

# The dual C and O isotope – gas exchange model: A concept review for understanding plant responses to the environment and its application in tree rings

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## Abstract

The combined study of C and O isotopes in plant organic matter has emerged as a powerful tool for understanding plant functional response to environmental change. The approach relies on established relationships between leaf gas exchange and isotopic fractionation to derive a series of model scenarios that can be used to draw inferences about changes in photosynthetic assimilation and stomatal conductance driven by changes in environmental parameters (CO<sub>2</sub>, water availability, air humidity, temperature, nutrients). We review the mechanistic basis for model and research to date, and discuss where isotopic observations don't match our current understanding of plant physiological response to environment. We demonstrate that 1) the model has been applied successfully in many, but not all studies, and 2), while originally conceived for leaf isotopes, the model has been applied extensively to tree ring isotopes in the context of tree physiology and dendrochronology. Where isotopic observations deviate from physiologically plausible conclusions, this mismatch between gas-exchange and isotope response provides valuable insights on underlying physiological processes. Overall, we found that isotope responses can be grouped into situations of increasing resource limitation versus higher resource availability. Thus, the dual isotope model helps to interpret plant responses to a multitude of environmental factors.

## The dual C and O isotope – gas exchange model: A concept review for understanding plant responses to the environment and its application in tree rings

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The combined study of C and O isotopes in plant organic matter has emerged as a powerful tool for understanding plant functional response to environmental change. The approach relies on established relationships between leaf gas exchange and isotopic fractionation to derive a series of model scenarios that can be used to draw inferences about changes in photosynthetic assimilation and stomatal conductance driven by changes in environmental parameters (CO<sub>2</sub>, water availability, air humidity, temperature, nutrients). We review the mechanistic basis for model and research to date, and discuss where isotopic observations don't match our current understanding of plant physiological response to environment. We demonstrate that 1) the model has been applied successfully in many, but not all studies, and 2), while originally conceived for leaf isotopes, the model has been applied extensively to tree ring isotopes in the context of tree physiology and dendrochronology. Where isotopic observations deviate from physiologically plausible conclusions, this mismatch between gas-exchange and isotope response provides valuable insights on underlying physiological processes. Overall, we found that isotope responses can be grouped into situations of increasing resource limitation versus higher resource availability. Thus, the dual isotope model helps to interpret plant responses to a multitude of environmental factors.

## Introduction

Plants are subject to a wide range of environmental impacts and even withstand environmental extremes, e.g. in temperature (e.g. -60 to + 45°C in boreal forests), water availability (e.g. prolonged months of drought in arid regions), nutrient availability (e.g. low nutrients in mountainous regions) and disturbance (e.g. storm damage, fires or land use change). Their ability to acclimate in place is therefore critical for their survival. To describe the nature of responses and acclimatization, detailed and comprehensive plant physiological measurements are necessary; however, the intensive nature of these measurements often limits the extent to which they can be applied across space and time. Moreover, numerous physiological measurements of plant responses to the environment (e.g. classical approaches such as plant gas exchange, light interception, sap flux measurements, or dendrometry, etc.) cannot be applied retrospectively. Here, the analysis of stable isotope ratios of plant organic matter can provide additional insights by effectively tracing and integrating physiological processes over both time and space (Dawson & Siegwolf, 2007).

The use of stable isotopes as a proxy for understanding the relationships between environment and plant function relies on a mechanistic understanding of the drivers of isotopic fractionation (Dawson *et al.*, 2002). For instance, changes in environmental conditions and related effects on photosynthesis and transpiration result in predictable carbon and oxygen isotope ratios that are imprinted on photosynthetic assimilates (e.g. carbohydrates). Although there may be further possible isotope fractionations between primary and secondary metabolites, these isotopic “fingerprints” are ultimately reflected in the biomass. The isotopic ratio of assimilates can thus be used as a record of the interaction between the plant and its environment over the lifetime of the specific tissue (e.g. leaf, roots or wood), since every biomolecule carries the specific isotope ratio from the moment it was synthesized.

In the last three decades, the application of stable carbon and oxygen isotope ratios (<sup>13</sup>C/<sup>12</sup>C and <sup>18</sup>O/<sup>16</sup>O) in plant ecophysiological research has become common for studies of short- and long-term effects of environmental changes on vegetation (Dawson & Siegwolf, 2007, Ehleringer *et al.*, 2000, Farquhar *et al.*, 1982, Griffiths *et al.*, 1997). As each isotope ratio reflects specific physiological responses caused by specific environmental changes, the use of both carbon and oxygen isotope ratios provides highly complementary information that improves the potential for interpreting cause and effect. Consequently, the two isotope ratios have been combined and linked with leaf-level CO<sub>2</sub> and H<sub>2</sub>O gas exchange in a formal conceptual

model that facilitates inferences about changes in assimilation and stomatal conductance in response to the environment (Scheidegger *et al.*, 2000).

The dual carbon and oxygen isotope model formally proposed by Scheidegger *et al.*, (2000), hereafter described as the DI-model, has been subject to a diversity of applications. With these applications have come new insights into the strengths and weaknesses of the model that have led to advances in our understanding of plant function. To highlight these insights, we carried out a quantitative review of studies that have engaged the DI-model to date. Specifically, we aimed to 1) review the mechanistic basis of the model, 2) determine the nature and extent of its application to date in different fields, and 3) review studies that provide data on the mechanistic relationships between plant physiology and carbon/oxygen isotopes to strengthen our ability to interpret the model.

### The dual carbon and oxygen isotope model for C3 plants

The purpose of the DI-model is to make inferences regarding the responses of net assimilation ( $A_{\text{net}}$ , Larcher, 2003) and stomatal conductance ( $g_s$ ) to environmental variables based on a dual-isotope (carbon and oxygen) response. Since 1) both carbon and plant oxygen isotope ratios are modified during  $\text{CO}_2$  and  $\text{H}_2\text{O}$  gas exchange in the same leaf, but by different processes (photosynthesis and transpiration), and 2) both carbon and oxygen are incorporated into organic matter equally, it provides a means by which to distinguish whether a change in isotope ratios is the result of a change in photosynthesis or in stomatal conductance. Current theory on carbon and oxygen isotope fractionations is summarized in Breakout Boxes 1 and 2.

In general, two conditions are compared so that it is possible to draw an arrow from condition A to condition B both with respect to the isotope and gas-exchange observations (Figure 1). The conditions A and B may represent two treatments in a controlled experiment, two functional groups (e.g. broad leaved plants and conifers) in the same ecosystem, leaf or stem samples from two positions in a canopy, one species compared between two sites, the same plant at two time points (temporal development), etc. Note that the red arrows in Figure 1 refer to a range of plant responses, indicating the plasticity of plants responding to environmental impacts within the indicated range.

First, the carbon and oxygen isotope ratios need to be measured in an organic compound (e.g. bulk leaf, cellulose, sugars, wood or root material) of the plants under investigation. Proper selection of the plant and compound is important, as it has consequences for the temporal scale at which the physiological processes are integrated. For instance, the time integrated by different compounds is usually longest for cellulose, intermediate for bulk, smaller for water-extracted compounds and shortest for isolated sucrose (Lehmann *et al.*, 2017). Second, the “input-scheme” of the DI-model, a plot of  $\delta^{18}\text{O}$  data versus  $\delta^{13}\text{C}$  data comparing the conditions of interest, can be drawn. Alternatively, the oxygen enrichment in the organic compound relative to source water ( $\Delta^{18}\text{O}$ ) can be presented. This is advantageous in cases where the  $\delta^{18}\text{O}$  of source water differs between treatment conditions A compared to B; given that this is not a leaf-level physiological effect, it could ultimately result in erroneous model interpretations (Roden & Siegwolf, 2012). Similarly, it is also possible to present the carbon isotope discrimination ( $\Delta^{13}\text{C}$ ) instead of original  $\delta^{13}\text{C}$  data, particularly in cases where the  $\delta^{13}\text{C}$  of source  $\text{CO}_2$  is not constant (e.g. atmospheric  $\text{CO}_2$  enrichment studies, or retrospective analyses of organic matter, tree ring, peat bogs). Note that in the case of  $\Delta^{13}\text{C}$ , the  $^{13}\text{C}$  arrows in the dual-isotope plot will be pointing inverse inclination as compared to using ( $\delta$ ) original data, whereas for  $\Delta^{18}\text{O}$  the direction of the arrows remain unchanged. Here, we assume the presentation of  $\delta^{18}\text{O}$  or  $\Delta^{18}\text{O}$  vs.  $\delta^{13}\text{C}$  (Figure 1).

Deducing the  $A_{\text{net}} - g_s$  response from the isotope pattern can be explained as a 3-step-process: 1) a change in  $c_i/c_a$  (the ratio of leaf internal to ambient  $\text{CO}_2$ ) is deduced from a change in the  $\delta^{13}\text{C}$ , 2) a change e.g. in the relative humidity (RH) or vapour pressure deficit (VPD) is causing a change in  $g_s$ , which is deduced from a change in the  $\delta^{18}\text{O}$ , and 3) the estimated  $c_i/c_a$  change is re-interpreted as a change in net photosynthesis ( $A_{\text{net}}$ ) and stomatal conductance ( $g_s$ ) based on the information derived in the previous steps. The first step is relatively straightforward based on the theory of carbon isotope fractionation during photosynthesis (Breakout Box 1) (Farquhar *et al.*, 1989, Farquhar *et al.*, 1982). Thus, a significant increase

in  $\delta^{13}\text{C}$  (scenarios #1, 2, 8) will be interpreted as a decrease in  $c_i/c_a$ , a decrease in  $\delta^{13}\text{C}$  (scenarios #4 to 6) as an increase in  $c_i/c_a$ , and no change in  $\delta^{13}\text{C}$  (scenarios #3 and #7) as no change in  $c_i/c_a$ . In the second step, a change in  $\delta^{18}\text{O}$  can be interpreted as a response of  $g_s$  to humidity (Breakout Box 2). This is also relatively straightforward, given established theory on oxygen isotope fractionation. In particular, enrichment is strongly driven by drier conditions (low RH or high VPD affecting  $g_s$ , resulting in a low leaf external to internal partial vapour pressure ratio ( $e_a/e_i$ , see Breakout Box 2) and leading to higher  $\text{H}_2^{18}\text{O}$  enrichment, as described by the Pécelet modified Craig-Gordon/Dongman model (Cernusak *et al.*, 2002, Craig & Gordon, 1965, Dongmann *et al.*, 1974, Farquhar & Lloyd, 1993, Kahmen *et al.*, 2008). The third step is the most critical one, resulting in the qualitative nature of the model. As an example, we discuss scenarios #4 and #6, which both indicate increasing  $c_i/c_a$  that can be caused by either increasing  $g_s$  or decreasing  $A_{\text{net}}$ . In scenario #4, we additionally know that there is higher  $\delta^{18}\text{O}$  (“drier conditions”), therefore, the case of increasing  $g_s$  seems physiologically implausible and the other possibility, decreasing  $A_{\text{net}}$ , is selected. In contrast, for scenario #6, we observe lower  $\delta^{18}\text{O}$  at increasing  $c_i/c_a$  and thus increasing  $g_s$  is more likely than decreasing  $A_{\text{net}}$ . This kind of reasoning directly results in the proposed  $A/g_s$  scenarios shown in the bottom row of Figure 1.

