Data Analysis and Modeling with Stable Isotope Ratios

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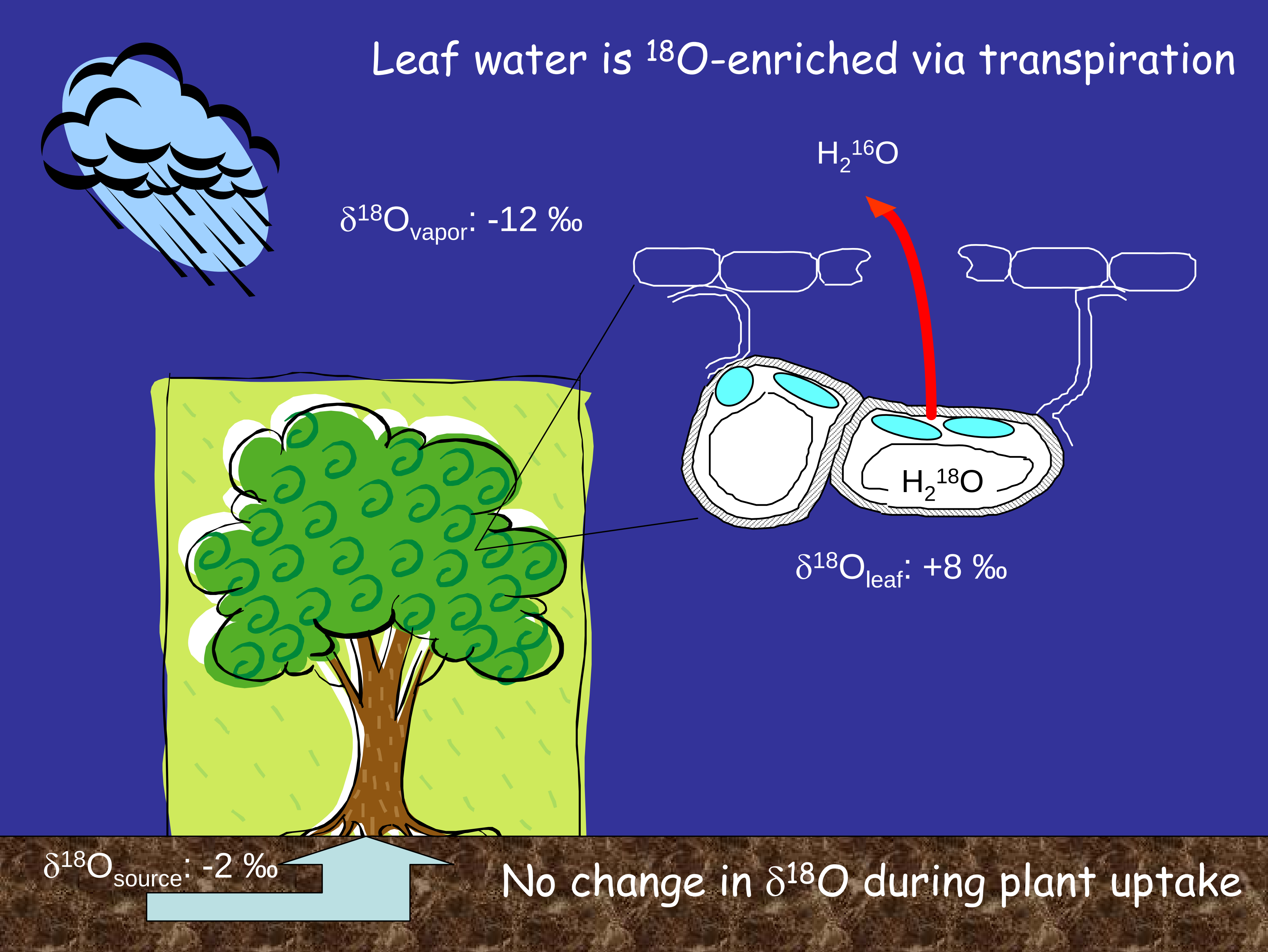
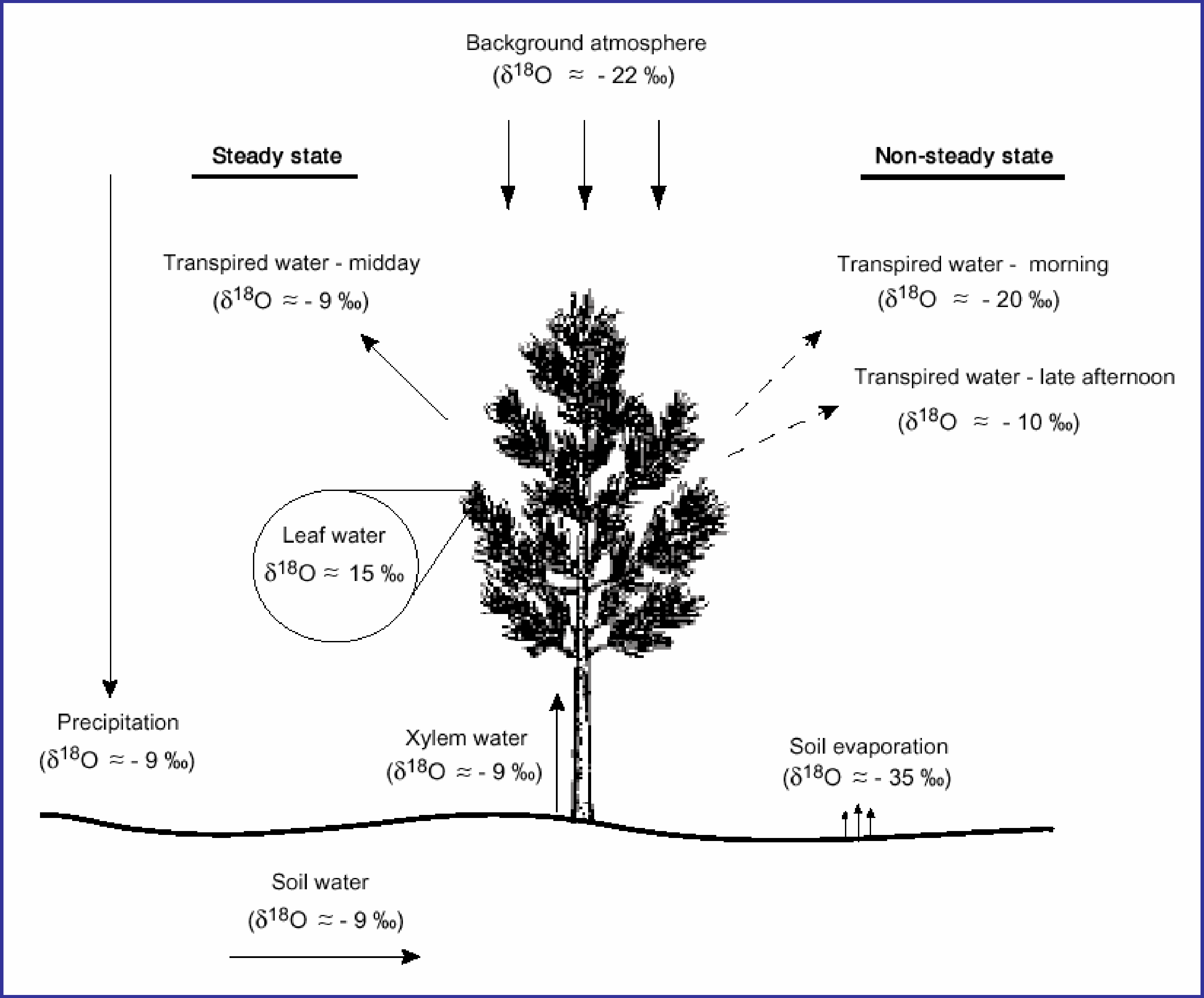
June 2008


