RESEARCH ARTICLE

Effects of Ontogeny on δ¹³C of Plant- and Soil-Respired CO₂ and on Respiratory Carbon Fractionation in C₃ Herbaceous Species

Yann Salmonⁿʳ*, Nina Buchmann, Romain L. Barnardⁿᵇ

Institute of Agricultural Sciences, ETH Zurich, Zurich, Switzerland

ⁿʳ Current address: Department of Physics, University of Helsinki, Helsinki, Finland
ⁿᵇ Current address: INRA, UMR 1347 Agroécologie, Dijon, France
* yann.salmon@helsinki.fi

Abstract

Knowledge gaps regarding potential ontogeny and plant species identity effects on carbon isotope fractionation might lead to misinterpretations of carbon isotope composition (δ¹³C) of respired CO₂, a widely-used integrator of environmental conditions. In monospecific mesocosms grown under controlled conditions, the δ¹³C of C pools and fluxes and leaf ecophysiological parameters of seven herbaceous species belonging to three functional groups (crops, forage grasses and legumes) were investigated at three ontogenetic stages of their vegetative cycle (young foliage, maximum growth rate, early senescence). Ontogeny-related changes in δ¹³C of leaf- and soil-respired CO₂ and ¹³C/¹²C fractionation in respiration (ΔR) were species-dependent and up to 7‰, a magnitude similar to that commonly measured in response to environmental factors. At plant and soil levels, changes in δ¹³C of respired CO₂ and ΔR with ontogeny were related to changes in plant physiological status, likely through ontogeny-driven changes in the C sink to source strength ratio in the above-ground plant compartment. Our data further showed that lower ΔR values (i.e. respired CO₂ relatively less depleted in ¹³C) were observed with decreasing net assimilation. Our findings highlight the importance of accounting for ontogenetic stage and plant community composition in ecological studies using stable carbon isotopes.

Introduction

The carbon isotopic composition (δ¹³C) of plant- and soil-respired CO₂ is often used to infer plant physiological responses (e.g., review by [1]) and compare the responses of plants and ecosystems to changes in environmental conditions (e.g., [2]). However, our understanding of the biological mechanisms generating the C isotopic signature of plant and soil respiration fluxes is still incomplete, and the interpretation of the ¹³C signature of respired CO₂ can be challenging since this isotopic signal is affected by both environmental and biological factors. In particular, the effects of ontogeny and plant species identity on respiratory signatures in the plant-soil continuum remain poorly understood. Indeed, these biological factors are often difficult to
Plant Ontogeny and $^{13}$C Signal of Respired CO$_2$

caused by carboxylation (27% was used here, see text for details); B, Total dry aboveground biomass [g]; $c_o$, Ambient CO$_2$ concentration [µmol CO$_2$ mol air$^{-1}$]; $c_i$, Substomatal CO$_2$ concentration [µmol CO$_2$ mol air$^{-1}$]; $g_o$, Stomatal conductance to H$_2$O [mmol H$_2$O m$^{-2}$ s$^{-1}$]; LA, Total leaf surface area [cm$^2$]; PAR, Photosynthetically active radiation [µmol m$^{-2}$ s$^{-1}$]; $R_e$, Leaf dark respiration rate [µmol m$^{-2}$ s$^{-1}$]; $R_s$, Soil respiration rate [µmol m$^{-2}$ s$^{-1}$]; $\Delta$, Isotope discrimination; $\Delta_i$, Predicted photosynthetic C isotope discrimination assuming infinite mesophyll conductance and neglect the effect of (photo) respiration [%]; $\Delta_o$, Observed C isotope discrimination between atmospheric CO$_2$ and the considered plant part (leaf biomass, bulk phloem sap organic matter, root biomass) [%]; $\Delta_{C_{leaf}}$, Isotope fractionation [%]; $\delta^{13}C_{P_{CO2-leach}}$, Isotope composition of leaf-respired CO$_2$ [%]; $\delta^{13}C_{P_{CO2-soil}}$, Isotope composition of soil CO$_2$ efflux [%]; $\delta^{13}C_{leaf}$, $\delta^{13}C$ of leaf total organic matter [%]; $\delta^{13}C_{mico}$, Isotope composition of soil microbial biomass C [%]; $\delta^{13}C_{p_{phloem}}$, $\delta^{13}C$ of bulk phloem sap organic matter [%]; $\delta^{13}C_{p_{phloem}}$ of new photosynthates [%]; $\delta^{13}C_{root}$, $\delta^{13}C$ of root total organic matter [%]; $\Delta_{p_{phloem-leach}}$, Respiratory C isotope fractionation between bulk phloem sap organic matter and leaf-respired CO$_2$ [%]; $\Delta_{p_{phloem-soil}}$, Respiratory C isotope fractionation between bulk phloem sap organic matter and soil CO$_2$ efflux [%].

The present study focused on the effect of ontogeny and species identity on the isotopic signature of respired CO$_2$ and the associated $\Delta_R$. Furthermore, we tested whether changes in $\delta^{13}C$ of leaf- and soil-respired CO$_2$ and $\Delta_R$ could be related to leaf gas exchange and soil CO$_2$ efflux, used as proxies for C source and sink activities. Seven temperate C$_3$ grassland and cropland plant species were grown in monoculture under controlled conditions over a whole life cycle. The $\delta^{13}C$ of leaf- and soil-respired CO$_2$ as well as the $\delta^{13}C$ of plant organs were used to determine the apparent respiratory fractionation during leaf and soil respiration, and were related to changes in leaf gas exchange, soil CO$_2$ emissions, and plant biomass. Our objectives were: 1)
to assess the effects of ontogeny on the $\delta^{13}$C of CO$_2$ respired by plants and soil, 2) to estimate the associated $\Delta_R$ and whether these ontogeny effects may be species-specific; and 3) to determine the relationship between $\delta^{13}$C of respired CO$_2$, $\Delta_R$ and leaf gas exchange and soil CO$_2$ emissions over a range of growth stages.

**Material and Methods**

**Experimental setup**

This experiment included seven C$_3$ herbaceous species covering three different functional groups, based on *a priori* plant biological characteristics related to C and nitrogen allocation strategies: *Arrhenatherum elatius* L., *Dactylis glomerata* L., *Lolium perenne* L. (forage grasses), *Hordeum vulgare* L., *Triticum aestivum* L. (crop grasses bred for grain production, expected to favour aboveground productivity and allocation to seeds), *Medicago sativa* L., *Trifolium pratense* L. (legumes, less prone to nitrogen limitation, but likely allocating significant amounts of C to their microbial partner in the symbiosis). Square pots (18x18x17 cm height) were filled with sieved (1 cm mesh) clay loam soil (30% clay, 41.8% silt, 28.1% sand; pH 6.8, organic matter content 28.5%). One week after seed germination on a thin layer of soil, the plantlets were transferred to the pots, following an even pattern (16 individuals in monoculture per pot, i.e., 658 plants m$^{-2}$) on three quarters of the pot area. Despite the high plant density, we did not find any indication that root growth was impaired at any stage of the experiment. A PVC collar (7 cm diameter, 5 cm high) for soil CO$_2$ efflux measurements was inserted 2.5 cm deep in the remaining quarter of the pot surface.

Plants were grown under similar and optimal conditions in six growth chambers (PGV36, Conviron, Winnipeg, Canada) set to a 14 hour light period (photosynthetically active radiation of ca. 400 $\mu$mol m$^{-2}$ s$^{-1}$) at 20°C and an 8 hour dark period at 15°C, with two gradual 1h transitions between light and dark periods. To avoid position effects, pots were randomly distributed within each chamber, and their position within the chambers was changed weekly. Additionally, enough space was left between the pots to avoid shading from taller species over smaller ones. The spacing was increased at each stage and facilitated by the removal of one third of the pots at each stage for measurements and sampling (see below). The chambers were not airtight: outside air was continuously pumped in from above the roof of the building to the room with the growth chambers—which acted as a large buffer from which the growth chamber pumped their air from—, resulting in chamber CO$_2$ concentration that was monitored to be at approximately 400 $\mu$mol mol$^{-1}$ (±10%), close to equilibrium with atmospheric CO$_2$ concentration. Air humidity was maintained between 60 and 70%.