The use of the original DI-model is applicable for a large number of studies. However, care must be taken when plants respond differently to specific conditions, e.g., to increasing  $\text{CO}_2$ , air pollutants, changes in nutrient supply, or extreme drought. This can lead to model outputs that suggest plant responses that contradict our current physiological understanding because such additional and potentially uncontrollable impacts are not considered by current C- or O-isotope fractionation models. Consequently, the DI-model will produce physiologically non-plausible results as it is strictly based on the C and O isotope fractionation and gas exchange principles (see sections 3, 5 and 6). Such discrepancies then need to be resolved, by considering the changes in fractionation mechanisms or different timing of leaf- and stem level processes.

An example for such discrepancies is cases of extreme and on-going drought. Under such conditions the isotopic signal of the leaves could not be found in the stems or other heterotrophic tissue. Since water became so limiting, no growth was possible and the assimilates were barely sufficient to maintain the metabolism. Therefore, no isotope signal representing these hot and dry conditions were evident in the wood (Pflug *et al.*, 2015, Sarris *et al.*, 2013).

Slightly deviating responses are possible and shown with the dashed red arrows in the model outputs, which reflect a certain range of physiological responses rather than a singular direction (Figure 1), as suggested also by (Grams *et al.*, 2007). Overall, the strength of the approach remains obvious: plant functional response to environmental impacts can generally be deduced using isotopes in the absence of detailed physiological measurements. Or, in the case of non-plausible results, the model facilitates the discovery of previously overlooked plant responses through a new lens.

### The C and O isotopic signals during carbohydrate transfer from leaf to whole plant (Post photosynthetic fractionation)

The DI-model was originally derived from leaf isotope and gas exchange data. This raises the question as to whether or not, and to what degree, its application to other tissues (e.g. tree rings, roots, etc.) is possible? As the isotope signals of the newly formed assimilates are dampened by post-photosynthetic processes, a careful evaluation is needed to understand whether the patterns are consistent among tissues. Given the available literature (Barbour *et al.*, 2017, Cernusak *et al.*, 2016, Cernusak *et al.*, 2013, Gessler *et al.*, 2014, and literature therein) we focus on those factors that have the most prominent post-photosynthetic impact on the isotope signals during the carbohydrate transfer processes between leaves and whole plant.

**a) Carbon isotopes:** Post-photosynthetic fractionations begin immediately following the sugar formation and prior to phloem export. For carbon, kinetic and equilibrium isotope fractionations related to aldolase-catalysed reactions can cause that transitory starch and remobilized sugars at night-time are more  $^{13}\text{C}$ -enriched than daytime sucrose (Gleixner *et al.*, 1998, Tcherkez *et al.*, 2004, Tcherkez *et al.*, 2011). However, starch related  $^{13}\text{C}$ -fractionations can be very small (Maunoury-Danger *et al.*, 2009) and their

significance can vary among species and are under debate (Bögelein *et al.*, 2019, Lehmann *et al.*, 2019a). Moreover,  $\delta^{13}\text{C}$  differences among individual sugars in leaf and phloem have been observed (Churakova *et al.*, 2018, Rinne *et al.*, 2015), with sucrose being often the most  $^{13}\text{C}$ -enriched soluble sugar. The  $^{13}\text{C}$ -fractionations have been related to the invertase reaction (Mauve *et al.*, 2009). In addition, tree tissues often have high abundances of sugar alcohols or cyclitols, which can be isotopically different from primary sugars (Lehmann *et al.*, 2017, Rinne *et al.*, 2015). The low turnover rate of sugar alcohols can strongly dampen the  $\delta^{13}\text{C}$  responses of bulk sugar fractions to changes in physiology and climate (Galiano Pérez *et al.*, 2017). Additional isotope fractionations may occur during the export of leaf sugars into the phloem and during their translocation to sink tissues (Gessler *et al.*, 2009a). Only recently it has been observed that phloem exudates can be more enriched compared to leaf assimilates and that the  $^{13}\text{C}$ -enrichment increased with canopy height (Bögelein *et al.*, 2019). The isotope fractionation was explained by compartmentalisation of leaf sugars in the mesophyll, causing that the designated export sugar sucrose is more  $^{13}\text{C}$ -enriched in the cytosol than stored sucrose in the vacuole. As a result of these fractionation processes, leaf  $\delta^{13}\text{C}$  values are on average often 2 - 3 (Badeck *et al.*, 2005, Chevillat *et al.*, 2005). Subsequent carbon isotope fractionation associated with branch respiration could also contribute to a shift in isotope ratios (Ghashghaie *et al.*, 2003). Furthermore, mixing between old, stored and new freshly assimilated carbohydrates occurs during phloem transport (Boegelein *et al.*, 2019), which is partly affected by the formation of fresh carbohydrates via stem photosynthesis (Brüggemann *et al.*, 2011).

During early wood formation in spring, trees (particularly broadleaves) utilize stored assimilates from previous years, then gradually switch to fresh more  $^{13}\text{C}$  depleted assimilates (Helle & Schleser, 2004). These stored carbohydrate compounds are generally enriched in  $^{13}\text{C}$  (Jaeggi *et al.*, 2002) compared to fresh assimilates, especially for starch and its derivatives (Gleixner & Schmidt, 1997). Therefore, we recommend for tree ring analyses to distinguish between early and latewood wherever possible to minimize the inclusion of isotopic signals from old carbohydrates from previous years.

Also, when considering longer time periods, the impact of industrialization (starting ca. 1850) on the C-isotope ratio in atmospheric  $\text{CO}_2$  becomes visible as  $\delta^{13}\text{C}$  continuously decreases (Suess effect) resulting from fossil fuel burning and land use change. For the evaluation of time series (tree rings or comparing conserved plant material) this effect needs to be considered (McCarroll & Loader, 2004).

**b) Oxygen Isotopes:** For  $\delta^{18}\text{O}$  in organic matter, the isotope ratio of source water is key. In early studies, the  $\delta^{18}\text{O}$  values of precipitation were used as surrogate for source water. However, plants acquire water from a range of lateral and vertical distances with considerable  $\delta^{18}\text{O}$  ( $\delta^2\text{H}$ ) gradients depending on the soil structure (Goldsmith *et al.*, 2019, Mueller *et al.*, 2014, Sprenger *et al.*, 2016), resulting in a strongly dampened variation of the  $\delta^{18}\text{O}$  values of the source water compared to those of precipitation. Thus the xylem water represents a mixture of water bodies extracted from the soil, with the highest  $\delta^{18}\text{O}$  values generally at the soil surface and the lowest at the deepest rooting depth. Further issues arise with seasonal changes in  $\delta^{18}\text{O}$  of source water (Saurer *et al.*, 2016). Allen *et al.* showed that the seasonal origin of the isotope signature of xylem water in summer originated in large part from winter precipitation (Allen *et al.*, 2019, Brinkmann *et al.*, 2018). Thus, source water varies as a function of both time and space. This temporal shift in the isotope signal needs critical consideration: The source water  $\delta^{18}\text{O}$  signal represents a delayed value depending on its seasonal origin relative to  $\delta^{18}\text{O}$  in precipitation and the given climatic conditions (Allen *et al.*, 2019, Brinkmann *et al.*, 2018). On the other hand, the effect of the seasonal origin could be balanced under continuous humid climate conditions, as the impact of  $\delta^{18}\text{O}$  of water vapour diffusing from the ambient air into the leaf intercellular spaces could over-modulate the isotopic signal of the source water (Lehmann *et al.*, 2019b, Roden *et al.*, 2004).

While no significant isotope fractionation is assumed during  $\text{H}_2\text{O}$  uptake and transport in the xylem along a tree trunk, leaf water is generally enriched in  $^{18}\text{O}$  in the leaves during transpiration with its magnitude depending on the atmospheric evaporative demand (VPD) and the  $\delta^{18}\text{O}$  of ambient water vapour (Kahmen *et al.*, 2011, Lehmann *et al.*, 2018, Breakout Box 2). During photosynthesis, an exchange between the oxygen atoms originating from  $\text{CO}_2$  and that of  $\text{H}_2\text{O}$  takes place imprinting the  $\delta^{18}\text{O}$  values of the leaf

water on the assimilates because the amount of O-atoms of water is by magnitudes larger than that of assimilated CO<sub>2</sub> (Lehmann *et al.*, 2017). Thus, freshly assimilated carbohydrates always reflect both the isotopic variations of source and leaf water. Biosynthetic fractionation causes sugars to be about 27‰ water used for photosynthesis (Yakir & Deniro, 1990; Sternberg & Deniro, 1983). During carbohydrate transport via phloem and concurrent cellulose synthesis, a partial O exchange with unenriched xylem water occurs. This exchange, resulting in a ca. 40‰ O-exchange, dampens the leaf water δ<sup>18</sup>O signal (Roden & Ehleringer, 1999, Barbour *et al.*, 2007), likely the largest modification of the δ<sup>18</sup>O signal in assimilates between the leaves and tree rings.

*To summarize:* For the δ<sup>13</sup>C values, the mixing of old stored carbohydrates (starch and sugar synthesis and remobilization) likely has the strongest dampening effect, probably stronger than phloem loading and (heterotrophic) stem and root respiration. For the δ<sup>18</sup>O values, the O-exchange during carbohydrate transport in the phloem and during tree-ring cellulose synthesis probably impacts the oxygen isotope signal the strongest, which might also be amplified by the seasonal origin of the source water (Allen *et al.*, 2019; Brinkmann *et al.*, 2018). To minimize the post-photosynthetic fingerprints on C and O isotope ratios, it is recommended to use late wood in tree rings whenever possible. However, in spite of these modifications and dampening of the C and O isotope values during the carbohydrate transport from leaves to whole plant and cellulose synthesis, the leaf level isotope signal is largely maintained in the wood (Saurer *et al.*, 1997, Song *et al.*, 2011).

### Overview of research engaging the model

We identified 261 studies citing Scheidegger *et al.*, 2000 (ISI Web of Knowledge, September, 2018). Of these studies, we excluded review and commentary articles and identified 184 containing new plant carbon and oxygen isotope data (Appendix S1). Studies after this date were considered in the text. These studies covered a broad range of plant life forms, although the majority (89 %) comprised woody (tree or shrub) species. Most studies were performed in temperate regions, but a few were from tropical (dry or moist), polar, and/or dry regions. Gymnosperms and angiosperms from evergreen and deciduous species were similarly represented. Notably, although the DI-model was originally applied to leaf isotope ratios, studies applying the model to wood are more numerous. Only a few studies combined leaf and wood measurements.