Leaf water is ^{18}O-enriched via transpiration
$H_2{}^{16}O$
$\delta^{18}O_{vapor}$: -12 ‰
$H_2{}^{18}O$
$\delta^{18}O_{leaf}$: +8 ‰
$\delta^{18}O_{source}$: -2 ‰
No change in $\delta^{18}O$ during plant uptake

Oxygen-18 ratios of water in a forest canopy



Lai et al. (2006) Plant Cell & Environment 29:77-94

Modeling leaf water ^{18}O enrichment

- Dissect biotic and abiotic influences

- Craig-Gordon model
- Péclet effect
- Effect of water vapor
- Steady state v.s. non-steady state

Measured leaf water ^{18}O enrichment (Δ_o) is expressed relative to the source water:

$$\Delta_o = (\delta_L - \delta_s)/(1 + \delta_s/1000)$$

δ_L: ^{18}O of bulk leaf water

δ_s: ^{18}O of stem water

Modeling leaf water ^{18}O enrichment

A modified Craig-Gordon formulation (Craig and Gordon 1965)

$$\Delta_{es} = \varepsilon^{*} + \varepsilon_k + (\Delta_v - \varepsilon_k)\frac{e_a}{e_i}$$

Δ_{es}: steady-state leaf water ^{18}O enrichment at the sites of evaporation

ε^{*}: equilibrium fractionation factor (see Barbour et al. 2004)

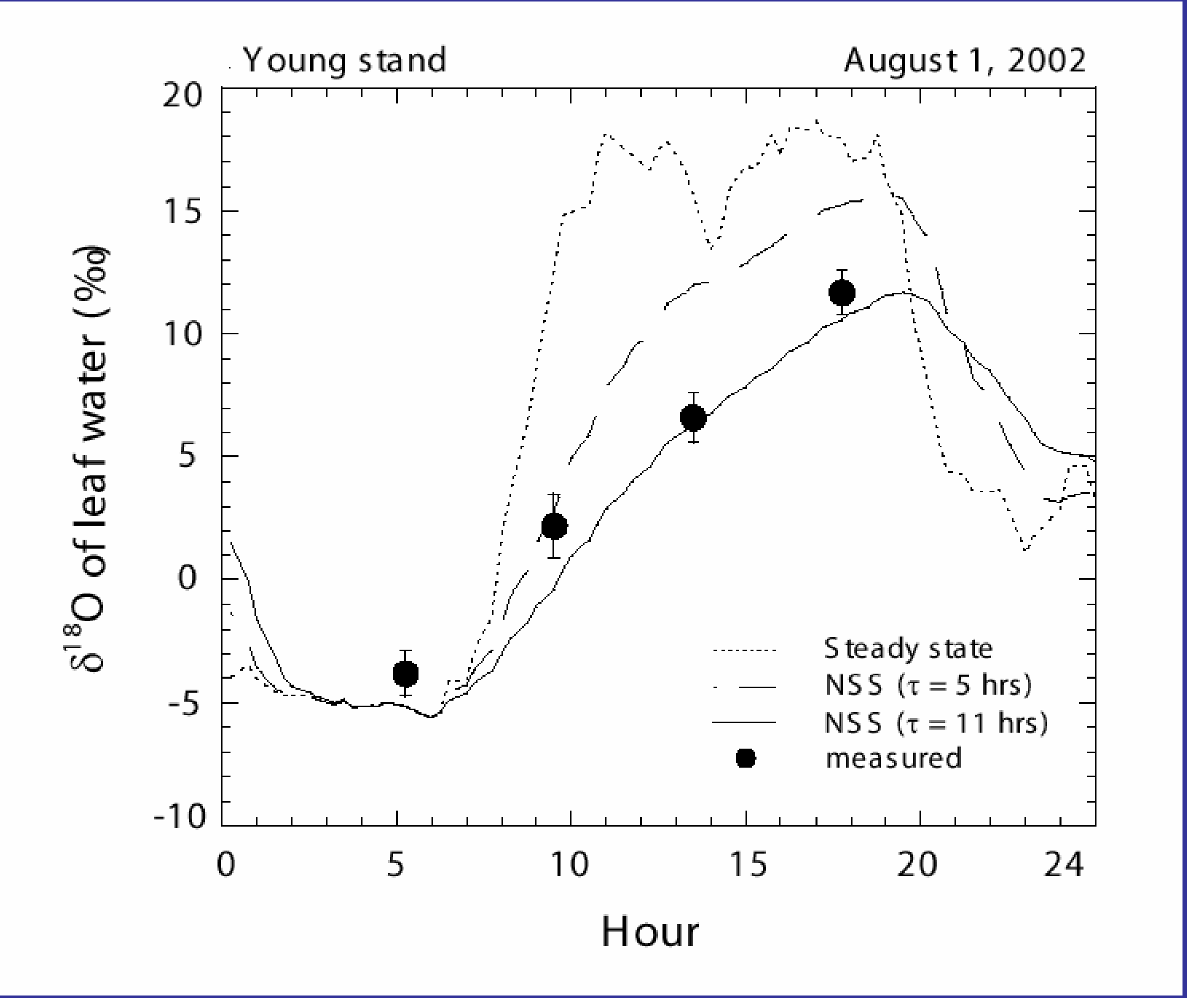
ε_k: kinetic fractionation factor

Δ_v: water vapor ^{18}O enrichment relative to the source water

e_a/e_i: ratio of vapor pressure in the air to leaf intercellular space

Farquhar et al. (1989)