Three vegetative ontogenetic stages were defined for each species prior to the experiment: 1) young foliage, where plants had autotrophic leaves and were just large enough (10 cm high) to be used for our measurements (1 to 4 weeks after germination, depending on the species; termed “young”), 2) maximum growth rate, based on weekly measurements of plant height increase (5 to 8 weeks; termed “mature”), and 3) beginning of senescence (8 to 10 weeks; termed “old”), dominated by maintenance respiration. All measurements were performed on non-senescent stems and leaves. These three growth stages were expected to be associated with different contributions of growth and maintenance respiration to total respiration [8], ranging from mostly growth respiration at the young stage due to the limited maintenance requirements of the small existing biomass, to both growth and maintenance respiration contributing to total respiration at the mature stage, and finally to mostly maintenance respiration at the old stage, during which biomass is no longer produced. Due to growth conditions of constant photoperiod and temperature, flowering and seed production were not initiated during this experiment.
Leaf-gas exchange measurements

The following ecophysiological variables were measured on fully expanded leaves of three plant replicates (i.e., growing in three different climate chambers) per ontogenetic stage and species, between the 6th and the 8th hour of the light period: transpiration rate (E), stomatal conductance of leaves to H2O in the light (gs) as well as net CO2 assimilation rate (A). Additionally, leaf respiration rate (Rl) was measured at the end of the dark period (between 5th and 7th dark hour) to avoid light-enhanced dark-respiration [20]. Five measurements were averaged per replicate. Measurements were carried out under standardised conditions with a portable photosynthesis system (Li-6400, Li-Cor Inc., Lincoln, NE, USA). A dewpoint generator (Li-610, Li-Cor Inc.) and a CO2 source ensured constant relative humidity (60%) and CO2 concentration (400 μmol mol−1) in the incoming flow of the Li-6400 leaf chamber. Temperature and light conditions were set to growth chamber conditions: 20°C, 400 μmol m−2 s−1 (light source: 6400-02B, Li-Cor Inc.). Leaf gas exchange was measured using a leaf chamber covering 6 cm² of leaf area. When the leaf was too small to cover the whole chamber, leaf area was determined after leaf gas exchange, using a portable area meter (Li-3000C, Li-Cor Inc.), and the gas exchange values were recomputed for the correct leaf area. Total leaf area (cut 1 cm above the ground) was measured (portable area meter LI-3000C) before drying (48h at 60°C) and weighing.

The soil CO2 efflux rate was measured on three replicates (i.e., growing in three different climate chambers) per ontogenetic stage and plant species. A custom-made PVC chamber (27 cm high, 14.5 cm diameter) was fitted on the collar installed in the pots, and connected to a CO2/H2O gas analyser (Li-840, Li-Cor Inc.). The soil CO2 efflux rate was calculated over 1 minute of linear CO2 concentration increase in the chamber.

Sample collection

Leaves, roots, soil, and phloem sap organic matter were collected (n = 6 replicates per ontogenetic stage and species combination, i.e. one per growth chamber) between the 3rd and 5th hour of the dark period. Note that these measurements preceded Rl measurements by 2 hours, during which some C export to phloem may have occurred. However, the potential offset between measured respiration rate and isotopic signature of phloem sap organic matter should be small under our experimental conditions [7]. The individuals sampled for organic matter were different from those used for leaf gas exchange measurements to avoid any confounding effects of the δ13C value of the CO2 source used during leaf gas exchange measurements. Aboveground biomass was cut 1 cm above the root crown. A first soil core (1.5 cm diameter core over the whole pot depth) was taken for bulk soil δ13C measurements, after manually removing roots. A second soil core (5 cm diameter core over the whole pot depth) was taken for microbial biomass δ13C measurements (see below). Roots were separated from the soil remaining in the pot by wet sieving. Leaf, root and soil samples for isotope composition analysis were dried (48h at 60°C) and finely ground (see below). Gravimetric soil water content was calculated after drying approximately 10 g soil at 105°C. Bulk phloem sap organic matter was collected by using an exudation method [21] adapted for herbaceous plants [5]. Briefly, for each species and ontogenetic stage replicate, one to three stems (or pseudostems) were cut at 1 cm height, rinsed with ultrapure water and carefully dabbed. Then, stems were inserted in a tube filled with 2 mL of 0.15M polyphosphate buffer at pH 7.5, sealed with parafilm® and placed in the dark (100% humidity, 4°C). After five hours, 1.5 mL of solution were collected, lyophilized, and used for C isotope composition analysis (see below).

For collection of soil CO2, a soil chamber (Li-6400-09, Li-Cor Inc.) was adapted to fit the collars installed in all pots. For collection of leaf respired CO2, a custom-made PVC chamber
(15x7x4 cm) was used. The chamber was connected to the closed path infrared gas analyser of the Li-6400 portable photosynthesis to monitor chamber [CO2]. Both chambers were equipped with a septum to allow sampling CO2 respired by soil and leaves for isotopic analysis.

C isotopic signatures of CO2 respired by soil and leaves (individual leaves, not total above-ground biomass) were calculated using a Keeling plot approach. Briefly, this is a two end-member mixing model between the CO2 emitted by a source and the background atmospheric CO2, which allows to determine the isotopic signature of the source [22]. If more than two components mix, it is however possible to integrate several of them as one, provided they are well mixed and their relative contribution to the overall flux remains constant over the sampling period [23]. For example, belowground autotrophic respiration and heterotrophic respiration can be considered as an overall soil respiration component when using soil chambers (see below). The mixing model was based on five samples of chamber air, collected at regular intervals over a [CO2] increase of at least 100 μmol mol⁻¹, and injected in vials (Exetainer®, Labco Ltd, High Wycombe, UK) that had been previously evacuated (<4.10³ Pa) and filled with N₂. Sample volume and vial volume for each measured compartment were chosen to represent less than 1% of the chamber volume and be within a practical [CO2] range for isotope composition measurements (soil: 5 mL sample, 2.7 mL vial; leaf: 3 mL sample, 2 mL vial). All samples were collected between the 3rd and 5th hour of the dark period, thus effectively avoiding light-enhanced dark-respiration [20]. Vials were stored in a CO2-free environment and measured for δ¹³C within 48h.

To allow comparison between samples taken at different times, all δ¹³C measurements were corrected for changes in background δ¹³C, weighed by the duration of each stage. Background δ¹³C was measured in a companion study [5] and the values are provided in S1 Table (δ¹³C_air).

Soil microbial biomass was extracted by fumigation-extraction [24] after soil sieving (2 mm mesh [24, 25]). For each soil sample, one 10 g subsample was fumigated 24 h with chloroform vapour before extracting microbial biomass, while a second 10 g subsample was extracted without prior fumigation. Microbial C was extracted by vigorous shaking for 30 minutes in 30 mM K₂SO₄ solution, then the extracts were filtered, frozen (-18°C) and lyophilised before isotope composition and C concentration analyses.

Isotope ratio mass spectrometry measurements

The measurement of δ¹³C values and C concentrations of plant biomass, soil and phloem sap organic matter was performed using a Flash EA 1112 Series elemental analyzer (Thermo Italy, former CE Instruments, Rhodano, Italy) coupled to a Finnigan MAT DeltaPlusXP isotope ratio mass spectrometer (Finnigan MAT, Bremen, Germany) via a 6-port valve [26] and a ConFlo III [27]. The positioning of samples, blanks and laboratory standards in a measurement series followed the principle described by Werner and Brand [28]. Post-run off-line calculations like blank-, offset- and possibly drift-corrections for assigning the final δ¹³C values on the V-PDB scale were performed according to Werner and Brand [28]. Calibration of laboratory standards (acetanilide, caffeine, tyrosine) was periodically performed by comparing them to the corresponding international reference materials (NBS 22, USGS24) provided by the IAEA (Vienna, Austria). The long-term precision (~1.5 years) of our quality control standard (caffeine) was 0.09 ‰ or better for δ¹³C.