Paired measurements of leaf gas exchange (i.e. A<sub>net</sub> and g<sub>s</sub>) and isotopes (δ<sup>13</sup>C, δ/Δ<sup>18</sup>O) serve as the basis for validating the DI-model to interpret plant functional response to environment; we identified 17 studies with such paired measurements (Table S1). The majority of these studies comprised broadleaf and coniferous trees of temperate and Mediterranean climate regions. Additionally, three studies were performed on grasses and one on herbs. Most of the measurements were carried out at the leaf level on field grown, mature plants, while some studies were performed under controlled conditions on saplings. Four studies compared leaf gas exchange with the isotope pattern of tree stem tissue.

Within the 17 studies with isotopes and leaf gas exchange, we identified 29 different conditions for which the model scenarios had been evaluated (Table 1S, Figure 2). In 18 of the 29 cases (62%), the gas exchange measurements were fully consistent with the observed isotope patterns, clearly validating the DI-model. In a few cases (21%), the scenarios of gas exchange and isotope patterns did clearly not match (e.g. under the influence of air pollutants, extreme droughts and various nitrogen regimes (see also section 5)). However, when grouping the responses into situations of improved versus reduced resource availability, rather than individual scenarios, a consistent pattern emerged (Figure 2): Studies that resulted in improved plant resource availability (e.g. light, water, nutrients and CO<sub>2</sub>) clustered around scenarios # 6 and 7, both with respect to isotopes and gas-exchange (Figure 2a), consistent with an increase in photosynthesis (A<sub>net</sub>) and/or stomatal conductance (g<sub>s</sub>, Figure 2b). In contrast, a limitation or degradation of resource availability (e.g. increased competition, reduced water/nutrient supply, or temperature stress) commonly reflected scenarios #2 to 4 (Figure 2a). Following the model, plants show a decrease in A<sub>net</sub> and/or g<sub>s</sub> (Figure 2 b). For both groups, these model interpretations are generally well confirmed by gas exchange measurements. As a consequence, this means that an isotope pattern can give reliable information about resource limitation also in the absence of gas-exchange data.

Nevertheless, the DI-model cannot resolve all cases, as it is based on generally accepted plant physiological gas exchange responses to the environment and the well-accepted isotope fractionation models. As indicated by the grey arrow in Figure 2b, the original DI-model does not predict all  $A_{\text{net}}/g_s$  cases, particularly not a negative relationship between  $A_{\text{net}}$  and  $g_s$ . The two “missing”  $A_{\text{net}}/g_s$  scenarios are only observed in rare situations; for instance, a change from cold and wet to moderate and dry conditions, scenario #2 (Figure 1) might cause a decrease in  $g_s$  and increase in  $A_{\text{net}}$ . A similar pattern is observed for increasing ambient  $\text{CO}_2$ , where  $A_{\text{net}}$  is stimulated with a constant or concomitant decline in  $g_s$ , corresponding to scenario #8 (Figure 1 and 2). Scenario #5 can be found for plants growing under very humid conditions and (opened stomata) decreasing light (decrease in  $A_{\text{net}}$  e.g. understory plants in the tropics). The DI-model can also yield non-plausible results for extreme stress conditions such as drought and air pollution. Under such conditions the assumptions of the isotope fractionation models are violated (i.e. See Section 5a and 5e), as the metabolic changes are not considered relative to known fractionation and gas exchange principles.

## Model Applications – Environmental Effects on Plant Carbon and Oxygen Isotopes

Here we describe how the DI-model has been applied to infer plant functional responses to common environmental factors over time and space. We explain, which isotope responses would be expected for a certain dominant driving variable, like drought, and review the most common applications of the DI-model as found in the literature, both at the scale of the leaf and that of the whole plant, with some representative examples. A summary of the physiological responses to these environmental drivers, as reflected in the C and O isotope ratios, is given in Table 2.

### a) Water Supply and Demand

Drought stress primarily affects plants through diminished soil water availability and increased atmospheric moisture demand (Grossiord *et al.*, 2020) that increases non-linearly with rising temperatures (Breshears *et al.*, 2013). Generally, stomata close with increasing drought stress to mitigate leaf turgor loss or stem hydraulic failure. This often leads to reduced photosynthetic rates due to limited  $\text{CO}_2$  diffusion (Flexas *et al.*, 2008). The strong stomatal response mostly results in increased  $\delta^{13}\text{C}$  (Farquhar *et al.*, 1989). Similarly,  $\delta^{18}\text{O}$  is expected to increase, particularly when air is getting dry. On the one hand, this is due to a reduction of the Péclet effect and thus a reduced dilution of the enriched leaf with non- $\text{H}_2^{18}\text{O}$  enriched xylem water at low transpiration (Cernusak *et al.*, 2016, Farquhar & Lloyd, 1993). On the other hand, it is due to a reduced back diffusion of ambient  $^{18}\text{O}$ -depleted water vapour via stomata into the leaf intercellular spaces (Lehmann *et al.*, 2018), corresponding to scenario #2 for the isotopes. However, when both  $A_{\text{net}}$  and  $g_s$  are reduced to similar degrees, this may result in a constant  $c_i/c_a$  (Ehleringer & Cerling, 1995, Saurer *et al.*, 2004b) and no change in  $\delta^{13}\text{C}$ , as reflected in scenario #3 (Tab. 2).

Leaf-level isotope and gas exchange studies focused on functional response to water supply and demand have frequently observed scenario #2, including for black poplar plants under various VPD regimes (Rasheed *et al.*, 2015); for conifer species along a wet-dry gradient in Australia (Brodribb *et al.*, 2013), and for leaves and phloem sap in beech trees along a climatic gradient in Europe (Keitel *et al.*, 2006). Therefore, the DI-model generally works for explaining drought-related physiological responses.

However, an isotopic decoupling between leaf-level and tree rings can sometimes result in implausible isotope patterns. During hot and dry summers with low precipitation, water availability is often insufficient for plant growth. Although some  $\text{CO}_2$  assimilation is still measurable, no tree growth occurs during these dry, but climatically interesting periods. Thus, there is a mismatch between the period of interest and the period in which the tree ring tissue of interest was formed. Therefore, the DI-model often demonstrates an increase in  $A_{\text{net}}$  and  $g_s$  (scenarios # 7 & 8, Tab 2), which is not a plausible response for hot and dry conditions (high VPD, low soil moisture; (Sarris *et al.*, 2013)). What is observed in the tree rings is actually the  $\delta^{18}\text{O}$  signal from cooler, more humid springtime periods, with lower  $\delta^{18}\text{O}$  values of precipitation (thus mimicking high  $g_s$  see Figure 3). Since most growth occurs during spring time, the remaining tree ring signal is not representative for a hot summer period with little or no growth (Sarris *et al.*, 2013). This has also been observed in a controlled drought experiment with *Quercus robur* and *Quercus petraea* seedlings (Pflug *et al.*

, 2015).

In contrast, conditions with high air humidity (RH [?] 90%) and high stomatal conductance allow for high bidirectional water vapour fluxes from leaf-intercellular cavities to the ambient atmosphere and vice versa (Goldsmith *et al.*, 2017, Lehmann *et al.*, 2018). As a result, the isotopic leaf water enrichment is very small and often not detectable. Therefore, the  $\delta^{18}\text{O}$  of leaf water is close to that of the source water (Barbour *et al.*, 2004, Roden *et al.*, 2005). This is mostly the case under long lasting rain and fog conditions, often found in tropical rain forests or given orographic precipitation and persistent fog at the mountainous tree line. Under such conditions, the variability in  $\delta^{18}\text{O}$  of leaf water and consequently in cellulose tends toward zero and limits any conclusions regarding  $g_s$  (Roden & Siegwolf, 2012).

*To summarize:* While there may be considerable utility at the leaf scale, the application of the DI-model to tree rings for scenarios involving considerable drought stress or conditions with high humidity must be addressed carefully. Ultimately, changes in water availability and demand are generally well reflected in isotope patterns (scenario 2 & 3, Table 2), as long as plants operate under non-extreme conditions, i.e. severe drought, near saturated air humidity, or at temperature extremes (see section 5b below).

## b) Temperature

Temperature plays a critical role in plant function by mediating photosynthesis and post-photosynthetic processes, water use, and ultimately growth. Increases in global temperature have been associated with decreased growth and increased tree mortality in a number of vegetation studies (Allen *et al.*, 2010). Assuming that water supply and VPD are not a limiting factor and thus the stomatal response and  $\delta^{18}\text{O}$  values remain unchanged, then temperature primarily affects plant photosynthetic activity at the biochemical level. Consequently, when approaching their optimum temperature range, plants get closer to maximum photosynthesis, leading to a decrease in  $c_i/c_a$  and less negative  $\delta^{13}\text{C}$  values, which is consistent with scenario #1. In contrast, low and high (non-optimal) temperatures cause a decrease in  $A_{\text{net}}$  and thus an increase in  $c_i/c_a$  and lower  $\delta^{13}\text{C}$  values, reflecting scenario #5 (Tab. 2).

Outside of highly controlled experimental conditions, however, a change in the daily air temperature is probably always accompanied by a change in air humidity and thus VPD. A change in  $g_s$  due to a possible change in VPD can therefore not fully be excluded and humidity often masks potential temperature effects on gas exchange and thus on isotope fractionation, particularly under warm and dry conditions (Liu *et al.*, 2014, Martin-Benito *et al.*, 2010, Moreno-Gutierrez *et al.*, 2012). In the field, as temperature increases VPD also increases, which affects stomatal conductance much more than temperature (Grossiord *et al.*, 2020). Thus, what is often described as temperature effects is in fact a VPD effect. This may explain the highly equivocal results with both gas exchange and stable isotopes in leaf-level and tree-ring studies; most studies on the effect of temperature did not show any significant response.

Studies at tree lines may be useful for assessing temperature effects on plant isotope ratios in the field (Streit *et al.*, 2013), as water availability is not limiting (yearly precipitation > 1000 mm) and atmospheric water demand (VPD) is low. A strong temperature and  $\text{CO}_2$  driven relationship was observed between isotope ratios and growth in conifers at the tree line of the Austrian Alps (Wieser *et al.*, 2016), reflecting scenario #6. An often-overlooked condition is low temperatures (0°C to 7°C). Although water is hardly limiting under such conditions, the fact that growth at low temperatures is very slow (Körner, 2015) results in small tree rings. Consequently, the proportion of tree-ring biomass that would contain an isotopic low temperature signal is very small compared to that of the remaining tree ring mass, which was formed under warmer conditions. Therefore, the low temperature signal is hardly visible. So far, only a few studies on low temperature effects to date have matched the predicted scenarios #1 and #5 (Tab.2).