CG model overestimates observed $\delta^{18}O$ of leaf water - the Péclet effect



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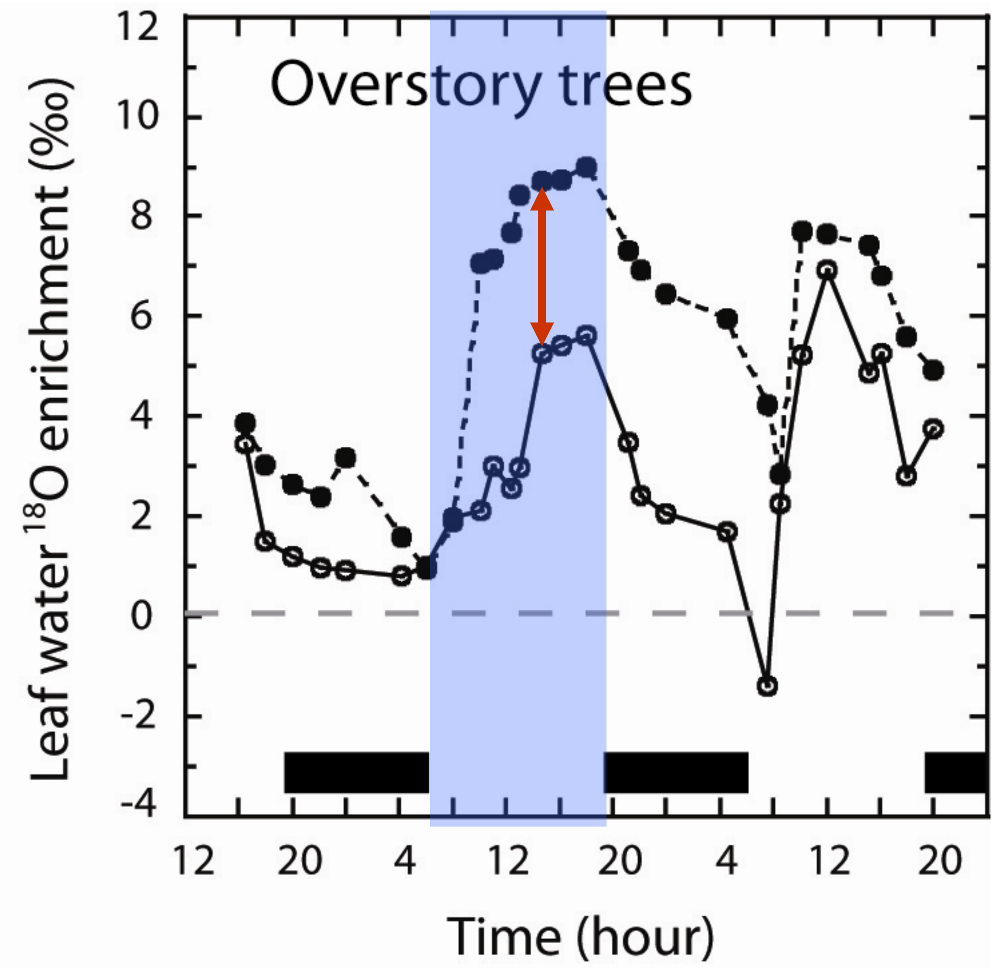
Observed leaf water ^{18}O enrichment



The Péclet effect

describes the convection of non-fractionated water to the site of evaporation opposed by the diffusion of the enriched water

$$\Delta_{Ls} = \frac{\left(1 - e^{-P}\right)}{P} \Delta_{es}$$

P is the Péclet number

Farquhar and Lloyd (1993)

Modeling leaf water ^{18}O enrichment

A modified Craig-Gordon formulation (Craig and Gordon 1965)

$$\Delta_{es} = \varepsilon^{*} + \varepsilon_{k} + (\Delta_{v} - \varepsilon_{k})\frac{e_{a}}{e_{i}}$$

Δ_v: water vapor ^{18}O enrichment relative to the source water

Δv needs to be known but is rarely measured in the field

Farquhar et al. (1989)