The δ¹³C values of CO₂ derived from gaseous samples were measured with a modified Gasbench II periphery (Finnigan MAT, Bremen, D) coupled to an isotope ratio mass spectrometer (DeltaPlusXP; Finnigan MAT). The modification of the Gasbench comprises the replacement of the GC-type split by a ConFloIII-like split and the addition of a home-built cold trap (filled with Ni-wire) instead of the loop of the 8-port valve inside the Gasbench (modification as described by Zeeman et al. [29]).
Post-run off-line calculation like offset- and drift correction for assigning the final $\delta^{13}$C values on the V-PDB scale were done as described above. The $\delta^{13}$C values of the laboratory CO$_2$-in-air standards were determined at the Max-Plack-Institut für Biogeochemie (Jena, Germany) as described by Werner et al. [28]. The measurement of the aliquots of the laboratory standards is routinely better than 0.15‰.

$\delta^{13}$C isotopic composition is expressed as the relative difference of the isotope abundance ratio of a sample relative to that of the VPDB international standard. This difference is expressed in per mil and defined as:

$$\delta^{13}C = \left( \frac{^{13}C/^{12}C}_{\text{sample}} / \frac{^{13}C/^{12}C}_{\text{VPDB}} - 1 \right) \times 1000 $$  \tag{1}

$\delta^{13}$C value of atmospheric CO$_2$ over each ontogenetic stage was calculated using phytometer leaves (see [5]).

For clarity, we use the following notation depending on whether the product is 1) the bulk $\delta^{13}$C value of a given plant part ($\delta^{13}$C$_{p}$: $\delta^{13}$C$_{\text{leaf}}$, $\delta^{13}$C$_{\text{root}}$, $\delta^{13}$C$_{\text{phloem}}$) or of soil microbial biomass ($\delta^{13}$C$_{\text{mic}}$) or 2) the $\delta^{13}$C value of respired CO$_2$ by either leaf or soil CO$_2$ efflux ($\delta^{13}$C$_{\text{CO}_2}$: $\delta^{13}$C$_{\text{CO}_2-\text{leaf}}$, $\delta^{13}$C$_{\text{CO}_2-\text{soil}}$).

$\delta^{13}$C$_{\text{mic}}$ was calculated using the following mass balance equation:

$$\delta^{13}C_{\text{mic}} = \frac{\delta^{13}C_{\text{F}} \times C_{\text{F}} - \delta^{13}C_{\text{NF}} \times C_{\text{NF}}}{C_{\text{F}} - C_{\text{NF}}}$$ \tag{2}

where $\delta^{13}$C$_{\text{F}}$ and $\delta^{13}$C$_{\text{NF}}$ are the $\delta^{13}$C values measured in fumigated and non-fumigated subsamples, respectively, and $C_{\text{F}}$ and $C_{\text{NF}}$ are C concentrations in fumigated and non-fumigated subsamples, respectively.

**Carbon isotope discrimination**

C isotope discrimination during a biochemical reaction (i.e., from a source to a product) can be calculated according to Farquhar et al. [30]:

$$\Delta = \frac{\delta_{\text{source}} - \delta_{\text{product}}}{1 + \delta_{\text{product}}}$$ \tag{3}

where $\Delta$ is the discrimination between $\delta_{\text{source}}$ and $\delta_{\text{product}}$, the $\delta^{13}$C values of the source and the product of the reaction, respectively. Unlike $\delta$ values, discrimination is independent of the isotopic composition of the source.

Respiratory fractionation ($\Delta_{\text{substrate-product}}$) is estimated as discrimination between the $\delta^{13}$C value of CO$_2$ respired (either leaf or soil) and its putative substrate:

$$\Delta_{\text{substrate-product}} = \frac{\delta_{s} - \delta_{\text{CO}_2-X}}{1 + \delta_{\text{CO}_2-X}}$$ \tag{4}

where $\delta_{s}$ is the $\delta^{13}$C value of the putative substrate (i.e. phloem sap organic matter in the main part of the study) and $\delta_{\text{CO}_2-X}$ is the $\delta^{13}$C value of the CO$_2$ respired by X. We use the explicit term $\Delta_{\text{substrate-product}}$, based on “$\Delta_{R}$” used in previous studies [31].

Since phloem is the main source of C for non-autotrophic tissues and its isotope signature a good proxy for total canopy C discrimination [32], we chose to present and discuss respiratory C isotope fractionation between leaf-respired CO$_2$ and phloem sap organic matter ($\Delta_{\text{phloem-leaf}}$). Nevertheless, respiratory fractionation was also calculated based on other C pools (i.e., leaf biomass) that may represent proxies for the actual leaf respiration substrate. Since CO$_2$ efflux
from the soil has multiple sources and quantifying their relative contributions was beyond our objectives, we chose to calculate belowground respiratory C isotope fractionation between soil CO₂ efflux and bulk phloem sap organic matter ($\Delta_{\text{phloem-soil}}$). However, as we did for leaf respiration, we also calculated soil respiratory fractionation based on other C pools that may represent proxies to soil respiration (i.e., leaf biomass and root biomass).

C isotope discrimination during photosynthesis is predicted from non-isotopic gas exchange measurements based on the widely accepted simplified model developed by Farquhar et al. [30], that assumes infinite internal conductance and neglects the effect of (photo)respiration, and further referred to as predicted photosynthetic C isotope discrimination ($\Delta_{i}$):

$$\Delta_{i} = a + (b - a) \frac{c_{a}}{c_{i}}$$

where $a$ is the fractionation occurring during CO₂ diffusion in air through the stomatal pore ($a = 4.4\%$o, [33]), $b$ is the net fractionation caused by carboxylation, $c_{a}$ and $c_{i}$ are ambient and substomatal partial pressures of CO₂, respectively. For higher C₃ plants, $b$ mostly results from the fixation of CO₂ by RuBisCO, the carboxylation enzyme, estimated at 29‰ in spinach [34]. Additional fractionation effects resulting from PEP-carboxylase fixation, CO₂ transfer through the leaf boundary layer, dissolution of CO₂ liquid-phase diffusion (in the mesophyll cells), photorespiration and dark respiration during photosynthesis are gathered under the term $d$ [35], which—when neglected—typically leads to the use of $b = 27\%$o ([16] see also [36]), as commonly used in ecological studies [37, 38] and also used in the present study. Note that $d$ was discussed in detail in our companion study [5].

Statistical analysis

Data were analysed using R 3.0.2 [39]. The effects of ontogeny and species identity were tested by analysis of variance, nesting species identity within the functional group, and including growth chambers as blocks to remove any chamber-related effects from the analyses. Differences of means among groups were tested with a Tukey honest significant difference test (HSD). Linear regression models were used to fit regression coefficients.

Results

Leaf gas-exchange

Species, functional group and ontogeny had significant effects on all leaf gas exchange variables (S2 Table). Furthermore, the effect of ontogeny differed among species (significant ontogeny × species interaction): in particular, leaf respiration ($R_{l}$) varied by an order of magnitude among different plant species and ontogenetic stages growing under controlled conditions (Table 1). Leaf respiration rates were the highest in mature Medicago foliage (1.68 μmol m⁻² s⁻¹), and the lowest in old Hordeum leaves (0.16 μmol m⁻² s⁻¹). Assimilation was highest in mature Triticum leaves (14.45 μmol m⁻² s⁻¹) and lowest in old Hordeum leaves (5.63 μmol m⁻² s⁻¹). Stomatal conductance values ranged from 43.8 mmol H₂O m⁻² s⁻¹ (old Hordeum) to 708.1 mmol H₂O m⁻² s⁻¹ (young Triticum).

Resulting $\Delta_{i}$ ranged from 14.8‰o to 26.3‰o, with an overall average of 23.4±0.6‰ [5]. Aboveground biomass and leaf area at the whole pot level both increased with age for all species ($p<0.001$), except for Trifolium that was more advanced in senescence and had already lost leaves between mature and old stages (Table 1). Soil CO₂ efflux rate ($R_{s}$) also varied among species and ontogenetic stages (0.6 to 44.3 μmol m⁻² s⁻¹, $p<0.001$). Arrhenatherum, Dactylis and
Trifolium exhibited high soil CO₂ efflux rates at mature and old stages, like Medicago and Lolium at the old stage.