*To summarize:* Since changes in temperature are mostly accompanied by changes in VPD, but also light intensities, seasonality, and nutrient availability, a single factorial assessment with regard to temperature is only possible in controlled experiments. Evaluating the impact of temperature must always include the effect of other factors. Nevertheless, there seems to be a temperature driven impact on isotopic fractionation above 15°C and below 40°C on average (see v. Caemmerer, and Evans, 2015).

### c) Light

Light drives the variations of  $c_i/c_a$  by mediating  $A_{\text{net}}$  and for variations in  $e_a/e_i$  by mediating  $g_s$  directly, and indirectly via leaf energy balance, changing the leaf temperature particularly with the given variability of responses under non-light saturated conditions (e.g. shaded plants). The theoretical  $\delta^{13}\text{C}$  response is rather straightforward given the strong  $A_{\text{net}}$  effects on  $c_i/c_a$  and thus on  $\delta^{13}\text{C}$  values (Ehleringer & Cerling, 1995). Therefore, the  $\delta^{13}\text{C}$  would follow the light response curve for  $A_{\text{net}}$ . However, experimental evidence is somewhat controversial because light effects on carbon isotope discrimination have often been inferred from canopy height gradient studies where other factors may interfere, like VPD gradients and hydraulic constraints for tall trees (Farquhar *et al.*, 1989, Waring & Silvester, 1994). Moreover, the apparent  $^{13}\text{C}$  fractionation increases considerably in the low light range (near light compensation point, Barbour *et al.*, 2017, Busch *et al.*, 2020; Liu *et al.*, 2021; see also Breakout Box 1). Yet the large part of carbon acquisition occurs mostly under high light and biomass production under non-limiting growth conditions (Körner, 2015; Zweifel *et al.*; 2021). Therefore, except for understorey plants the low light impact on  $^{13}\text{C}$  fractionation is hardly visible in tree rings. In comparison to  $\delta^{13}\text{C}$ , changes in  $\delta^{18}\text{O}$  might be rather low or follow the inverse  $g_s$  direction of the  $A_{\text{net}}$  response given constant water supply and VPD conditions.

Studies with both gas-exchange and dual-isotope data that considered the influence of light are rare. The results of Roden & Farquhar (Roden & Farquhar, 2012) and Boegelein *et al.* (Boegelein *et al.*, 2012) show that “pure” light effects may be faithfully described by the DI-model Scenario 7 or 8 (Tab. 2), but that there are often overlapping abiotic effects. Studies focused on understanding the effect of thinning (Giuggiola *et al.*, 2016) using tree rings showed that changes in soil water  $\delta^{18}\text{O}$  due to evaporation or changes in transpiration may complicate the application of the model, as soil water availability may become the dominant driver and lead to Scenario 1 or most likely 2 (Tab. 2).

*To summarize:* What might appear straightforward at first sight turns out to be more complex, as water, temperature, or nutrient regimes can confound interpretations of light as a sole driver of plant physiological response. The strongest impact of light on isotopic fractionation is found under non-saturated light conditions where  $A_{\text{net}}$  and  $g_s$  show its greatest variability (i.e. in the understory); with decreasing light intensity the fractionation of photo- and dayrespiration has an increasing impact on the net fractionation (Busch *et al.*, 2020; Tcherkez *et al.*, 2017), which is in support of generally lower  $\delta^{13}\text{C}$  values of understory or shaded leaves in contrast to sun lit leaves ( see Breakout Box 1).

### d) $\text{CO}_2$

Understanding the influence of increasing  $\text{CO}_2$  concentration on plant gas exchange and carbon allocation is essential for a correct interpretation of the isotope ratios and to improving carbon cycle models (Schimel *et al.*, 2001). Tree-ring isotope studies, particularly when applied in large spatial networks, can provide unique information on how forests have responded to increases in  $\text{CO}_2$  since the start of the industrialization (Frank *et al.*, 2015, Voelker *et al.*, 2016). Based on  $\delta^{13}\text{C}$  trends over the last 100 years, presumably caused by increasing  $\text{CO}_2$ , three types of gas-exchange responses caused by a variable  $g_s$  and  $A_N$  interaction have been inferred (Saurer *et al.*, 2004b): a)  $c_i = \text{constant}$ , i.e. the supply function ( $g_s$ ) decreases and demand functions ( $A_N$ ) stays constant; b)  $c_i/c_a = \text{constant}$ ,  $g_s$  and  $A_N$  change proportionally; c)  $c_a - c_i = \text{constant}$ ,  $g_s$  stays constant and  $A_N$  increases. If we assume that  $\delta^{18}\text{O}$  remains constant (no stomatal conductance response) or increases (stomatal conductance decreases), we can deduce the following from the DI-model: for case a) we find either scenario #1 or #2, and for cases b) and c) we find scenarios #4 or #5 (Table 2). However, these are theoretical assumptions and applications of the DI-model to  $\text{CO}_2$  responses are relatively rare, particularly in combination with leaf gas-exchange measurements. A 9-year study at an alpine site with a free air  $\text{CO}_2$  enrichment (FACE) experiment observed an increase in  $A_{\text{net}}$  in two conifer species, but no stomatal response to  $\text{CO}_2$  (no changes in  $\delta^{18}\text{O}$ ), which is consistent with scenario #1 (Streit *et al.*, 2014). At three FACE sites, (Battipaglia *et al.*, 2013) found changes in intrinsic water-use efficiency between tree species growing at ambient atmospheric (control) and elevated  $\text{CO}_2$  treatments. An increase in  $\delta^{13}\text{C}$  of tree-ring cellulose for all species at all  $\text{CO}_2$  elevated study sites was observed, but elevated  $\text{CO}_2$  resulted in only a slight increase in  $\delta^{18}\text{O}$  for some species during some years of the experiment (scenario #1 or #2, Tab.

2).

Natural springs emitting geological CO<sub>2</sub> can be used as long-term CO<sub>2</sub> fertilization experiment with a source isotope signal similar to atmospheric air, thus facilitating the application of the DI-model. Oak trees in a Mediterranean ecosystem in Italy exposed to ca. 800 ppm CO<sub>2</sub> during their lifetime demonstrated increased  $\Delta^{13}\text{C}$  (decreased  $\delta^{13}\text{C}$ ) values and unchanged  $\delta^{18}\text{O}$  values (scenario #1), indicating a down-regulation of  $A_{\text{net}}$  and constant  $g_s$  for these rather harsh conditions in a dry and nutrient-limited environment (Saurer *et al.*, 2003).

*To summarize:* The wide variety of isotopic patterns in response to CO<sub>2</sub> changes reflects the variability of species-specific responses to elevated CO<sub>2</sub>. This includes a) stimulation of  $A_{\text{net}}$  under high CO<sub>2</sub> levels (Streit *et al.*, 2014, Bader *et al.*, 2013), b) down regulation of photosynthesis (Grams *et al.*, 2007, Sharma & Williams, 2009), c) reduction in stomatal conductance, or d) no stomatal response to changes in CO<sub>2</sub> (Keel *et al.*, 2007, Klein *et al.*, 2016, Streit *et al.*, 2014; Bader *et al.*, 2013) as summarized in Table 2. Therefore, each isotope data set should be analysed for its response to increasing CO<sub>2</sub> before drawing any further conclusion

#### e) Atmospheric Pollution

**Ozone (O<sub>3</sub>):** Atmospheric pollution has been shown to affect plants on local and global scales (Omsa *et al.*, 2005; Mils *et al.*, 2018). At the regional scale, O<sub>3</sub> is the most relevant phytotoxic air pollutant (Ashmore, 2005; Ainsworth *et al.*, 2012). Species respond differently to elevated O<sub>3</sub> depending on uptake, mesophyll exposure, detoxification capacity, and plant age (Fuhrer & Booker, 2003, Matyssek & Sandermann, 2003, Paoletti *et al.*, 2020). A unique DI-model study observed that young, but not adult, beech trees were affected by elevated O<sub>3</sub> concentrations (Grams *et al.*, 2007), with an increase in  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$  in leaf cellulose (scenario #2). Increasing  $\delta^{18}\text{O}$  values in response to O<sub>3</sub> exposure have also been observed in other studies with various species; this was explained by reduced  $g_s$  values (Gessler *et al.*, 2009b, Grams & Matyssek, 2010). However, the response of  $\delta^{13}\text{C}$  and thus in  $A_{\text{net}}$  was more variable (scenario #2 and #3).  $A_{\text{net}}$  responses to O<sub>3</sub> might potentially be biased by the increased enzymatic activity of phospho-enol pyruvate carboxylase (PEPC) (Saurer *et al.*, 1995; Doubnerova & Ryslava, 2011). In contrast to RuBisCo, PEPC does not discriminate against but enriches <sup>13</sup>C during CO<sub>2</sub> fixation (Vogel 1993), which results in an increase in plant tissue  $\delta^{13}\text{C}$ . This observation would intuitively be the result of a reduced  $c_i/c_a$  ratio, thus suggesting an increased  $A_{\text{net}}$ . However, this is in contrast to observed, reduced leaf gas-exchange fluxes with higher  $c_i/c_a$  ratios in plants exposed to O<sub>3</sub>, which should result in more negative  $\delta^{13}\text{C}$  values (Farquhar *et al.*, 1989). The impact of O<sub>3</sub> on C-isotope fractionation demonstrates that once the traditional fractionation model for C3 plants is no longer applicable, the model will yield physiologically implausible results.

**Sulphur dioxide (SO<sub>2</sub>):** Since high ambient SO<sub>2</sub> concentrations have been a rather common problem in the industrialized countries, particularly before the mid-1980s, this pollutant may have had a stronger impact on the stable isotope ratios of plant organic matter than previously recognized. Wagner & Wagner (Wagner & Wagner, 2006) report that the long-term trend in tree ring  $\delta^{13}\text{C}$  showed an extraordinary increase between 1945 and 1990 and a rapid decrease after 1990, mirroring trends in atmospheric SO<sub>2</sub> concentrations. Savard *et al.*, (Savard *et al.*, 2004, Savard 2020) showed that sulphur dioxide emissions from smelters induced an increase in  $\delta^{13}\text{C}$  by up to 4 reduction of stomatal conductance. SO<sub>2</sub> exposure impacts  $\delta^{18}\text{O}$  of leaf water only to a minor degree by reducing stomatal opening (Farquhar & Lloyd, 1993, Sensula & Wilczynski, 2017). Thus, the combined physiological response to high pollution levels is far more pronounced in  $\delta^{13}\text{C}$  (Martin *et al.*, 1988, Wagner & Wagner, 2006). Based on the reported isotope patterns, we expect scenarios #1 and #2, i.e. a strong increase in  $\delta^{13}\text{C}$  and none-to-moderate change in  $\delta^{18}\text{O}$ . However, gas exchange responses suggested by the model does not correspond with published CO<sub>2</sub> and H<sub>2</sub>O gas exchange values. Atkinson & Winner, (1987), Kropff *et al.*, (1990), Wedler *et al.*, (1995); Douanet *et al.*, (2019) unanimously report a reduction in  $A_{\text{net}}$  and  $g_s$ , which would match Scenarios #3 and #4 (Table 2). The impact of enzymatic detoxification mechanisms, (Randewig *et al.*, 2012), or a possible enhanced PEP-carboxylase activity as found for Ozone, lead to a considerable <sup>13</sup>C enrichment, which outweighs the standing model of C-isotope fractionation.