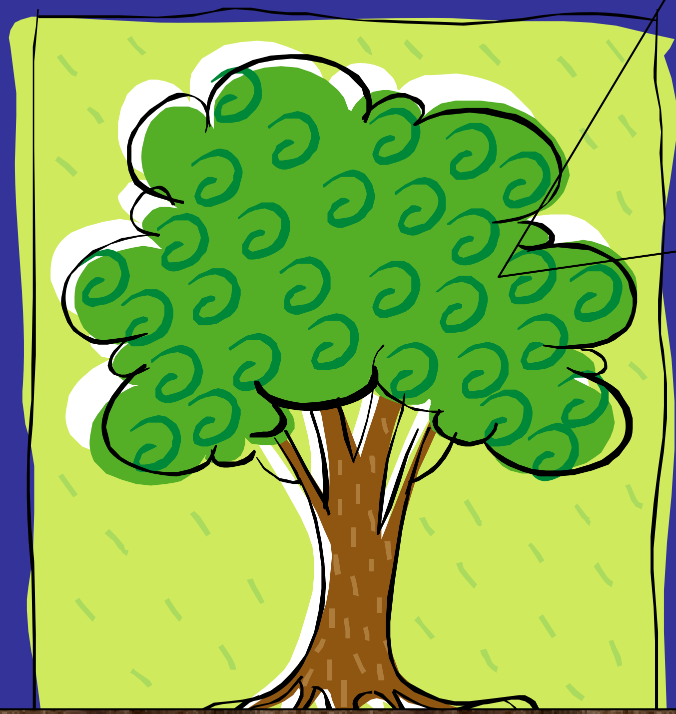
Oecologia
DOI 10.1007/s00442-008-1071-5

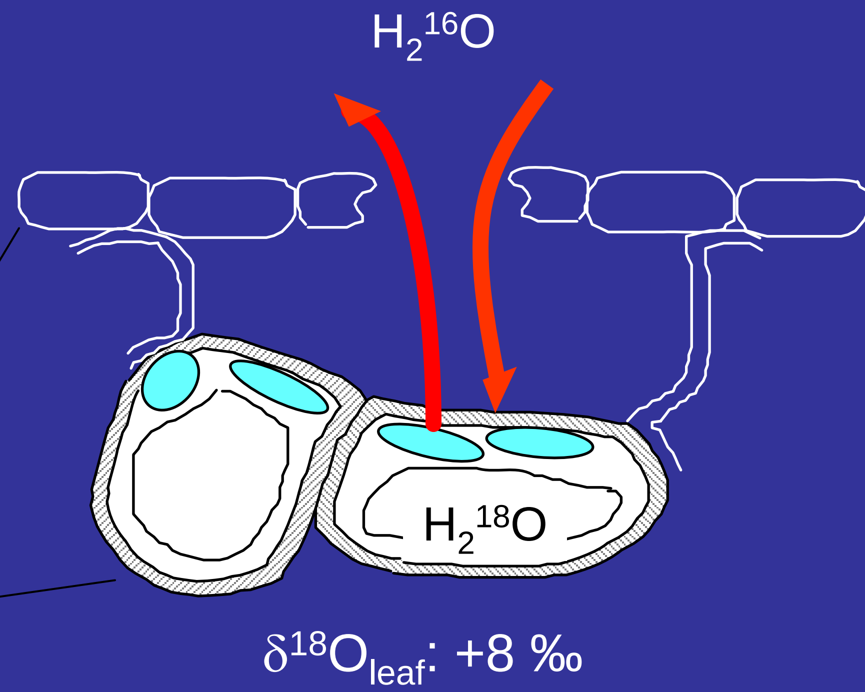
PHYSIOLOGICAL ECOLOGY - ORIGINAL PAPER

Life form-specific variations in leaf water oxygen-18 enrichment in Amazonian vegetation

Lai et al. (2008)

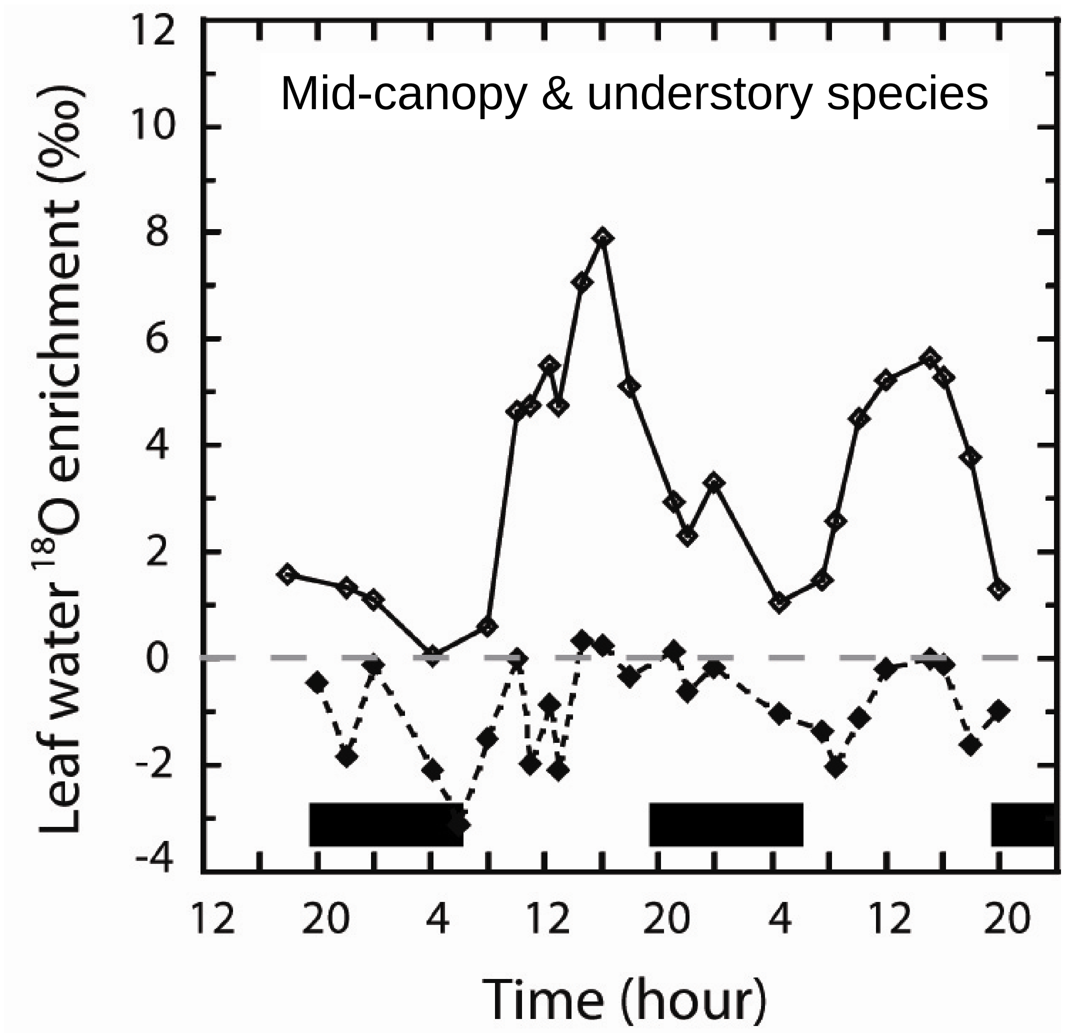
^{18}O effects of water vapor on leaf water





Leaf water is in isotopic equilibrium with water vapor !

Diel changes of leaf water ^{18}O enrichment in the understory of tropical forests



Modeling leaf water ^{18}O enrichment

A modified Craig-Gordon formulation (Craig and Gordon 1965)

$$\Delta_{es} = \varepsilon^{*} + \varepsilon_{k} + (\Delta_{v} - \varepsilon_{k})\frac{e_a}{e_i}$$

Δ_v: water vapor ^{18}O enrichment relative to the source water

Δv needs to be known but is rarely measured in the field

Farquhar et al. (1989)

^{18}O exchange between water vapor and leaf water

$$\Delta_{es} = \varepsilon^{*} + \varepsilon_{k} + (\Delta_{v} - \varepsilon_{k}) \times 1$$

When $e_a/e_i = 1$ (i.e. RH=100%, nighttime)

$$\Delta_{es} = \varepsilon^{*} + \Delta_{v}$$

Leaf water is in isotopic equilibrium with water vapor !