Isotopic signature of plant tissues and leaf-respired CO₂

δ¹³C_leaf, δ¹³C_phloem and δ¹³C_root values were previously published [5]. The isotopic signature of leaf biomass (δ¹³C_leaf) was on average -31.1±0.3‰ (mean±SE, S1 Table), significantly lower than phloem sap organic matter (δ¹³C_phloem, -30.3±0.3‰, 0.001<p≤0.01) and root biomass (δ¹³C_root, -29.4±0.4‰, p<0.001). Ontogeny and species significantly affected δ¹³C_leaf, δ¹³C_phloem and δ¹³C_root (p<0.001 in all three cases). The effect of ontogeny differed among species (significant ontogeny x species interaction) for all δ¹³C_p (p<0.01), except for δ¹³C_phloem.

Across all ontogenetic stages and species, δ¹³CCO₂-leaf ranged from about -30% to -22‰, showing larger variation than δ¹³CCO₂-soil (Table 2, S1 Table). ¹³C of leaf-respired CO₂ was enriched compared to leaf biomass and phloem sap organic matter (Fig 1). However, as mentioned above, we only calculated Δδ based on phloem sap organic matter (see below). Over all ontogenetic stages and species, δ¹³CCO₂-leaf (~26.0±0.3‰ overall mean±SE) was significantly lower (p<0.001) than δ¹³CCO₂-soil (~24.4±0.3‰ overall mean). δ¹³CCO₂-leaf was significantly affected by ontogenetic stage and species, but not by functional group (Table 3, S1 Fig). Furthermore, over all ontogenetic stages and species, δ¹³CCO₂-leaf was positively related with leaf

Table 1. Leaf respiration rate (Rₛ), net assimilation rate (A), leaf stomatal conductance to H₂O (gₛ), instantaneous predicted photosynthetic discrimination (Δᵢ), aboveground biomass at the whole pot level (B), leaf area at the whole pot level (LA) and soil respiration rate (Rₛ) for different plant species at three ontogenetic stages (young foliage, maximum growth rate and beginning of senescence, indicated by young, mature and old, respectively). A, gₛ and Δᵢ (recalculated with b = 27‰) values are from Salmon et al. (2011). Values are mean±SE (n = 3).

| Ontogenetic Stage | Species        | Rₛ  | A          | gₛ         | Δᵢ         | B           | LA         | Rₛ         |
|------------------|----------------|-----|------------|------------|------------|-------------|------------|------------|
| Young            | Armeratherum   | 0.68±0.01 | 8.8±0.9 | 334.4±57.1 | 24.0±0.8 | 0.15±0.03 | 36.8±8.6 | 23.1±1.3  |
|                  | Dactylis       | 0.41±0.03 | 12.01±0.1 | 355.9±47  | 23.2±0.1 | 0.55±0.06 | 107.6±9.6 | 4.1±0.5   |
|                  | Hordeum        | 0.93±0.07 | 13.97±1.7 | 512.2±11.5 | 25.5±1.2 | 0.48±0.06 | 202.9±19.2 | 2±0.4     |
|                  | Lolium         | 1.04±0.01 | 10.04±1.9 | 354.4±136.5 | 25.5±1.8 | 0.28±0.03 | 71±4.2 | 4±0.8     |
|                  | Medicago       | 0.8±0.01  | 10.11±1.6 | 329.9±31.7 | 25.2±2.4 | 0.27±0.01 | 73.6±2.4 | 2.8±1.3   |
|                  | Trifolium      | 1.38±0.01 | 11.46±0.2 | 180.7±0.2 | 21.9±0.0 | 0.26±0.03 | 98.5±7.1 | 3±1.1     |
|                  | Triticum       | 0.85±0.01 | 13.79±1.4 | 708.1±24.5 | 26.3±0.7 | 0.38±0.03 | 164.4±10.6 | 1.2±0.4   |
| Mature           | Armeratherum   | 0.84±0.13 | 10.44±2.1 | 171.7±51.4 | 20.1±1.0 | 7.15±0.83 | 2975.6±191.6 | 25.1±3.7 |
|                  | Dactylis       | 0.49±0.06 | 6.02±1.2 | 75.8±15.5 | 20.5±0.6 | 6.26±0.39 | 1174.7±184.7 | 19.4±4.3 |
|                  | Hordeum        | 0.78±0.04 | 13.12±0.5 | 515.4±60.3 | 25.7±0.3 | 3.95±0.39 | 1345.6±130.8 | 1.4±0.2   |
|                  | Lolium         | 0.61±0.06 | 7.72±0.5 | 163.3±19.4 | 23.5±0.3 | 5.54±0.18 | 1253±69.4 | 0.8±0.2   |
|                  | Medicago       | 1.68±0.25 | 11.33±0.4 | 249±26.4 | 23.5±0.5 | 1.01±0.03 | 490.9±25.6 | 0.6±0.1   |
|                  | Trifolium      | 1.09±0.18 | 11.17±0.8 | 213±12.9 | 23.0±0.1 | 4.25±0.58 | 1306.6±224.6 | 21.6±0.9  |
|                  | Triticum       | 0.71±0.05 | 14.45±0.5 | 625.7±50.4 | 25.9±0.4 | 2.64±0.34 | 918±79.7 | 1.1±0.1   |
| Old              | Armeratherum   | 1.28±0.33 | 7.33±1.2 | 182.7±31.4 | 22.6±0.2 | 9.62±1.69 | 4178.8±1044.4 | 26.1±10.3 |
|                  | Dactylis       | 1.33±0.17 | 8.83±0.7 | 176.8±13.9 | 23.2±0.1 | 12.21±1.53 | 3375.1±412.2 | 26.7±7.8  |
|                  | Hordeum        | 0.16±0.03 | 5.63±1.2 | 43.8±14.2 | 14.8±1.2 | 8.61±0.73 | 1767.6±473.9 | 1.1±0.2   |
|                  | Lolium         | 0.46±0.1  | 7.04±0.3 | 97±15.6 | 20.8±1.0 | 9.52±0.78 | 2066.6±228.2 | 20.3±2.1  |
|                  | Medicago       | 0.58±0.08 | 11.19±0.6 | 150±18 | 20.7±0.3 | 5.8±0.58 | 1641.2±70 | 41.1±11.8 |
|                  | Trifolium      | 0.98±0.27 | 14.35±1.17 | 464.9±22.2 | 25.0±0.4 | 3.7±0.5 | 934.4±161.8 | 44.3±29.8 |
|                  | Triticum       | 0.27±0.07 | 11.37±1.1 | 227.6±100 | 21.3±2.2 | 10.4±0.84 | 2418.6±447.2 | 2±0.1     |

doi:10.1371/journal.pone.0151583.t001
Table 2. $\delta^{13}C$ values of leaf-respired CO$_2$ ($\delta^{13}C_{\text{CO}_2}\text{-leaf}$), soil-respired CO$_2$ ($\delta^{13}C_{\text{CO}_2}\text{-soil}$), microbial biomass ($\delta^{13}C_{\text{mic}}$) and bulk soil $\delta^{13}C$ ($\delta^{13}C_{\text{soil}}$) at three ontogenetic stages (young foliage, “young”; maximum growth rate, “mature”; beginning of senescence, “old”) in seven species (Arrhenatherum elatius, Dactylis glomerata, Hordeum vulgare, Loli um perenne, Medicago sativa, Trifolium pratense, Triticum aestivum). Values are given as means±SE (n = 6). Within one column, different letters indicate significant differences between ontogenetic stages within a species (p<0.05). Note that only significant differences are shown.