The isotope effects on  $\delta^{13}\text{C}$  induced by  $\text{SO}_2$  detoxification are not taken into account by the C-isotope fractionation model for C3 plants. Thus, the DI-model output does not correspond with the plant physiological response. It is critical to keep these  $\text{SO}_2$  effects in mind when analysing isotopic chronologies from tree ring that originate from regions and periods with large  $\text{SO}_2$  emissions (i.e. smelter industries, coal burning, etc.).

**Gaseous nitrogen, ( $\text{NO}_2$ ):** We cannot exclude effects of gaseous  $\text{NH}_x$  or  $\text{NO}$  compounds on plant metabolism and C and O isotope fractionation. Since we found no literature describing isotopic effects resulting from these compounds, we discuss only the effects of  $\text{NO}_2$  on plant physiology (Sparks, 2009; Wellburn, 1990). Plants demonstrate a proportional increase in  $\delta^{13}\text{C}$  with increasing  $\text{NO}_2$  concentrations (Bukata & Kyser, 2005, Siegwolf *et al.*, 2001). An increase in  $\delta^{13}\text{C}$  with a concomitant decrease of  $\delta^{18}\text{O}$ , irrespective of the soil nitrogen supply, has also been observed in a growth chamber  $\text{NO}_2$  fumigation experiment on *Populus euramericana* (Siegwolf *et al.*, 2001). The interpretation of the C and O isotopic patterns (increase in  $A_{\text{net}}$  and  $g_s$ ) corresponded with measured  $\text{CO}_2$  and  $\text{H}_2\text{O}$  gas exchange (scenario #8, Tab 2). This was subsequently confirmed by field studies (Guerrieri *et al.*, 2009, Saurer *et al.*, 2004a), but the pattern might be changed when drought occurs. Obviously, protection against drought has the higher priority for plant survival, thus the drought response outweighs the influence of  $\text{NO}_2$  (Guerrieri *et al.*, 2010).

*To summarize:* Air pollutants have remarkable effects on isotopic fractionation, particularly for  $\text{O}_3$  and  $\text{SO}_2$ . Specific changes of enzyme activities mostly result in altered isotope fractionation, which do not agree and are not plausible in the context of well-accepted isotope fractionation and gas exchange principles. While  $\text{NO}_2$  can have a fertilizing effect, it can also be toxic for plants at high concentrations.

f) Soil-N fertilization ( $\text{NH}_4^+/\text{NO}_3^-$ ):

The significance of N-depositions and incorporation into the plants is described in Etzold *et al.*, 2020 and Savard *et al.*, (2019). An increase in soil N supply generally reduces  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  (scenario #6), even while exposure to atmospheric  $\text{NO}_2$  increases  $\delta^{13}\text{C}$  and reduces  $\delta^{18}\text{O}$  (Siegwolf *et al.*, 2001). These two different nitrogen sources,  $\text{NO}_2$  compared to soil N supply, can have opposite effects on carbon and water relations. One experiment has demonstrated that the addition of N to the soil increases the ratio of  $A_{\text{net}}$  to  $g_s$  in favour of  $A_{\text{net}}$ , indicating a N-fertilization effect (Guerrieri *et al.*, 2011). This is consistent with the response for resource improvement. However, it has also been observed that a change in the soil N supply to subalpine species resulted in isotopic patterns that were specific to plant functional groups (Bassin *et al.*, 2009). For instance, in the sedge *Carex sempervirens*, both leaf C and O isotope values increased, suggesting a decrease in  $g_s$  and a slight increase or constant  $A_{\text{net}}$  (scenario #2). In contrast, both isotopes declined in forb species, suggesting a constant  $A_{\text{net}}$  at an increasing  $g_s$  (scenario #6). Talhelm *et al.* (Talhelm *et al.*, 2011) and Marshall *et al.*, (2022) also observed a diversity of isotope responses as a result of soil N supply. In their study, *Acer saccharum* foliage and leaf litter material from four different sites was analysed, resulting in four different DI-scenarios (#1, #6, #7 and #8).

*To summarize:* While plants exposed to atmospheric  $\text{NO}_2$  showed a consistent isotope pattern (scenario #8), we find highly diverse isotope responses for soil N supplied plants (Tab 2), with a slight trend towards scenario #6. This high diversity of responses may be a result of variable soil conditions (pH, soil moisture and structure, acidic or loamy soil etc.). But it also reflects that increased soil N input is not always beneficial, but can shift the competitive balance between species resulting in “winners” and “losers” that respond very differently.

## Reconciling Theory and Reality, General Conclusions

The theories of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  leaf gas exchange are explicitly linked with those of C and O isotope fractionation, as both isotopic patterns occur concurrently in leaves (Cernusak *et al.*, 2016, Dongmann *et al.*, 1974, Farquhar *et al.*, 1989, Farquhar & Lloyd, 1993, Farquhar *et al.*, 1982). However, when applying the DI-model to real measurements, our review reveals that we sometimes find deviations between measurements and theory.

What is the cause for such deviations between measured data and measured values?

While measured data are mostly analysed given one or maybe two driving variables, a whole spectrum of environmental factors of varying intensities impact gas exchange processes, plant metabolism, and isotopic fractionation in the field. Often these impacts are difficult to identify or to disentangle, e.g. temperature and air humidity (VPD) (see section 5a and 5b). With increasing air temperature, VPD also increases. Changes in isotopic ratios in plants may have been attributed solely to temperature, whereas the major impact was in fact VPD. The effect of varying CO<sub>2</sub> is often difficult to detect depending on site conditions, nutrients, species or climate. This is especially true given that studies of CO<sub>2</sub> in this context are generally carried out retrospectively on tree rings. While stomata respond readily to changes in CO<sub>2</sub> in lab experiments, hardly any stomatal response to CO<sub>2</sub> was observed in field and FACE studies (Körner *et al.*, 2005, Bader *et al.*, 2013, Streit *et al.*, 2014, Klein *et al.*, 2016). As for O<sub>3</sub> exposed plants, the C-fractionation model for C3 plants is no longer valid because PEPC activity is increased, resulting in a considerable increase in  $\delta^{13}\text{C}$  of plant organic matter (Saurer *et al.*, 1995). A similar effect is found for SO<sub>2</sub>. Thus, studies focusing on a specific plant-environment interaction may easily overlook the concurrent impact of other factors.

Does this invalidate the DI-model?

Whenever the DI-model “fails to fulfil our expectations” the first conclusion is that the DI-model does not work. However, the physiological nature of the model makes it a powerful diagnostic tool. Analysing isotope data in a physiologically mechanistic context facilitates the detection of anomalies or non-plausible responses, which otherwise would not be recognized if  $\delta^{13}\text{C}$  or  $\delta^{18}\text{O}$  data were studied and interpreted independently from each other. A good example is the tree-ring chronologies from a period and location with heavy SO<sub>2</sub> pollution (Wagner & Wagner, 2006). The anomaly of the carbon isotope values would hardly be detectable by evaluating the  $\delta^{13}\text{C}$  time series separately. With the application of the DI-model, the physiologically unrealistic interpretation became apparent and demands further exploration (See section 5e, SO<sub>2</sub>). Yet, for a plausible diagnosis of such data constellations, a thorough analysis of plant functional response to specific environmental impacts is essential. Expecting a “plug and play tool,” which can be blindly applied without the essential physiological background can lead us astray and result in wrong conclusions, as also found in the literature. To counteract such misinterpretations, Roden & Siegwolf (2012) published a list of points to consider when the DI-model is applied. Furthermore, the data analysis with the DI-model can be strengthened by including additional parameters, such as growth data (e.g. tree-ring width; (Gessler *et al.*, 2018), or anatomical parameters (Churakova *et al.*, 2019), or extend by considering other enzymatic fractionation processes e.g. including the C4 plant fractionation approach as suggested by Farquhar *et al.*, 1989 and Ubierna *et al.*, 2018.

The use of the DI-model showed that certain isotope patterns can be indicative for an increase or decrease of resource limitation in a wide range of conditions. Based on various studies, we found that scenarios 2-4 (Figure 2) mostly reflect a decrease of resource availability or more stressful conditions that is consistent with gas-exchange results. In this interpretation, there is no need for a perfect match between isotope and gas-exchange scenarios, but rather a range of scenarios is considered. Regarding the application of the DI-model, this re-iterates the qualitative nature of the model, but also its wide-ranging application.

*To conclude:* Ultimately, whether conceptual (qualitative) or mechanistic (quantitative), such models are a synthesis of our current knowledge and provide a powerful platform to test and interpret our measured data. Inconsistencies reveal the lack of consideration of a certain mechanism or reveal knowledge gaps in our understanding of metabolic plant processes. Mismatches between models (representing our current understanding) and reality open doors for further research and enhance our understanding of plant-environment interactions. Given these considerations, the DI-model has proven to be a successful and powerful tool in plant ecophysiological research.

### Authors contributions

R.T.W.S., and G.R.G. planned, and together with M.M.L. and M.S. designed the study. All authors collected the literature, and drafted a first manuscript during a workshop (Stans, CH), which was completed by R.T.W.S., M.S., M.M.L., and G.R.G.. All authors commented and accepted the last version of the

manuscript.

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**Table 1:** Summary of research studies containing plant  $^{13}\text{C}$  and  $^{18}\text{O}$  measurements that cite and apply the DI-model of Scheidegger et al., (2000). Information listed contains the type of material analysed, the availability of gas-exchange data and the region where the study was carried out. Controlled conditions indicate greenhouse or growth chamber studies.

