenging experiments with labeling and concurrent measurements of isotope abundance in gases, with a very high precision (because of the very low rates involved). The position-specific decarboxylation rate measurements presented here were done with ¹³C-glucose only, and we recognize that further experiments, with a variety of other substrates (such as citrate, or pyruvate) would provide a more integrative picture of metabolic fluxes along AᵢPAR response curves. Further work with a higher time-resolution, using high-resolution GC-MS metabolomics (able to distinguish ¹³C₂ and ¹⁸O isotopologues), gas exchange, fluorescence and PSI absorbance monitoring would certainly shed more light on changes in metabolic pools and the origin of the Kok effect, including by monitoring ¹³C-isotope enrichment in quantitatively minor compounds that are not visible by NMR.

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Author contributions

PPGG and NS performed gas exchange and labeling experiments to measure decarboxylation rates. GT carried out NMR analyses and metabolic flux calculations, and wrote the first draft of the paper, including figures. PPGG, DW and KLG contributed to the interpretation of the results and participated in finalizing the paper.

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Supplementary Information

Additional Supporting Information may be found online in the Supporting Information section at the end of the article.

Fig. S1 Relationship between refixation-corrected and uncorrected glucose decarboxylation rate.

Fig. S2 Relationship (or lack thereof) between decarboxylation rates and internal conductance.

Fig. S3 Ratios of decarboxylation rates.

Fig. S4 Example of 1H-NMR spectrum used to quantify metabolites.

Fig. S5 Potential roles of alternative metabolic pathways.

Fig. S6 Positional 13C-enrichment in sugars.

Fig. S7 Relative decarboxylation rates for curve shape comparison.

Notes S1 Gas exchange system and calculations.

Notes S2 Calculation of the contribution of the OPPP.

Notes S3 Metabolic flux calculations.

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