| Ontogenetic stage | Species            | $\delta^{13}C_{\text{CO}_2}\text{-leaf}$ | $\delta^{13}C_{\text{CO}_2}\text{-soil}$ | $\delta^{13}C_{\text{mic}}$ | $\delta^{13}C_{\text{soil}}$ |
|-------------------|--------------------|------------------------------------------|------------------------------------------|-----------------------------|-----------------------------|
| Young             | Arrhenatherum      | -24.08±0.40                             | -24.27±0.66                             | -23.68±0.19                 | -25.39±0.09                 |
|                   | Dactylis           | -27.19±1.13                             | -24.20±0.54                             | -24.26±0.59                 | -25.49±0.02                 |
|                   | Hordeum            | -27.60±1.39                             | -22.31±0.70                             | -21.89±0.13                 | -25.35±0.08                 |
|                   | Lolium             | -26.58±0.63                             | -24.40±0.52                             | -23.08±0.23                 | -25.37±0.12                 |
|                   | Medicago           | -29.69±0.40                             | -26.83±1.22                             | -23.15±0.31                 | -25.38±0.07                 |
|                   | Trifolium          | -25.69±0.40                             | -25.39±0.83                             | -25.63±0.56                 | -25.42±0.10                 |
|                   | Triticum           | -26.10±0.91                             | -21.36±1.51                             | -21.31±0.57                 | -25.29±0.09                 |
| Mature            | Arrhenatherum      | -25.84±0.99                             | -24.07±0.39                             | -23.47±1.31                 | -25.64±0.07                 |
|                   | Dactylis           | -25.37±1.14                             | -25.09±0.74                             | -24.57±1.27                 | -25.43±0.05                 |
|                   | Hordeum            | -26.31±0.96                             | -26.45±0.44                             | -25.71±0.56                 | -25.53±0.04                 |
|                   | Lolium             | -26.25±0.82                             | -24.57±0.41                             | -25.10±0.33                 | -25.55±0.04                 |
|                   | Medicago           | -26.35±1.04                             | -24.10±0.77                             | -25.41±0.46                 | -25.48±0.06                 |
|                   | Trifolium          | -25.87±0.95                             | -23.38±0.90                             | -23.81±0.37                 | -25.49±0.10                 |
|                   | Triticum           | -26.73±0.64                             | -25.09±0.67                             | -25.43±1.26                 | -25.59±0.06                 |
| Old               | Arrhenatherum      | -25.55±0.77                             | -24.65±0.64                             | -24.60±0.46                 | -25.61±0.05                 |
|                   | Dactylis           | -24.95±1.44                             | -23.34±0.42                             | -25.23±0.39                 | -25.47±0.08                 |
|                   | Hordeum            | -22.35±2.26                             | -25.00±0.60                             | -24.84±0.36                 | -25.42±0.13                 |
|                   | Lolium             | -26.14±1.57                             | -25.05±0.64                             | -23.44±1.14                 | -25.51±0.06                 |
|                   | Medicago           | -28.19±1.09                             | -24.96±0.14                             | -22.44±2.27                 | -25.57±0.03                 |
|                   | Trifolium          | -25.30±0.93                             | -23.19±0.45                             | -25.33±0.72                 | -25.49±0.08                 |
|                   | Triticum           | -23.69±1.07                             | -24.80±0.71                             | -24.26±0.47                 | -25.49±0.05                 |

doi:10.1371/journal.pone.0151583.t002

Plant respiratory fractionation

$\Delta_{\text{Rphloem-leaf}}$ values were generally negative (Fig 3 and S2 Fig) except in young Medicago. $\Delta_{\text{Rphloem-leaf}}$ was significantly affected by ontogeny (Table 2, Table 4, overall mean±SE: -3.6±0.3%), and differed significantly among functional groups (Table 3, S2 Fig). $\Delta_{\text{Rphloem-leaf}}$ tended to be positively related to assimilation rate ($R^2 = 0.19, p = 0.051$; Fig 3).

Calculating plant respiratory fractionation based on other potential substrates, i.e., leaf biomass and photoassimilates, showed patterns that were generally similar to that of $\Delta_{\text{Rphloem-leaf}}$ for the seven studied species, despite a few exceptions particularly with photoassimilates as a source for respiration (S3 Table).

Isotopic signature of microbial biomass and soil-respired CO$_2$

$\delta^{13}C$ values of microbial biomass ranged from about -25% to -21% (-23.9±0.2% overall mean, Fig 3), and were overall significantly more enriched (p<0.001) than bulk soil $\delta^{13}C$ (-25.5‰...
δ¹³Cmic was significantly affected by ontogeny. No significant correlations were observed between any measured ecophysiological parameter and δ¹³Cmic. Bulk soil δ¹³C was -25.48±0.01‰ (overall mean±se, Table 2) and was not affected by either ontogeny or the species growing in.

The ¹³C signal of soil CO₂ efflux was enriched compared to all plant components and generally also compared to bulk soil, but not compared to microbial biomass (Fig 1). The effect of ontogeny on δ¹³CCO₂-soil differed among functional groups (Table 3, S1 Fig), driven by significant differences among ontogenetic stages that were found only in the crops Triticum and...
No significant correlations were observed between measured leaf-gas exchange variables and $\delta^{13}C\text{CO}_2$-soil. Belowground respiratory fractionation $\Delta_{\text{phloem-soil}}$ values (overall mean±SE: $-6.5±0.4\%\delta$) were negative (Table 4, S2 and S3 Figs), indicating enrichment in $^{13}C$ of respired CO$_2$ compared to the putative respiration substrates. $\Delta_{\text{phloem-soil}}$ was significantly affected by ontogeny (Table 3, Table 4) and the interaction between functional group and ontogeny. Furthermore, $\Delta_{\text{phloem-soil}}$ tended to be negatively related to $\Delta_i$ ($R^2 = 0.19$, $p = 0.051$) and positively to WUE ($R^2 = 0.16$, $p = 0.069$). In contrast, $\Delta_{\text{phloem-soil}}$ was positively related to $A/R_l$ for plants at the old stage ($R^2 = 0.68$, $p = 0.021$). Considering other potential substrates for belowground respiratory fractionation (i.e., leaf and root biomass, photoassimilates,) showed similar patterns of the ontogeny response as for $\Delta_{\text{phloem-soil}}$ for the seven species studied, despite a few exceptions, particularly when choosing photoassimilates as a source for respiration (S3 Table).

**Discussion**

**Isotopic signature of plant-respired CO$_2$**

We found large, significant effects of ontogeny and species identity on $\delta^{13}C_{\text{CO}_2}$-leaf. The magnitude of change due to both ontogeny and species identity effects on the $\delta^{13}C$ signal of respired...
CO₂ was up to 7‰, and the associated respiratory fractionation reached up to 7‰ in Δₚₕlₒₑₘ-leaf. This is in agreement with the 6‰ increase in δ¹³C of leaf-respired CO₂ during the first 22 days of growth of French beans and peanuts, documented in the only other studies about the impact of ontogeny on δ¹³C of CO₂ [3, 17, 18]. These values thus span a similar range as changes in the δ¹³C of leaf-respired CO₂ resulting from changes in environmental conditions (e.g., about 8‰ in [40]). Thus, our results emphasise the relevance of accounting for ontogeny and species identity when using respiratory δ¹³C values to infer plant responses to changing environments. Furthermore, δ¹³C of CO₂-leaf was more enriched than its potential substrate.
in all species and stages considered, indicating that respiratory fractionation in leaves should be accounted for when using δ\textsuperscript{13}C to study respiration in C\textsubscript{3} herbaceous species. The large ontogenetic and species effects that we found on δ\textsuperscript{13}CCO\textsubscript{2}-leaf were associated with significant changes in Δ\textsubscript{Rphloem-leaf} driven by ontogeny and the identity of species or functional groups.