Plant functional type	No. of studies	Wood isotopes only	Leaf isotopes only	Leaves & wood or phloem isotopes	Pl
Gymno-sperms	78	59	15	4	7
Angio-sperms	79	30	43	6	26
Both	27	13	11	3	5

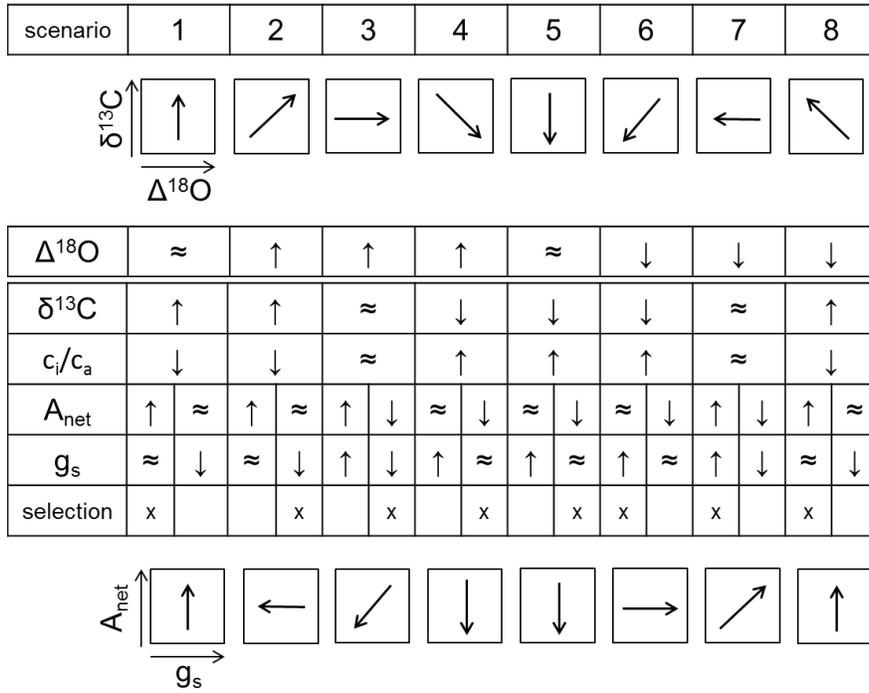
**Table 2:** Impact of the dominant environmental drivers on tree physiological parameters and stable C and O isotope fractionation: the theoretical responses might deviate from field observations, since other environmental factors impact gas exchange and isotopic fractionation besides the dominant drivers, which does not always correspond with all responses from field observations.  $g_s$  ... stomatal conductance;  $A_{\text{net}}$  ... net photosynthesis;  $c_i/c_a$  ... ratio between leaf intercellular versus ambient  $\text{CO}_2$  concentration;  $\Delta^{13}\text{C}$  ... net carbon isotope fractionation;  $e_a/e_i$  ... ratio between ambient and substomatal partial water vapour pressure;  $\Delta^{18}\text{O}$  ... oxygen isotope fractionation; VPD ... Vapour Pressure Deficit; LAVPD ... Leaf to Air Vapour Pressure Deficit; FACE Free air  $\text{CO}_2$  exposure. DI-Model scenario corresponds with the scenario

numbers in Figure 1. The red scenario numbers indicate non-plausible gas exchange responses, as derived from the C and O isotope values.

Dominant driving variables	$g_s$	$A_{net}$	$c_i/c_a$	$\delta^{13}C / \Delta^{13}C$	$e_a/e_i$	$\delta^{18}O / \Delta^{18}O$	DI-Model Scenario
VPD	Decreasing with increasing VPD. The degree of decrease is species dependent	Initially constant, then decreasing with increasing VPD	Progressively decreasing with increasing VPD.	$\delta^{13}C$ : increases $\Delta^{13}C$ : decreases with increasing VPD	Decreasing with increasing VPD	Both increase with increasing VPD	<b>2, 3 7, 8</b> (isotopic decoupling Sect. 5a)
Temperature	High at low temperatures, $\pm$ constant over the temperature range between 15°C and 40°C, given that VPD stays constantly low (VPD [?] 0.5 KPa). Decreasing with increasing temperature, mostly due to increasing VPD	Follows an optimum curve increasing from low to higher temperatures decreasing at higher temperatures with an average optimal range between 15°C–30°C. Temperature compensation points on average at 3°C and 40°C	Follows an inverse curve of $A_{net}$ ; with increasing temperature the ratio decreases to remain constant for the optimal range of $A_{net}$ , then increases with decreasing $A_{net}$ .	$\delta^{13}C$ : Follows an optimum curve, and is decreasing in the low and high temperature ranges. $\Delta^{13}C$ : Follows an inverse curve of $A_N$ , with increases in the low and high temperature ranges.	Decreasing trend with increasing temperature, as a result of a higher leaf than ambient temperature (increasing LAVPD)	$\delta^{18}O$ and $\Delta^{18}O$ : Increasing trend due to decreasing $e_a/e_i$ caused by increasing leaf temperature, resulting in increasing LAVPD	<b>1 &amp; 5</b>
PAR	Increasing, following a saturation curve	Increasing, following a saturation curve; light saturation is species and light exposition (sunlit shade) dependent	Declines logarithmically (x-axis mirrors the saturation curve) depending on the $A_{net}/g_s$ ratio	$\delta^{13}C$ : increases, following the $A_{net}$ curve $\Delta^{13}C$ : decreases, following an inverse curve of $A_{net}$	Constant or decrease with increasing PAR	Both constant or decrease with increasing PAR	<b>7 or 8</b>

Dominant driving variables	$g_s$	$A_{net}$	$c_i/c_a$	$\delta^{13}C / \Delta^{13}C$	$e_a/e_i$	$\delta^{18}O / \Delta^{18}O$	DI-Model Scenario
CO <sub>2</sub>	<b>Lab conditions:</b> decreasing with increasing CO <sub>2</sub> <b>Field studies (FACE)</b> minimal decrease to no response (see Sect. 5d)	Increasing, following a saturation curve, degree of CO <sub>2</sub> saturation is species- and nutrient-specific.	<b>Lab conditions:</b> decreasing with increasing CO <sub>2</sub> <b>Field studies: a)</b> decreasing if $c_i$ constant <b>b)</b> $c_i/c_a$ constant <b>c)</b> increasing if $c_a - c_i$ constant	<b>Lab conditions:</b> $\delta^{13}C$ increasing $\Delta^{13}C$ decreasing <b>Field studies a)</b> $\delta^{13}C$ increasing $\Delta^{13}C$ decreasing <b>b)</b> $\delta^{13}C$ decreasing $\Delta^{13}C$ decreasing <b>c)</b> $\delta^{13}C$ decreasing $\Delta^{13}C$ increasing	<b>Lab conditions:</b> decreasing with increasing CO <sub>2</sub> <b>Field studies (FACE)</b> constant or slight decrease	$\delta^{18}O$ and $\Delta^{18}O$ : <b>Lab conditions:</b> increasing with increasing CO <sub>2</sub> $\delta^{18}O$ and $\Delta^{18}O$ : <b>Field studies (FACE)</b> constant or slight increase	<b>a) 1 or 2 b, c) 4, 5 1, (2) (see Sect. 5d)</b>
Ozone	Initially decreases, but with increasing duration stomata become non-functional	Decreases with progressive duration of exposure (depending on the concentration)	Increases with progressive duration of exposure (depending on the O <sub>3</sub> concentration)	$\delta^{13}C$ : increases while $\Delta^{13}C$ decreases as a consequence of increased PEP carboxylase activity	Increases with progressive duration of exposure (depending on the O <sub>3</sub> concentration)	Decreases with progressive duration of exposure (depending on the O <sub>3</sub> concentration)	<b>1 &amp; 2 (PEP-carboxylase driven isotope patterns) 3 (supported by gas exchange measurements)</b>
SO <sub>2</sub>	Initially decreases, but with increasing duration stomata become non-functional	Decreases with progressive duration of exposure (depending on the concentration)	Increases with progressive duration of exposure (depending on the SO <sub>2</sub> concentration)	$\delta^{13}C$ : increases $\Delta^{13}C$ : decreases; possibly as a consequence of increased PEP carboxylase activity and other detox. mechanisms	Constant or increasing with progressive duration of exposure (depending on the SO <sub>2</sub> concentration)	Constant or decreasing with progressive duration of exposure (depending on the SO <sub>2</sub> concentration)	<b>1 &amp; 2 (biochemically driven isotope patterns) 3 &amp; 4 (based on gas exchange measurements)</b>
NO <sub>2</sub>	Increases for non-toxic concentrations	Increases for non-toxic concentrations	Decreases for non-toxic concentrations	$\delta^{13}C$ : increases $\Delta^{13}C$ : decreases	decreases	decreases	<b>8</b>

Dominant driving variables	$g_s$	$A_{net}$	$c_i/c_a$	$\delta^{13}C / \Delta^{13}C$	$e_a/e_i$	$\delta^{18}O / \Delta^{18}O$	DI-Model Scenario
Soil N supply	a) Increasing	a) Increasing	a) Increasing	a) Constant	a) Increasing	$\delta^{18}O$ and $\Delta^{18}O$ decreasing	a) 6 b) 2 c) 1 d) 7 e) 8
$NO_3^-$ and $NH_4^+$ Highly variable responses, strongly plant species and Habitat dependent (see Sect. 5f)	b) Decreasing c) Constant d) Increasing e) Constant to decreasing	b) Constant c) Increasing d) Increasing e) Increasing	b) when $A_{net}$ / $g_s$ ratio is in favour of $g_{st}$ b) Decreasing c) Decreasing d) constant e) decreasing	b) decreasing $\delta^{13}C$ b) constant to slightly decreasing and $\Delta^{13}C$ b) constant $\delta^{13}C$ increasing, $\Delta^{13}C$ decreasing d) $\delta^{13}C$ and $\Delta^{13}C$ constant e) $\delta^{13}C$ increasing, $\Delta^{13}C$ decreasing	b) Decreasing c) Constant d) Increasing e) Increasing	b) $\delta^{18}O$ and $\Delta^{18}O$ increasing c) $\delta^{18}O$ and $\Delta^{18}O$ constant d) $\delta^{18}O$ and $\Delta^{18}O$ decreasing e) $\delta^{18}O$ and $\Delta^{18}O$ decreasing	



**Figure 1** : The dual C-O isotope model according to Scheidegger et al., (2000). Arrows compare “two varying situations: A and B” as explained in the text. The symbol “ [?] ” indicates no significant change. Arrows pointing up (—) or down (—) stand for an increase/decrease of the respective values.  $\Delta^{18}\text{O}$  is the isotopic fractionation for  $^{18}\text{O}$  vs.  $^{16}\text{O}$ ;  $\delta^{13}\text{C}$  is the value for the stable carbon isotope;  $c_i/c_a$  is the ratio between the intercellular vs. ambient  $\text{CO}_2$  concentration;  $A_{\text{net}}$  is the net photosynthesis (sensu Larcher, 2003); and  $g_s$  the stomatal conductance. Red dotted arrows show intermediate  $A_{\text{net}}-g_s$ -responses not covered in the original model.