Estimating $\delta^{18}O$ of water vapor from leaf water $\delta^{18}O$ measurements

When RH = 100%

$$\Delta_{vapor} = \Delta_{es} - \varepsilon^*$$

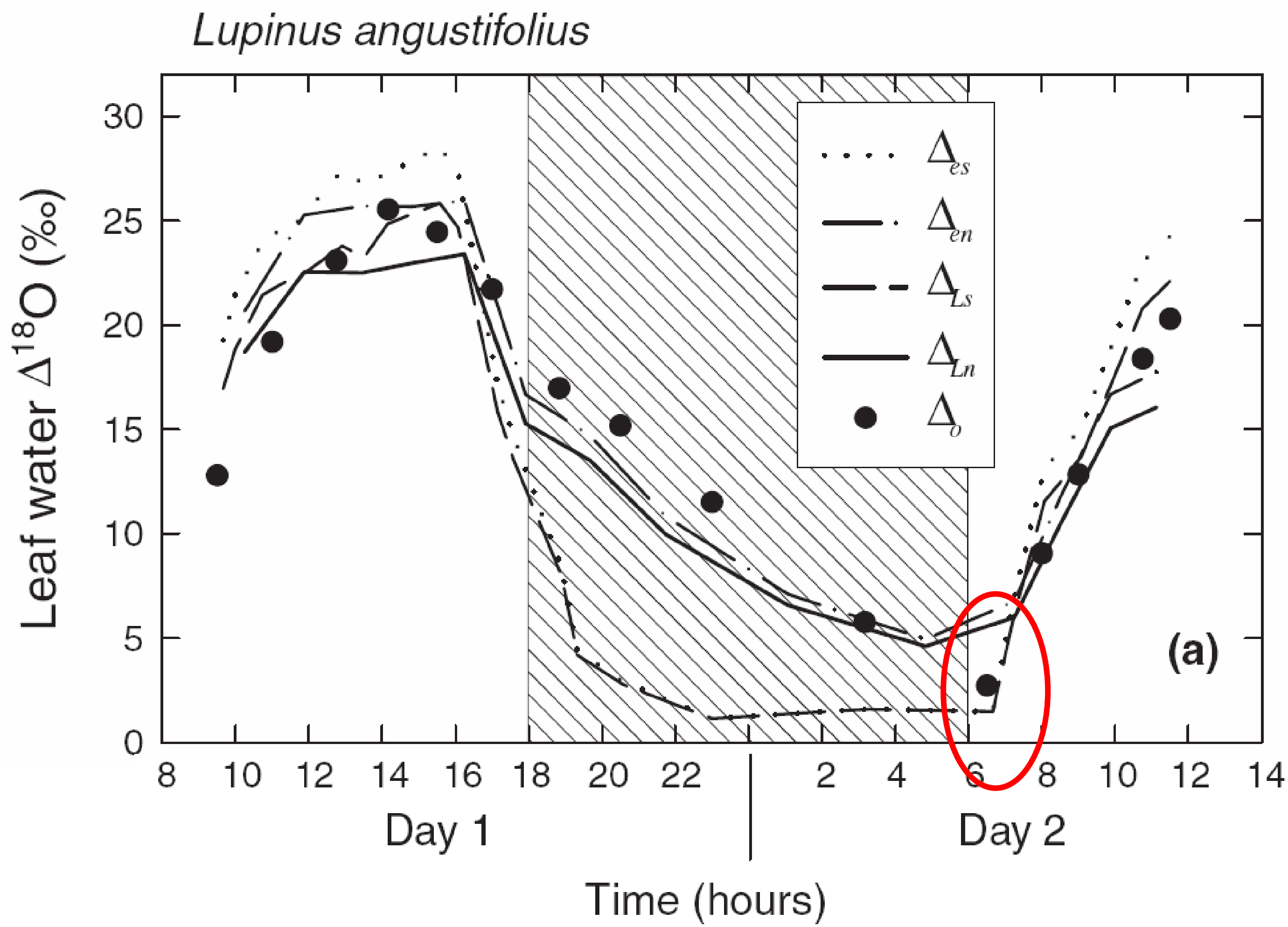
Can we use measured $\delta^{18}O$ values of bulk leaf water as a proxy to estimate $\delta^{18}O$ of water vapor on daily time scales?

Requirements:

Δ_{es}: steady state

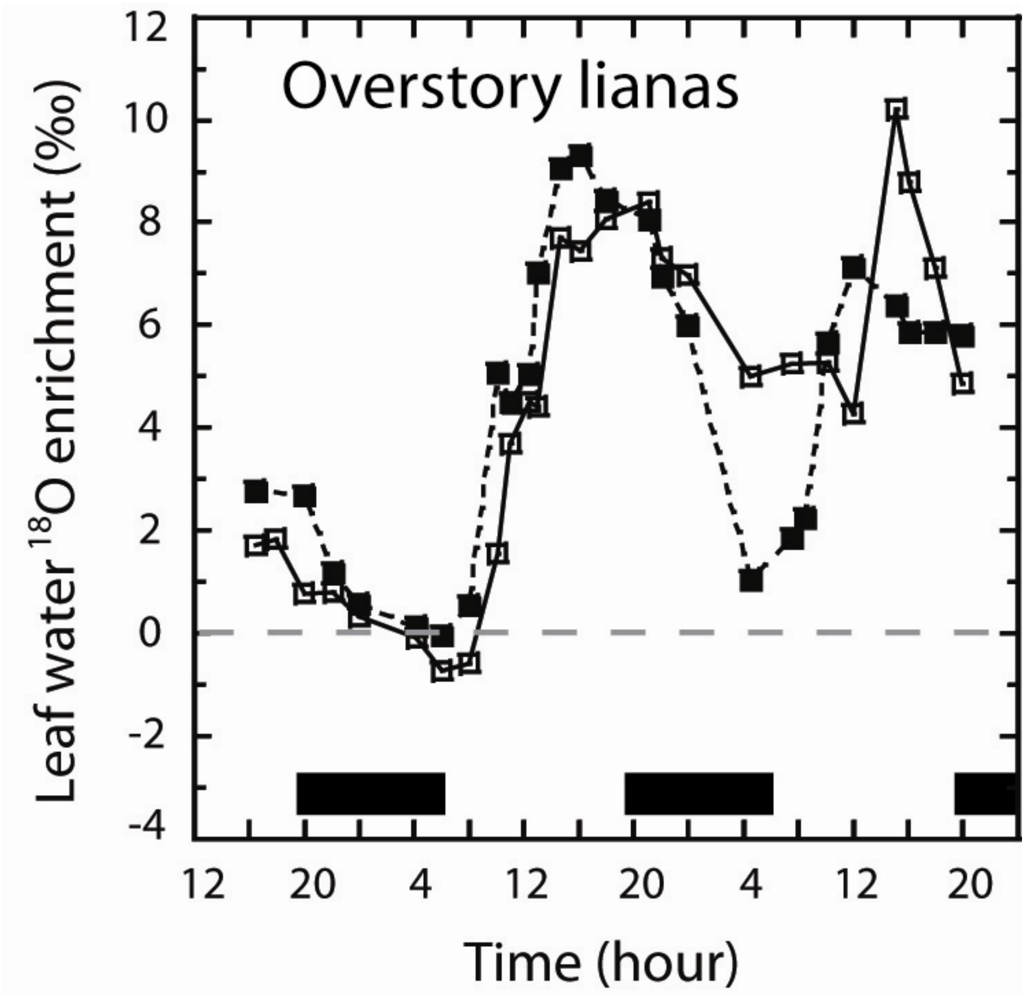
Δ_{es}: sites of evaporation (vs bulk leaf)