Short-term processes imprint the isotopic signature of photoassimilates that will be allocated to fast- or slow-turnover C pools. Long-term processes control the isotopic signature of slow-turnover C pools. Our results illustrate how both short- and long-term processes are involved in the changes in δ\textsuperscript{13}C of respired CO\textsubscript{2} with species and ontogenetic stages. In the short-term, δ\textsuperscript{13}CCO\textsubscript{2}-leaf was significantly negatively related to Δ\textsubscript{i}, especially at the mature stage, which is directly related to the isotopic signature of fast-turnover C pools [41–43]. The coupling between δ\textsuperscript{13}CCO\textsubscript{2}-leaf and Δ\textsubscript{i} is in agreement with general predictions for annuals and fast-growing species with small C reserves [44], and suggests that a fraction of the newly-synthesized assimilates was likely directly respired by the leaf. Furthermore, Δ\textsubscript{i} is mostly driven by A and gs: it is therefore highly dependent on plant regulation of gas exchange. Under controlled conditions, in the absence of day-to-day environmental variation, changes in leaf gas exchange rates are not driven by changes in climatic conditions, but are responding to changes in the ratio of plant C source to sink strengths [45–47], either directly, as decreasing C source:sink ratios will stimulate leaf gas exchange to meet the increasing C demand, or indirectly, as

| Ontogenetic stage | Species             | Δ\textsubscript{Rphloem-leaf} | Δ\textsubscript{Rphloem-soil} |
|-------------------|---------------------|------------------------------|------------------------------|
| Young             | Arrhenatherum       | -6.94±0.74                   | -6.91±1.13                   |
|                   | Dactylis            | -3.84±1.39                   | -6.96±0.90                   |
|                   | Hordeum             | -1.18±1.96                   | -6.11±0.99                   |
|                   | Lolium              | -4.04±0.50                   | -6.44±0.85                   |
|                   | Medicago            | 0.40±0.66                    | -1.87±1.38                   |
|                   | Trifolium           | -2.51±0.53                   | -3.49±0.74                   |
|                   | Triticum            | -2.51±1.06                   | -6.81±1.73                   |
| Mature            | Arrhenatherum       | -5.43±0.94                   | -6.59±0.65                   |
|                   | Dactylis            | -5.09±1.98                   | -6.43±0.96                   |
|                   | Hordeum             | -4.20±0.35                   | -4.24±0.82                   |
|                   | Lolium              | -5.15±1.03                   | -7.19±0.93                   |
|                   | Medicago            | -3.72±1.00                   | -6.05±1.10                   |
|                   | Trifolium           | -2.71±1.36                   | -6.19±0.70                   |
|                   | Triticum            | -3.74±0.66                   | -5.41±0.98                   |
| Old               | Arrhenatherum       | -3.37±0.84                   | -4.30±1.26                   |
|                   | Dactylis            | -5.54±1.36                   | -6.21±0.64                   |
|                   | Hordeum             | -5.07±1.58                   | -2.44±0.78                   |
|                   | Lolium              | -3.40±1.59                   | -4.55±0.86                   |
|                   | Medicago            | -0.72±1.76                   | -3.69±0.35                   |
|                   | Trifolium           | -3.06±0.56                   | -5.28±0.55                   |
|                   | Triticum            | -4.03±1.07                   | -2.87±0.94                   |

Table 4. Respiratory C isotope fractionation (Δ\textsubscript{o}) at three ontogenetic stages (young foliage, “young”; maximum growth rate, “mature”; beginning of senescence, “old”) in seven species (Arrhenatherum elatius; Dactylis glomerata; Hordeum vulgare; Lolium perenne; Medicago sativa; Trifolium pratense; Triticum aestivum). Δ\textsubscript{o} is calculated between phloem sap organic matter and leaf-respired CO\textsubscript{2} (Δ\textsubscript{Rphloem-leaf}) as well as between phloem sap organic matter and soil-respired CO\textsubscript{2} (Δ\textsubscript{Rphloem-soil}). Within one column, different letters indicate significant difference between ontogenetic stages within a species (p<0.05). Note that only significant differences are shown.

doi:10.1371/journal.pone.0151583.t004
increasing C sinks will translate to increasing leaf and root biomass. Increasing leaf biomass in turn results in higher photosynthesis and transpiration, while increasing root biomass allows better access to water resource, which in turn can translate in higher transpiration, A and gₛ.

Therefore, the relationship between leaf gas exchange and Δ across species and ontogenetic stage suggests that species-related differences in δ¹³C CO₂-leaf could be related to shifts in the balance between C sources and sink strengths. Considering the possible fate of C once assimilated or released from storage, it can either be used to build biomass, be respired or exported. While information about the δ¹³C of exported C—particularly out of the plant (e.g. exudates)—are lacking, in the long-term, we found that δ¹³C CO₂-leaf became more enriched as the plants grew older. Even in the absence of the isotopic signature of exported C, this relationship between δ¹³C of C incorporated in biomass and respired is likely due to changes in the balance between maintenance and growth respiration as plant grew older. Indeed, young and growing plants synthesize large amount of proteins—in particular RuBisCO [48]—and cellulose, both of which generally slightly enriched in ¹³C compared to leaf organic matter [13], thus generating CO₂ that is more ¹³C-depleted than bulk leaf material. At later growth stages, RuBisCO degradation [48] could result in the release of more enriched ¹³C-CO₂.

**Plant respiratory fractionation and C balance**

Over all species and ontogenetic stages, we found a positive relationship between Δₚₚₕₜₜₜₜₑₜₑₜₑ and A. Under our controlled experimental conditions, and within the limits set by the available light intensity and photosynthetic capacity (e.g., as a function of available RuBisCO), changes in the balance between C source and sink strengths were very likely influencing photosynthetic activity [45–47]. Our results suggest that increased C demand from respiring and growing tissues stimulate higher assimilation rates to meet the additional C costs and is associated with less fractionation. In a conifer forest, Ubierna & Marshall [14] also found that C allocation played a key role, but the relationship between A and the difference between δ¹³C leaf and δ¹³C CO₂-leaf was negative. This relationship was attributed to changes in respiratory fractionation resulting from changes in available C that could be diverted to secondary metabolism. Although the relationship between secondary metabolism and δ¹³C respired CO₂ has not been formally proven, this hypothesis is well supported by experimental data (see for example [4] for details). These opposite results might, however, be driven by the same underlying mechanism: higher C availability for secondary metabolism increases respiratory fractionation.

Under field conditions, A is mostly regulated by environmental conditions and particularly light availability, while under constant day-to-day environmental conditions such as in our experiment, A will respond positively to an increase in C sink strength relative to C source. This can be both direct, i.e. increased carbohydrate demand by respiring and growing tissues stimulating C assimilation [45–47, 49], or indirect, when growing aboveground tissue leads to an increase in photosynthetically active tissue. Thus, under field conditions, in addition to covering respiratory C costs and growth, higher photosynthesis rates allow to have carbohydrates available for secondary metabolism, resulting in more apparent fractionation between δ¹³C of respired CO₂ and δ¹³C of respiratory substrate [14]. However, when photosynthetic rate is stimulated by higher C sink strength, higher C demand for growth and maintenance respiration will lead to both higher A and less fractionation between respired CO₂ and its substrate (smaller Δₚₚₚₚₜₜₑₜₑₜₑ in absolute value), since less C is available for secondary metabolism. Therefore, while our results only describe an ontogenetic trend among herbaceous C₃ species and do not allow formal testing of the underlying mechanisms, they are consistent with the hypothesis that respiratory fractionation in leaves is likely responding to changes in the ratio between the strength of C sinks and sources.
Isotopic signature of soil-respired CO₂

At the timescale of our study, we found little overall effects of species, functional group or ontogeny on δ¹³C_{CO₂-soil}, in line with the expected low ontogenetic variability in δ¹³C of root-respired CO₂ (see recent review by [17]). However, the ontogenetic pattern of δ¹³C_{CO₂-soil} differed among functional groups (significant ontogeny × functional group interaction), as a significant ontogenetic effect was detected in crops (namely in Triticum and Hordeum) but not in the other groups. δ¹³C_{mix} showed a response pattern that was similar to that of δ¹³C_{CO₂-soil}, suggesting that the crop-specific ontogenetic effects on the isotopic signature of soil CO₂ emissions were, at least in part, shaped by the metabolic activity of the soil microbial community. Changes in microbial community structure have been associated with changes in the isotopic signature of CO₂ respired by heterotrophs [50, 51]. Thus, our results suggest that plant-microbial interaction dynamics over time may differ between crops and the other functional groups included here.