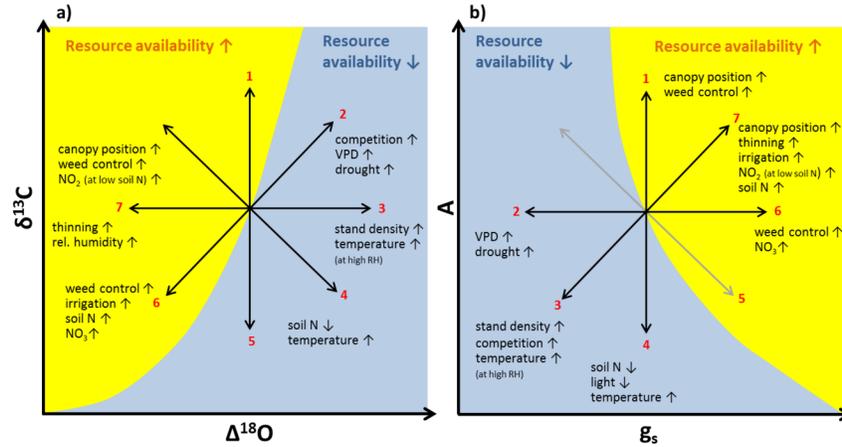


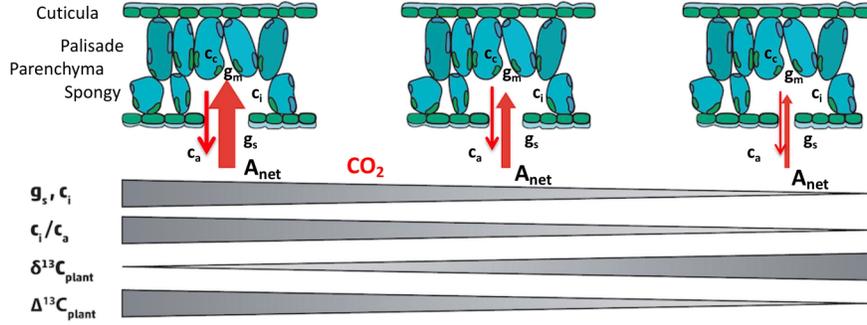
Figure 2: Stable C/O isotope and  $A_{\text{net}}/g_s$  scenarios and their environmental drivers as observed from experimental studies, including a) Isotope patterns reflecting DI-model scenarios #1-8 and b) corresponding observed gas exchange scenarios #1-8. The yellow and grey areas reflect scenarios with generally increasing and decreasing resource availability, respectively.

### Hosted file

image4.emf available at <https://authorea.com/users/449155/articles/547747-the-dual-c-and-o-isotope-gas-exchange-model-a-concept-review-for-understanding-plant-responses-to-the-environment-and-its-application-in-tree-rings>

**Figure 3:** Pattern of carbon and oxygen isotopes in a) leaves and b) tree-ring cellulose of *Quercus robur*. Black arrows indicate the directional trend in isotopic patterns due to drought treatments. Open circles represent irrigated plants (control) and open triangles irrigated and warmed plants. Filled circles represent drought treatment and filled triangles stand for drought treatments and warmed plants. Data are means  $\pm$  SE,  $n = 8$ , experiment from 2009 (Pflug *et al.*, 2015). The red arrow and symbols represent the expected values, according to the isotopic pattern in the leaves, whereas the black arrow and symbols are measured data.

**Breakout Box 1:** The mechanistic linkages between plant physiology and isotopes of carbon at leaf level.

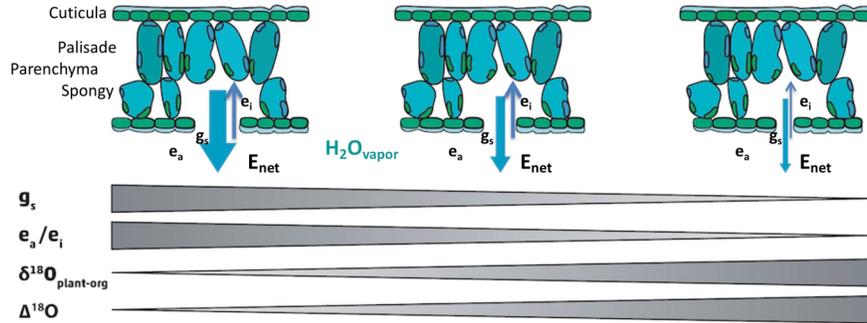


**Carbon Isotopes:** The Figure above shows a situation with increasing environmental stress from left to right, e.g. increasing drought. The variability of the  $^{13}\text{C}/^{12}\text{C}$  isotope ratio in organic matter is predominantly determined by the extent of  $\text{CO}_2$  and  $\text{H}_2\text{O}$  gas exchange during photosynthesis (Farquhar *et al.*, 1989, Farquhar *et al.*, 1982, Vogel, 1980). The degree of the stomatal opening regulates the water loss (i.e. transpiration). This leads to a concomitant decrease in the diffusion of  $\text{CO}_2$  along the gradient between the ambient air, ( $c_a$ ) and the leaf intercellular spaces ( $c_i$ ). Thus, depending on the stomatal conductance ( $g_s$ ) and the drawdown of  $[\text{CO}_2]$  by photosynthesis ( $A_{\text{net}}$ ),  $c_i$  will decrease. Farquhar *et al.*, (1989; 1982) showed that a reduction in  $c_i/c_a$ , decreases the fractionation between  $^{13}\text{C}$  and  $^{12}\text{C}$  ( $[\delta^{13}\text{C}]$ ). This results in a higher  $^{13}\text{C}/^{12}\text{C}$  ratio because the partial pressure of  $^{12}\text{CO}_2$  decreases faster, as a consequence of the isotopic effect, (Bigeleisen, 1965) than that of the  $^{13}\text{CO}_2$ , resulting in an increase of the  $^{13}\text{CO}_2$  relative to the  $^{12}\text{CO}_2$  partial pressure. This higher  $^{13}\text{C}/^{12}\text{C}$  partial pressure ratio leads to a higher incorporation rate of  $^{13}\text{C}$ , expressed in decreased  $[\delta^{13}\text{C}]$  (less negative  $\delta^{13}\text{C}$ ) values of organic matter synthesized under the respective conditions. Consequently,  $\delta^{13}\text{C}$  values reflect the interplay between  $g_s$  and  $A_{\text{net}}$ , which is controlled by environmental variations in water supply and demand, as well as photosynthetically active radiation, temperature or  $\text{CO}_2$  concentration. This isotope ratio is transferred to sugars, the primary photosynthetic product, and used for metabolic processes and biomass synthesis (see also Cernusak *et al.*, 2013).

However, the observed (net) fractionation ( $\Delta^{13}\text{C}_{\text{observed}}$  [ $\Delta^{13}\text{C}_{\text{net}}$ ]) is a composite of numerous, complex biochemical and physical processes, and can be summarized as  $\Delta^{13}\text{C}_{\text{observed}} = \Delta_b - \Delta_{g_s} - \Delta_{g_m} - \Delta_e - \Delta_f$ , where each fractionation term is flux-rate weighted, (Ubierna *et al.*, 2018). A range of fractionation values are provided by Ubierna & Farquhar (2014).  $\Delta_b$  is the fractionation associated with the carboxylation of  $\text{CO}_2$  via RuBisCo, in the absence of any respiratory fractionation.  $\Delta_{g_s}$  is the fractionation associated with diffusion of  $\text{CO}_2$  through the boundary layer and the stomata.  $\Delta_{g_m}$  is the fractionation associated with mesophyll conductance  $g_m$ .  $\Delta_e$  reflects fractionations associated with the day-respiration rate  $R_d$  (cytoplasmic decarboxylation, mitochondrial metabolism, C-remobilization and respiration of the heterotrophic tissues, Tcherkez *et al.*, 2017). Since  $\Delta_b$  and  $\Delta_{g_s}$  are linked to the largest C-flux and they reflect the largest part of the observed fractionation in the biomass, while  $\Delta_e$  and  $\Delta_f$  are associated with the small respiratory C-fluxes and are often neglected. Thus, the  $\Delta^{13}\text{C}_{\text{observed}}$  can be described by the simplified equation 11 The simplified net isotope fractionation for C3-plant is described as  $\Delta^{13}\text{C}_{\text{observed}} = a + (b - a) * c_i / c_a$ , with  $a$ , the fractionation of  $\text{CO}_2$  in the air and through the stomata,  $b$  the fractionation during the carboxylation and  $c_i$  and  $c_a$  are the mol fractions for the inter cellular and ambient  $\text{CO}_2$  concentration. (Ubierna & Farquhar, 2014; Cernusak *et al.*, 2016). However, for plants operating at low light conditions, (e.g. understory plants) the respiratory fractionations might become more relevant (Barbour *et al.*, 2017; Busch *et al.*, 2020; Liu *et al.*; 2021). A comprehensive overview on day respiration and its impact of  $e$  is given in Tcherkez *et al.*, (2017). Moreover, after entering the intercellular spaces the  $\text{CO}_2$  molecules traverse the mesophyll cell walls and chloroplast membranes with their diffusional resistance  $r_{\text{mb}}$  and  $r_c$  respectively, which is summarized as  $g_m = 1/(r_{\text{mb}} + r_c)$ . As  $g_m$  can contribute significantly to the limitation of photosynthesis by regulating the chloroplast  $\text{CO}_2$  concentration ( $c_c$ ), it impacts the  $^{13}\text{C}$ -isotope fractionation ( $\Delta_{g_m}$ ) accordingly (Evans 2021, Evans & Von Caemmerer, 2013; Sharkey *et al.*; 2012). Yet its experimental determination is challenging and often not possible therefore mostly a model based estimation.

What are the implications of  $\Delta_{gm}$ ,  $\Delta_e$  and  $\Delta_f$  with regard to the use of the Dual C and O isotope approach? Mostly the observed fractionation,  $\Delta^{13}\text{C}_{\text{observed}}$  or  $\delta^{13}\text{C}_{\text{observed}}$  is used, which is driven by the most dominating C-flux that is controlled by  $A_{\text{net}}$  and  $g_s$  with its associated fractionation  $\Delta_b$  and  $\Delta_{gs}$ . Therefore  $\Delta_{gm}$ ,  $\Delta_e$  and  $\Delta_f$  can be neglected. However, as soon as any of these components are separately studied, or derivatives of the fractionation model, e.g. intrinsic water use efficiency (iWUE, Wei et al., 2021, Gimeno et al., 2020) it is essential that the respective fractionation components are taken into account accordingly.

**Breakout Box 2:** The mechanistic linkages between plant physiology and isotopes of oxygen at the leaf level.



**Oxygen Isotopes:** We must keep in mind that major fractionation processes occur on two different levels: 1<sup>st</sup> processes, which alter the isotope ratio before water is taken up by plants and 2<sup>nd</sup> changes, which are a result of fractionation processes during transpiration ( $E_{\text{net}}$ ) and incorporation into plant organic matter.