When do measured $\delta^{18}O$ of bulk leaf water resemble Δ_{es}?



Cernusak et al. 2002 PCE 25:893

Observed leaf water ^{18}O enrichment



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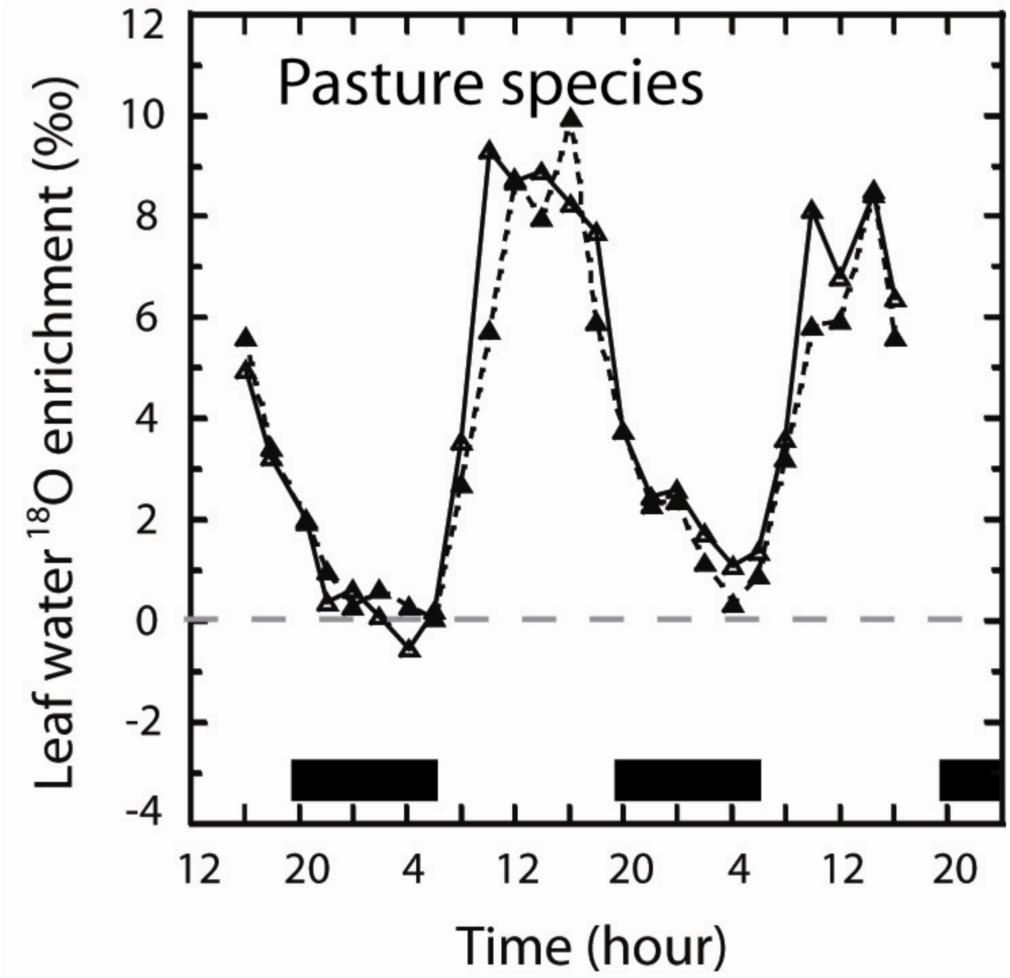
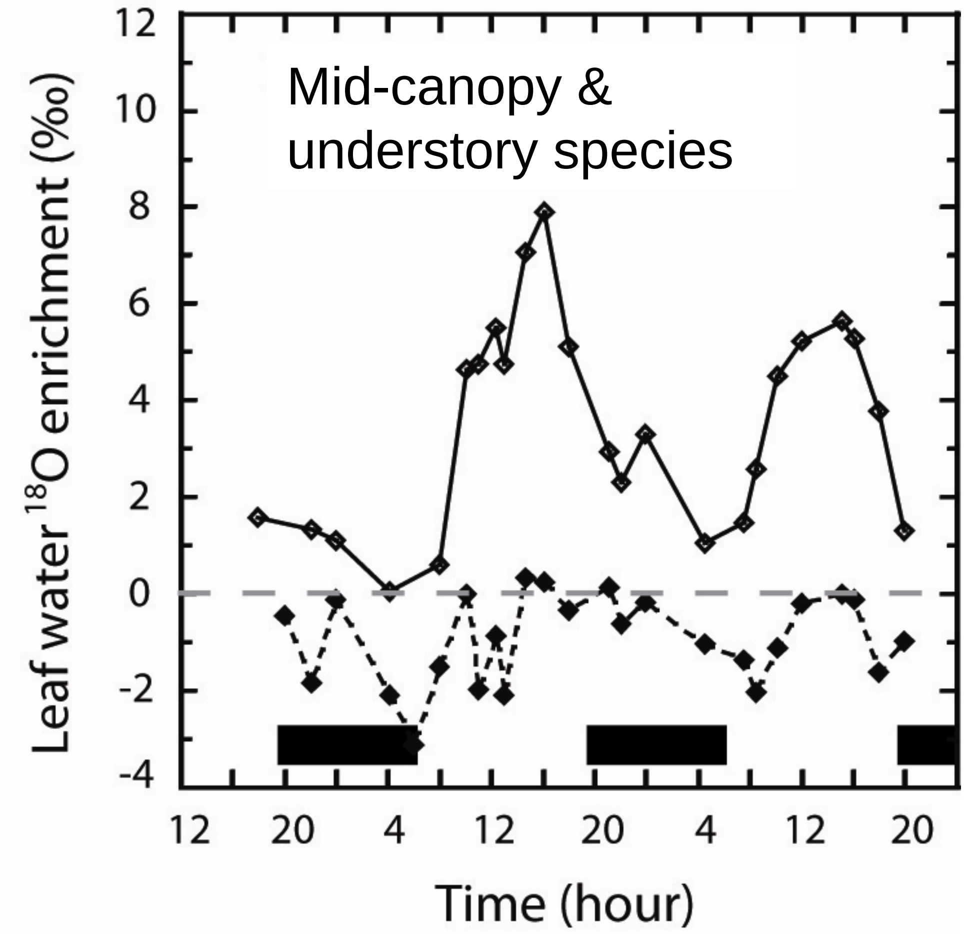