The large soil organic matter pool most likely contributed as a substrate for microbial respiration and thus for soil CO₂ efflux in our experiment, especially for plants in the young stage. Based on the relative plant assimilation and soil respiration rates at different ontogenetic stages, we can at least determine stages at which soil organic C may have been contributing to soil CO₂ efflux. At the young stage, overall photosynthesis was likely not sufficient to sustain the total soil CO₂ efflux, except in crops (S4 Table). At the mature stage, soil CO₂ efflux could have been fuelled by assimilation in all species, except Dactylis. Finally, at the old stage, the overall assimilation flux was potentially sufficient to meet respiration costs, except for legumes. Thus, the discrimination associated with soil microbial respiratory processes may change with ontogeny, as a consequence of several processes, including shifts in the relative activity of different microbial populations [50, 51] or in the organic substrate preferentially metabolized [52], but our experimental setup does not allow to quantify these processes.

Additionally, the changes in δ¹³C_{CO₂-soil} and associated changes in Δ_{R-soil-phloem} with ontogeny and functional group were possibly driven by 1) changes in the relative contribution of plants to the overall soil CO₂ efflux, both through root respiration and microbial respiration fed by plant rhizodeposits, and 2) changes in the fractionation between respired CO₂ and respiratory substrate provided by the plants, i.e., phloem sap organic matter, either directly as a source for root respiration or indirectly as C exudates. Little information is available to discuss (1), especially in terms of root exudation. Nonetheless, the contribution of root-respired CO₂ (and its isotopic signature) to total soil CO₂ efflux and its signature is expected to increase with the development of the plant root system. The lack of a significant relationship in our study between Δ_{R-soil-phloem} and aboveground biomass (the latter should be correlated with root biomass [53]) does not support an increased contribution of roots to total CO₂ efflux with growth. However, our results support (2) as a mechanism shaping part of the ontogeny and functional group effects on δ¹³C_{CO₂-soil}. As expected, ontogeny strongly affected Δ_{R-soil-phloem}, since it also affected its putative substrate, δ¹³C_{phloem}. Nevertheless, considering a different proxy for respiration substrate, such as root biomass, showed very similar results (S3 Table). Thus, the Δ_{R-soil-phloem} response to ontogeny was not solely driven by change in δ¹³C_{phloem}, but reflected actual changes in respiratory processes. In contrast, we detected no overall ontogeny effects on δ¹³C_{CO₂-soil}, suggesting that although ontogeny affects the ¹³C signature of plant material, these changes do not propagate to the isotopic signature of soil respiration.

Moreover, our study showed consistent relationships on different time scales between Δ_{R-soil-phloem} and leaf gas exchange. Δ_{R-soil-phloem} was negatively related to Δ (i.e., dependent on A and gₛ) and positively related to the ratio of assimilation to leaf respiration (A/Rₛ) at the old stage. Note that similar relationships were found when considering another proxy than phloem as
respiration substrate, indicating that these results were not an artefact due to the correlation between δ13C of phloem and leaf gas exchange. Both relations suggest that, in agreement with results for aboveground tissues, increased C assimilation (higher A, resulting in both higher A/RI and lower Δi) leads to smaller respiratory fractionation in absolute values, most likely since most assimilated C is directed towards primary rather than secondary metabolism. This hypothesis is supported by several studies that documented the importance of aboveground controls of C allocation to root respiration ([54] and references therein). Additionally, C fixation by PEPC in belowground plant tissues might also play an important role in the isotopic signature of respiratory substrates in roots [17] and thus lead to an apparent fractionation between phloem sap organic matter and respired CO2.

The ontogeny effect on ΔRsoil-phloem was specific to each functional group. In particular, crops showed a significant decrease in absolute values between younger and older stages, while little differences were found in forage grasses and legumes. Crops, unlike legumes and forage grasses, are selected for grain rather than vegetative biomass production. Despite grain filling did not take place in this study (see above), C allocation and nutrient uptake in crops may have been switching towards storage (for example as sucrose and fructans in the stem [55] and references therein) in preparation for grain filling, possibly leading to the measured changes in apparent respiratory C fractionation and consequently in δ13C CO2-soil efflux. Furthermore, crop is the only functional group for which total assimilation was sufficient to cover total C lost through respiration at every ontogenetic stage (S4 Table). This is consistent with a tighter coupling between respiration fractionation in soil and plant C dynamics in crops than in other functional groups.

Conclusion

Our results show that biological factors (i.e., ontogeny and species identity) can strongly affect the carbon isotopic signature of respired CO2 and respiratory fractionation. These factors need to be accounted for in studies inferring physiological responses of plants to their biotic and abiotic environment based on δ13C of respired CO2 and respiratory fractionation. Furthermore, we show that these ontogeny-related changes in δ13C of respired CO2 and respiratory fractionation are associated with changes in physiological processes involved in the plant C budget and particularly with changes in photosynthesis, biomass and respiration. Therefore, our results suggest that ontogeny-related changes in the ratio of plant internal C source to sink strengths drove the measured changes in δ13C of respired CO2 and respiratory fractionation.

Supporting Information

S1 Fig. δ13C values of leaf-respired CO2 and soil-respired CO2 at three ontogenetic stages in three functional groups.
(DOCX)

S2 Fig. Respiratory carbon isotope fractionation (ΔR) in three functional groups.
(DOCX)

S3 Fig. Response of ΔRphloem-soil to Δi and to A/RI.
(DOCX)

S1 Table. δ13C values (in per mil) of leaf biomass, root biomass, phloem organic matter as well as leaf and soil respired CO2 for different plant species at three ontogenetic stages.
(DOCX)
S2 Table. ANOVA results for $R_l$, $A$, $g_s$, $\Delta_i$, $B$, $L_A$ and $R_s$.

(SDOCX)

S3 Table. Respiratory C isotope fractionation ($\Delta_R$) at three ontogenetic stages in seven species.

(SDOCX)

S4 Table. Estimated average daily C balance of pots.

(SDOCX)

Acknowledgments

We thank Markus Schäuble for precious help with growing plants and sampling, Gérome Tokpa for help with leaf-gas exchange measurements, Roland A. Werner and Karin Sörgel for help with isotope measurements, Karin Beer, Josua Bizozzero, Sandro Fornallaz, Gopal Joshi, Caroline Kulongara and Carolin Ries for help with sample preparation. We thank two anonymous reviewers for their helpful comments. This project was supported by the Swiss National Science Foundation (project n°3100A0-105273/1 to NB).

Author Contributions

Conceived and designed the experiments: YS NB RLB. Performed the experiments: YS RLB. Analyzed the data: YS. Contributed reagents/materials/analysis tools: YS RLB. Wrote the paper: YS NB RLB. Funding: NB.

References

1. Dawson TE, Mambelli S, Plamboeck AH, Templer PH, Tu KP. Stable isotopes in plant ecology. Annu Rev Ecol Syst. 2002; 33:507–59. PMID:ISI:000180007000019.
2. McDowell NG, Bowling DR, Schauer A, Irvine J, Bond BJ, Law BE, et al. Associations between carbon isotope ratios of ecosystem respiration, water availability and canopy conductance. Global Change Biology. 2004; 10:1767–84.
3. Bathellier C, Badeck F-W, Couzi P, Harscoët S, Mauve C, Ghashghaie J. Divergence in $\delta^{13}C$ of dark respired CO$_2$ and bulk organic matter occurs during the transition between heterotrophy and autotrophy in Phaseolus vulgaris plants. New Phytologist. 2008; 177:406–18. PMID:17953651
4. Priault P, Wegener F, Werner C. Pronounced differences in diurnal variation of carbon isotope composition of leaf respired CO$_2$ among functional groups. New Phytologist. 2009; 181:400–12. PMID: WOS:000261792900015. doi:10.1111/j.1469-8137.2008.02665.x
5. Salmon Y, Barnard RL, Buchmann N. Ontogeny and leaf gas exchange mediate the carbon isotopic signature of herbaceous plants Plant, Cell & Environment. 2011; 34:465–79. doi: 10.1111/j.1365-3040.2010.02256.x
6. Duranceau M, Ghashghaie J, Badeck F, Deléens E, Cornic G. $\delta^{13}C$ of CO$_2$ respired in the dark in relation to $\delta^{13}C$ of leaf carbohydrates in Phaseolus vulgaris L. under progressive drought. Plant, Cell & Environment. 1999; 22:515–23. PubMed Central PMCID: PMChtml only.
7. Tcherkez G, Noguès S, Bleton J, Cornic G, Badeck F, Ghashghaie J. Metabolic origin of carbon isotope composition of leaf dark-respired CO$_2$ in french bean. Plant Physiology. 2003; 131:237–44. PMID:12529531
8. Ocheltree TW, Marshall JD. Apparent respiratory discrimination is correlated with growth rate in the shoot apex of sunflower (Helianthus annuus). Journal Of Experimental Botany. 2004; 55:2599–605. PMID:ISI:000225252600014.
9. Badeck FW, Tcherkez G, Nogues S, Piel C, Ghashghaie J. Post-photo synthetic fractionation of stable carbon isotopes between plant organs—a widespread phenomenon. Rapid Communications in Mass Spectrometry. 2005; 19:1381–91. PMID:ISI:000229518600004.
10. Bathellier C, Tcherkez G, Bligny R, Gout E, Cornic G, Ghashghaie J. Metabolic origin of the $\delta^{13}C$ of respired CO$_2$ in roots of Phaseolus vulgaris. New Phytologist. 2009; 181:387–99. doi: 10.1111/j.1469-8137.2008.02679.x PMID:19021866
Gessler A, Tcherkez G, Karyanto O, Keitel C, Ferrio JP, Ghaghiaie J, et al. On the metabolic origin of