1. The isotope ratio of precipitation water varies depending on i) its **origin**. i.e. water vapour from warm regions like the Mediterranean is more enriched in  $\text{H}_2^{18}\text{O}$  than northern vapour masses (Rozanski et al., 1993). Furthermore continental (Bowen *et al.*, 2005) or altitudinal (Poage MA & Chamberlain CP, 2001) effects change  $\delta^{18}\text{O}$  of precipitation significantly. ii) **Seasonality** of the precipitation is another source of variation in  $\delta^{18}\text{O}$  of precipitation water. That, however, is closely linked to the temperature dependence of  $\delta^{18}\text{O}$  (Daansgard, 1964). Further fractionations occur during atmospheric transport, rainfall, canopy throughfall and infiltration in the soil, where it is subject to further fractionation particularly during warm periods with high evaporation demands. Depending on the soil structure, season and climate  $\delta^{18}\text{O}$  of soil water shows a great vertical variability (Sprenger *et al.*, 2016). iii) As plant roots seem to take up water from any soil depth, where its accessibility enables its uptake under a minimum of energy, roots potentially have a large range in soil depths from where they absorb the water. Allen et al., (2019) and Brinkmann et al., (2018) found that considerable amounts of absorbed soil water originate from winter water, resulting in temporal shifts (described as temporal origin) of soil  $\delta^{18}\text{O}$ . Accordingly this leads to a strongly dampened variability of the source water isotope signal (xylem water), the isotopic basis for leaf water  $\text{H}_2^{18}\text{O}$  enrichment in leaves.

2. The variability of the  $^{18}\text{O}/^{16}\text{O}$  isotope ratio in leaf organic matter is predominantly determined by the extent of  $\text{H}_2\text{O}$  gas exchange of plants during photosynthesis. In particular, as water from the leaf transpires out of the stomata, the lighter  $\text{H}_2^{16}\text{O}$  evaporates more readily than the heavier  $\text{H}_2^{18}\text{O}$  molecule. This leaves the remaining leaf water more enriched in  $\text{H}_2^{18}\text{O}$  (Craig & Gordon, 1965, Dongmann *et al.*, 1974). The extent of enrichment is dependent on the transpiration rate ( $E$ ), which is driven by the water vapour gradient between the intercellular spaces ( $e_i$ ) and the ambient air ( $e_a$ ). Numerous experiments demonstrate a negative relationship between  $g_s$  and the  $\delta^{18}\text{O}$  of leaf water. However, the water lost via transpiration is continuously replenished with  $^{18}\text{O}$  depleted source (xylem) water, which dilutes the effect of  $^{18}\text{O}$  enrichment in leaf water. And as noted above, plants also regulate their water loss via stomata. This impact can be corrected by accounting for a two pool approach (Song *et al.*, 2015; Yakir *et al.*, 1990), by the Péclet effect (Farquhar &

Lloyd, 1993), which takes  $g_s$  and leaf anatomical traits into account, or by the combination of both approaches (Roden *et al.*, 2015). Spatial patterns of isotopic composition within leaves were observed, as the isotopic composition tends to be more and more enriched towards the tip of the leaf or at greater distance from the mid-vein (Cernusak *et al.*, 2016). Farquhar & Gan (2003) considered such effects by expanding the one-dimensional Péclet model, separating advection-diffusion effects in the leaf xylem and lamina. Further, conditions of non-steady state may occur when the transpired water has an isotopic composition differing from that of source water (Farquhar & Cernusak 2005). This is expected to be significant when stomatal conductance is low or when leaf water concentration is high (like in succulent plants). For most plants, this is, however, only important for night-time conditions, where no photosynthesis takes place and thus no organic matter is produced. Consequently,  $\delta^{18}\text{O}$  values of leaf water reflect the effects of  $g_s$  and  $e_i/e_a$  on transpiration, as well as the source water supplied to the leaf (Kahmen *et al.*, 2008, Roden & Ehleringer, 1999, Song *et al.*, 2013). As with carbon, this isotope ratio is transferred to sugars and in turn used for metabolic processes and biomass synthesis. Extensive reviews are provided by (Barbour, 2007, Cernusak *et al.*, 2016).

### Supporting Information

**Table S1:** Reviewed studies containing both isotope and gas exchange measurements. DI-model scenarios are given for isotope patterns (ISO) and for the gas exchange (GAS). RH = relative humidity, WSOM = Water soluble organic matter,  $A_{\text{net}}$  = net photosynthetic assimilation rate,  $A_{\text{sat}}$  = light-saturated photosynthetic assimilation rate. RH = relative humidity. VPD = Vapour pressure deficit. Leaf material: 1= lower, inner canopy, 2=lower, outer canopy, 3=upper, inner and outer canopy.

ISO	GAS	TREATMENT	SPECIES TREATED	SPECIES TYPE	GASEX TYPE	TISSUE	BIOME	CLASSIFICATION	Author
0	0	control to weed removal	<i>Corymbia citriodora</i>	tree	$A_{\text{sat}}$ and $g_s$	leaf bulk material <sup>1</sup>	Temperate Broadleaf and Mixed Forests	angiosperm	Hu et al. 2006
0	0	control to increased temperature (under low RH)	<i>Eucalyptus globulus Labill.</i>	tree	$A_{\text{net}}$ and $g_s$	stem cellulose	Controlled conditions	angiosperm	Roden & Cernusak 2010
0	0	control to defoliation (across growing periods)	<i>Abies balsamea</i>	tree	$A_{\text{sat}}$ and $g_s$	stem cellulose	Controlled conditions	gymnosperm	Sinclair et al. 2006
0	5	control to low light (across both RH)	<i>Eucalyptus globulus Labill.</i>	tree	$A_{\text{net}}$ and $g_s$	stem cellulose	Controlled conditions	angiosperm	Roden & Cernusak 2010

ISO	GAS	TREATMENT	SPECIES TREATED	SPECIES TYPE	GASEX TYPE	TISSUE	BIOME	CLASSIFICATION	Reference
2	2	grass/herb to shrub/tree	<i>various</i>	various	$A_{net}$ and $g_s$	leaf cellulose	Mediterranean Forests, Woodlands and Shrub	both	McGuire et al. 2019
2	2	low to high VPD (across genotypes)	<i>Populus nigra</i>	tree	$A_{sat}$ and $g_s$	leaf bulk material and sugar	Controlled conditions	angiosperm	Raich et al. 2000
2	3	low to high intraspecific competition intensity	<i>Stipa tenacissima</i>	grass	$A_{net}$ and $g_s$	leaf bulk material	Mediterranean Forests, Woodlands and Shrub	angiosperm	Raich et al. 2000
3	3	open to dense forest	<i>Pinus halepensis</i>	tree	$A_{net}$ and $g_s$	stem cellulose	Mediterranean Forests, Woodlands and Shrub	gymnosperm	McGuire et al. 2019
3	3	control to increased temperature (under high RH)	<i>Eucalyptus globulus Labill.</i>	tree	$A_{net}$ and $g_s$	stem cellulose	Controlled conditions	angiosperm	Roques & Quirion 2019
3	0	control to drought (across both RH)	<i>Eucalyptus globulus Labill.</i>	tree	$A_{net}$ and $g_s$	stem cellulose	Controlled conditions	angiosperm	Roques & Quirion 2019
5	5	control to nitrogen deficiency (across both RH)	<i>Eucalyptus globulus Labill.</i>	tree	$A_{net}$ and $g_s$	stem cellulose	Controlled conditions	angiosperm	Roques & Quirion 2019

ISO	GAS	TREATMENT	SPECIES TREATED	SPECIES TYPE	GASEX TYPE	TISSUE	BIOME	CLASSIFICATION	YEAR
6	6	control to weed removal	<i>Corymbia citriodora</i>	tree	A <sub>sat</sub> and g <sub>s</sub>	leaf bulk material <sup>2</sup>	Temperate Broadleaf and Mixed Forests	angiosperm	Hu et al 2019
6	6	ambient to high NO <sub>3</sub>	<i>Acer saccharum</i>	tree	A <sub>net</sub> and g <sub>s</sub>	leaf bulk material	Temperate Broadleaf and Mixed Forests	angiosperm	Ta et al 2019
6	7	control to irrigation	<i>Triticum durum</i>	grass	A <sub>net</sub> and g <sub>s</sub>	leaf bulk material	Mediterranean Woodlands and Scrub	angiosperm	Ca et al 2019
6	7	ambient to high soil N (across NO <sub>2</sub> exposures)	<i>Populus x euramericana</i>	tree	A <sub>net</sub> and g <sub>s</sub>	leaf bulk material	Controlled conditions	angiosperm	Sie et al 2019
7	7	moderate to heavy thinning	<i>Pinus halepensis</i>	tree	A <sub>sat</sub> and g <sub>s</sub>	leaf bulk material	Mediterranean Forests, Woodlands and Shrub	gymnosperm	M Gu et al 2019
7	7	shift in time (over years)	<i>Larix de-cidua</i>	tree	A <sub>sat</sub> and g <sub>s</sub>	stem cellulose	Temperate Coniferous Forests	gymnosperm	W et al 2019
7	0	low to high RH (across treatments: drought, nitrogen, light)	<i>Eucalyptus globulus Labill.</i>	tree	A <sub>net</sub> and g <sub>s</sub>	stem cellulose	Controlled conditions	angiosperm	Ro & qu 2019
8	8	base to top canopy gradient	<i>Pseudotsuga menziesii</i>	tree	A <sub>net</sub> and g <sub>s</sub>	leaf and phloem WSOM	Temperate Broadleaf and Mixed Forests	gymnosperm	Bo et al 2019

ISO	GAS	TREATMENT	SPECIES TREATED	SPECIES TYPE	GASEX TYPE	TISSUE	BIOME	CLASSIFICATION	Author
8	8	control to weed removal	<i>Corymbia citriodora</i>	tree	A <sub>sat</sub> and g <sub>s</sub>	leaf and bulk material <sup>3</sup>	Temperate Broadleaf and Mixed Forests	angiosperm	Hu et al 2020
8	7	base to top canopy gradient	<i>Fagus sylvatica</i>	tree	A <sub>net</sub> and g <sub>s</sub>	leaf and phloem WSOM	Temperate Broadleaf and Mixed Forests	angiosperm	Bo et al 2020
8	7	low to high NO <sub>2</sub> at low soil N	<i>Populus x euramericana</i>	tree	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Controlled conditions	angiosperm	Sie et al 2020
8	0	low to high NO <sub>2</sub> at high soil N	<i>Populus x euramericana</i>	tree	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Controlled conditions	angiosperm	Sie et al 2020
5	5	temperature	<i>H. squamatum</i>	shrub	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Arid	angiosperm	Lee et al 2020
3	3	Drought 2014	<i>Triticale</i>	crop	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Arid	angiosperm	Mu et al 2020
7	3	Drought 2013	<i>Triticale</i>	crop	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Arid	angiosperm	Mu et al 2020
8	3	Drought	<i>Capsicum annuum</i>	herb	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Controlled conditions	angiosperm	Sen et al 2020
2	2	drought	<i>Lycopersicon L</i>	herb	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Controlled conditions	angiosperm	Wang et al 2020
0	0	nitrogen	<i>Lycopersicon L</i>	herb	A <sub>net</sub> and g <sub>s</sub>	leaf and bulk material	Controlled conditions	angiosperm	Wang et al 2020

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