Observed leaf water ^{18}O enrichment



A plant-based approach to estimate $\delta^{18}O$ of water vapor

$$\delta_v = \delta_L - (\delta_s + 1) \cdot \varepsilon^*$$

δ_V: ^{18}O of water vapor

δL: ^{18}O of bulk leaf water

δs: ^{18}O of stem water

ε^*: equilibrium fractionation factor

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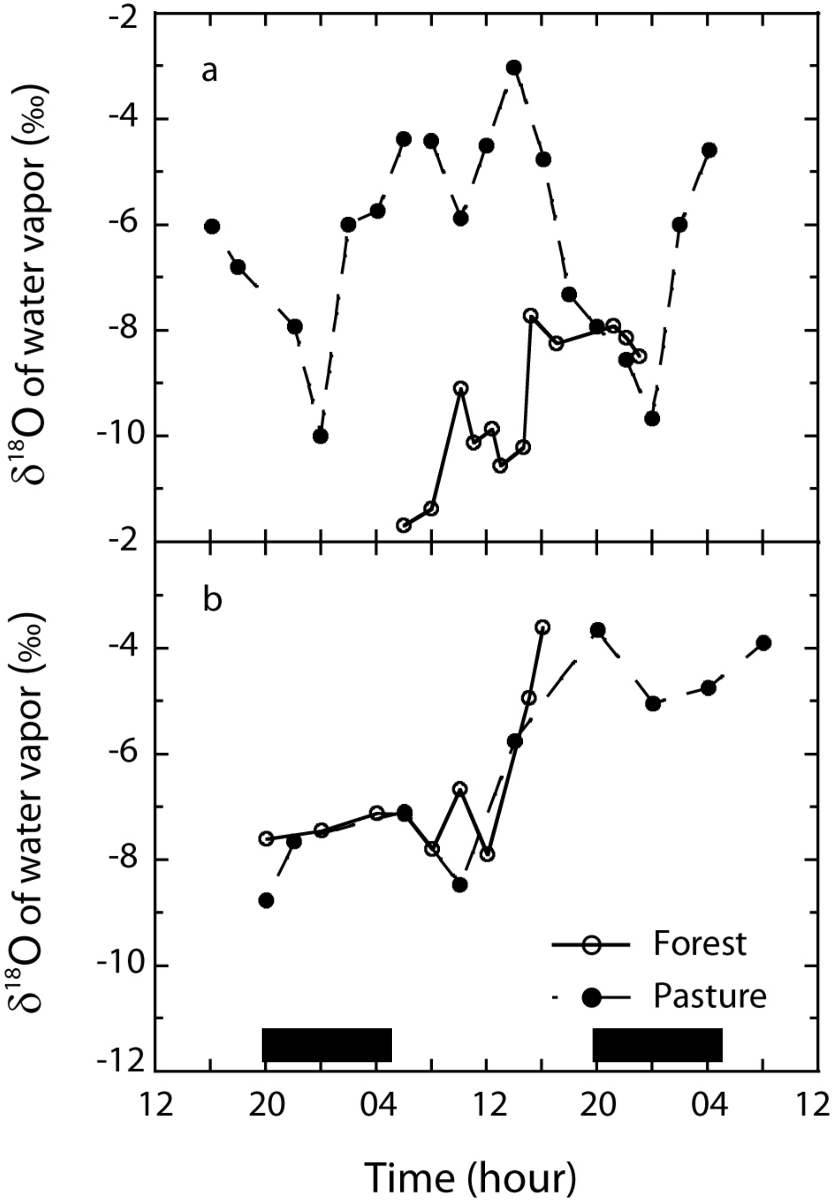

Plant-based estimates	Rain-based estimates
forest –13.4 ± 0.8‰ pasture –14.9 ± 1.1‰	–15.8‰

Comparison between measured and estimated $\delta^{18}O$ of water vapor for the two study periods

A plant-based approach to estimate $\delta^{18}O$ of water vapor

$$\delta_v = \delta_L - (\delta_s + 1) \cdot \varepsilon^*$$

This approach takes into account the contribution of local vegetation (via transpiration) to water vapor contents in the atmosphere !!!