Wegener F, Beyschlag W, Werner C. Dynamic carbon allocation into source and sink tissues determine

27. Werner RA, Brand WA. ConFlo III—An interface for high precision δ13C and δ15N analysis with an extended dynamic range. Rapid Communications in Mass Spectrometry. 1999; 13:1237–41. PMID: 10407304

28. Werner RA, Brand WA. Referencing strategies and techniques in stable isotope ratio analysis. Rapid Communications in Mass Spectrometry. 2001; 15.;501–19. PMID: 11268135

29. Zeeman MJ, Werner RA, Eugster W, Siegwolf RTW, Wehrle G, Mohn J, et al. Optimization of automated gas sample collection and isotope ratio mass spectrometric analysis of δ13C of CO2 in air. Rapid Communications in Mass Spectrometry. 2008; 22:3883–92. doi: 10.1002/rcm.3772 PMID: 18988208

30. Farquhar GD, O’Leary MH, Berry JA. On the relationship between carbon isotope discrimination and the intercellular carbon dioxide concentration in leaves. Australian Journal of Plant Physiology. 1982; 9:121–37.
31. Gessler A, Tcherkez G, Peuke AD, Ghashghaie J, Farquhar GD. Experimental evidence for diel variations of the carbon isotope composition in leaf, stem and phloem sap organic matter in *Ricinus communis*. Plant Cell and Environment. 2008; 31:941–53. PMID: WOS:000256620500005.

32. Rascher KG, Maguas C, Werner C. On the use of phloem sap δ13C as an indicator of canopy carbon discrimination. Tree Physiol. 2010; 30:1499–514. doi: 10.1093/treephys/tpq092 PMID: WOS:000284644100003; PubMed Central PMCID: PMCPlant.

33. Craig H. Carbon-13 in plants and the relationships between carbon-13 and carbon-14 variations in nature. Journal of Geology. 1954; 62:115–49. PMID: WOS:A1954UY68100001.

34. Roeseke CA, O’Leary MH. Carbon isotope effects on the enzyme-catalyzed carboxylation of ribulose bisphosphate. Biochemistry. 1984; 23:6275–84. PMID: WOS:A1984TX68300058.

35. Farquhar GD, Ehleringer JR, Hubick KT. Carbon isotope discrimination and photosynthesis. Annual Review of Plant Physiology and Plant Molecular Biology. 1989; 40:503–37. PMID: A1989U857900019.

36. Pons TL, Flexas J, Caemmerer SV, Evans JR, Genty B, Ribas-Carbo M, et al. Estimating mesophyll conductance to CO2: methodology, potential errors, and recommendations. Journal of Experimental Botany. 2009; 60:2217–34. doi: 10.1093/jxb/erp081 PMID: 19357431.

37. Farquhar GD, Richards RA. Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. Australian Journal of Plant Physiology. 1984; 11:539–52.

38. Lloyd J, Farquhar GD. δ13C discrimination during CO2 assimilation by the terrestrial biosphere. Oecologia. 1994; 99:201–15. PMID: A1994PP22700001.

39. R Development Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2013.

40. Sun W, Resco V, Williams DG. Diurnal and seasonal variation in the carbon isotope composition of leaf dark-respired CO2 in velvet mesquite (*Prosopis velutina*). Plant, Cell & Environment. 2009; 32:1390–400. doi: 10.1111/j.1365-3040.2009.02006.x.

41. Lehmeier CA, Lattanzi FA, Schäufele R, Wild M, Schnyder H. Root and shoot respiration of perennial ryegrass are supplied by the same substrate pools—assessment by dynamic 13C labeling and compartmental analysis of tracer. Plant Physiology. 2008; 148:1148–58. doi: 10.1104/pp.108.127324 PMID: 18715953.

42. Schnyder H, Schaufele R, Lotscher M, Gebing T. Disentangling CO2 fluxes: direct measurements of mesocosm-scale natural abundance 13CO2/12CO2 gas exchange, 13C discrimination, and labelling of CO2 exchange flux components in controlled environments. Plant, Cell & Environment. 2003; 26:1863–74. PMID: 000186500700006.

43. Nogués S, Tcherkez G, Cornic G, Ghashghaie J. Respiratory carbon metabolism following illumination in intact french bean leaves using 13CO12C isotope labeling. Plant Physiology. 2004; 136:3245–54. PMID: 15377781.

44. Mortazavi B, Conte MH, Chanton JP, Smith MC, Weber JC, Crumsey J, et al. Does the 13C of foliage-respired CO2 and biochemical pools reflect the 13C of recently assimilated carbon? Plant Cell and Environment. 2009; 32:1310–23. doi: 10.1111/j.1365-3040.2009.01999.x PMID: WOS:000269592300003.

45. Rolland F, Moore B, Sheen J. Sugar sensing and signaling in plants. Plant Cell. 2002; 14:S185–S205. PMID: 0001761875000013.

46. Franck N, Vaast P, Genard M, Dauzat J. Soluble sugars mediate sink feedback down-regulation of leaf photosynthesis in field-grown *Coffea arabica*. Tree Physiol. 2006; 26:517–25. PMID: 000236438900012.

47. Hermans C, Hammond JP, White PJ, Verbruggen N. How do plants respond to nutrient shortage by biomass allocation? Trends In Plant Science. 2006; 11:610–7. PMID: 000243054100008.

48. Thomas H. Senescence, ageing and death of the whole plant. New Phytologist. 2013; 197:696–711. doi: 10.1111/nph.12047 PMID: 23176101.

49. Kömer C. Paradigm shift in plant growth control. Current Opinion in Plant Biology. 2015; 25:107–14. doi: http://dx.doi.org/10.1016/j.pbi.2015.05.003. doi: 10.1016/j.pbi.2015.05.003 PMID: 26037389.

50. Andrews JA, Matamala R, Westover KM, Schlesinger WH. Temperature effects on the diversity of soil heterotrophs and the δ13C of soil-respired CO2. Soil Biology & Biochemistry. 2000; 32:699–706. PMID: 000086959600014.

51. Crow SE, Sulzman EW, Rugh WD, Bowden RD, Lajtha K. Isotopic analysis of respired CO2 during decomposition of separated soil organic matter pools. Soil Biology & Biochemistry. 2006; 38:3279–91. doi: 10.1016/j.soilbio.2006.04.007 PMID: 000241484700010.

52. Lerch T, Nunan N, Dignac MF, Chen Y, Mariotti A. Variations in microbial isotopic fractionation during soil organic matter decomposition. Biogeochemistry. 2011; 106:5–21.
53. Barnes A. Vegetable plant part relationships. II. A quantitative hypothesis for shoot/storage root development. Annals of Botany. 1979; 43:487–99.

54. Lambers H, Chapin FS, Pons T. Plant physiological ecology. New York, USA: Springer 1998.

55. Pheloung PC, Siddique KHM. Contribution of stem dry matter to grain yield in wheat cultivars. Australian Journal of Plant Physiology. 1991; 18:53–64.