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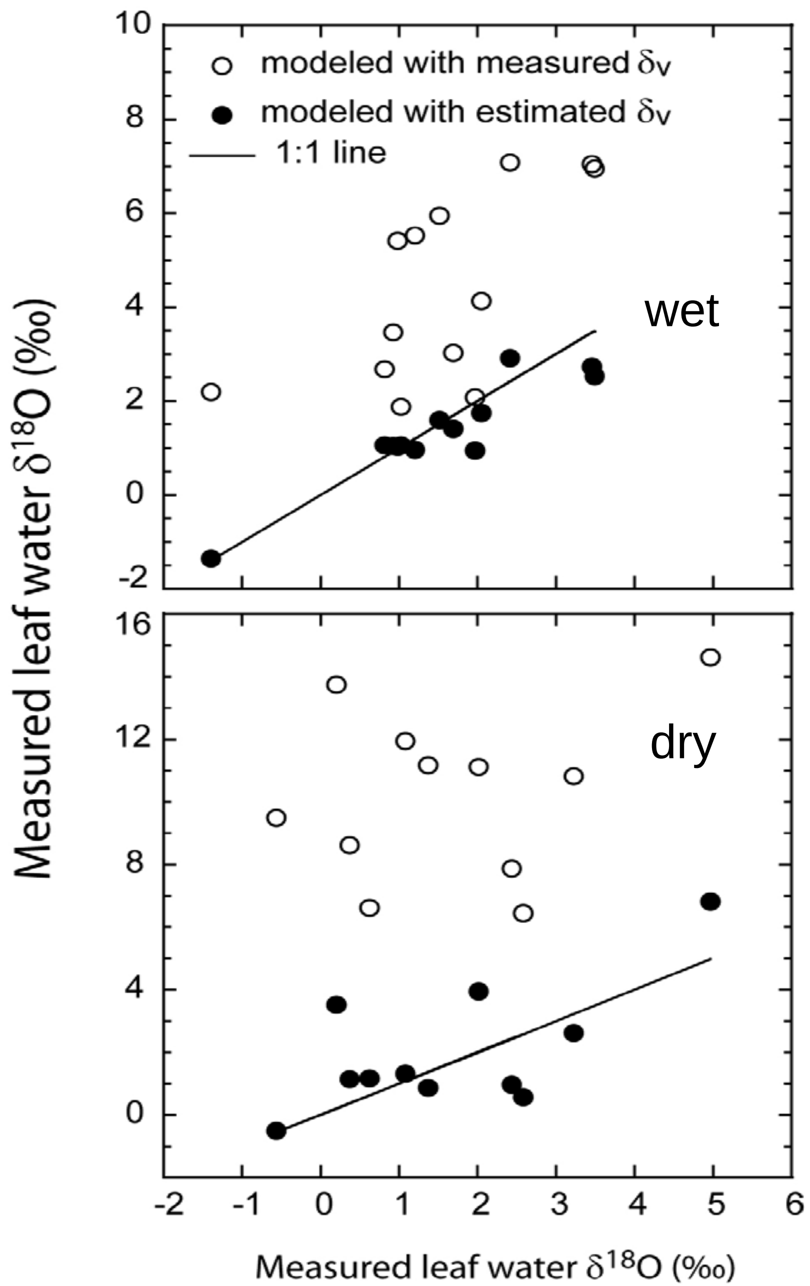

modeled with measured δ_v
modeled with estimated δ_v
1:1 line
wet
dry
Measured leaf water $\delta^{18}O$ (‰)
Measured leaf water $\delta^{18}O$ (‰)

Steady-state vs Non-steady state

$$\tau = \frac{W\alpha_k\alpha^*}{gw_i}$$

τ: turnover time of leaf water

$\alpha_k\alpha^* \approx 1$

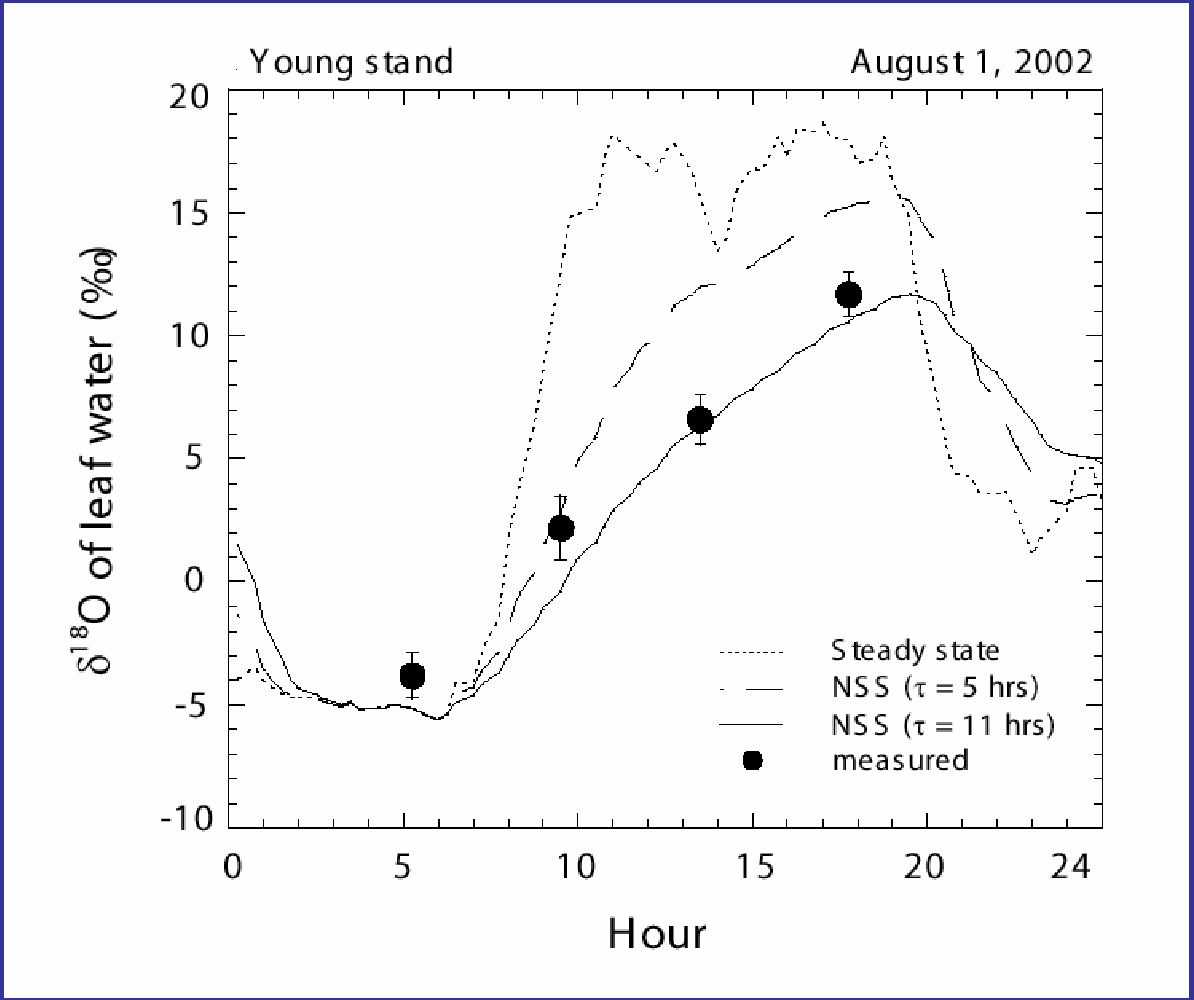
g : stomatal conductance

w : leaf water content

Dongmann et al. 1974

$$\delta_{en}(t) = \delta_e(t) - [\delta_e(t) - \delta_{en}(t-1)]\exp(\frac{-\Delta t}{\tau\varsigma})$$

Plants subject to drought are more likely to transpire at isotopic non-steady state



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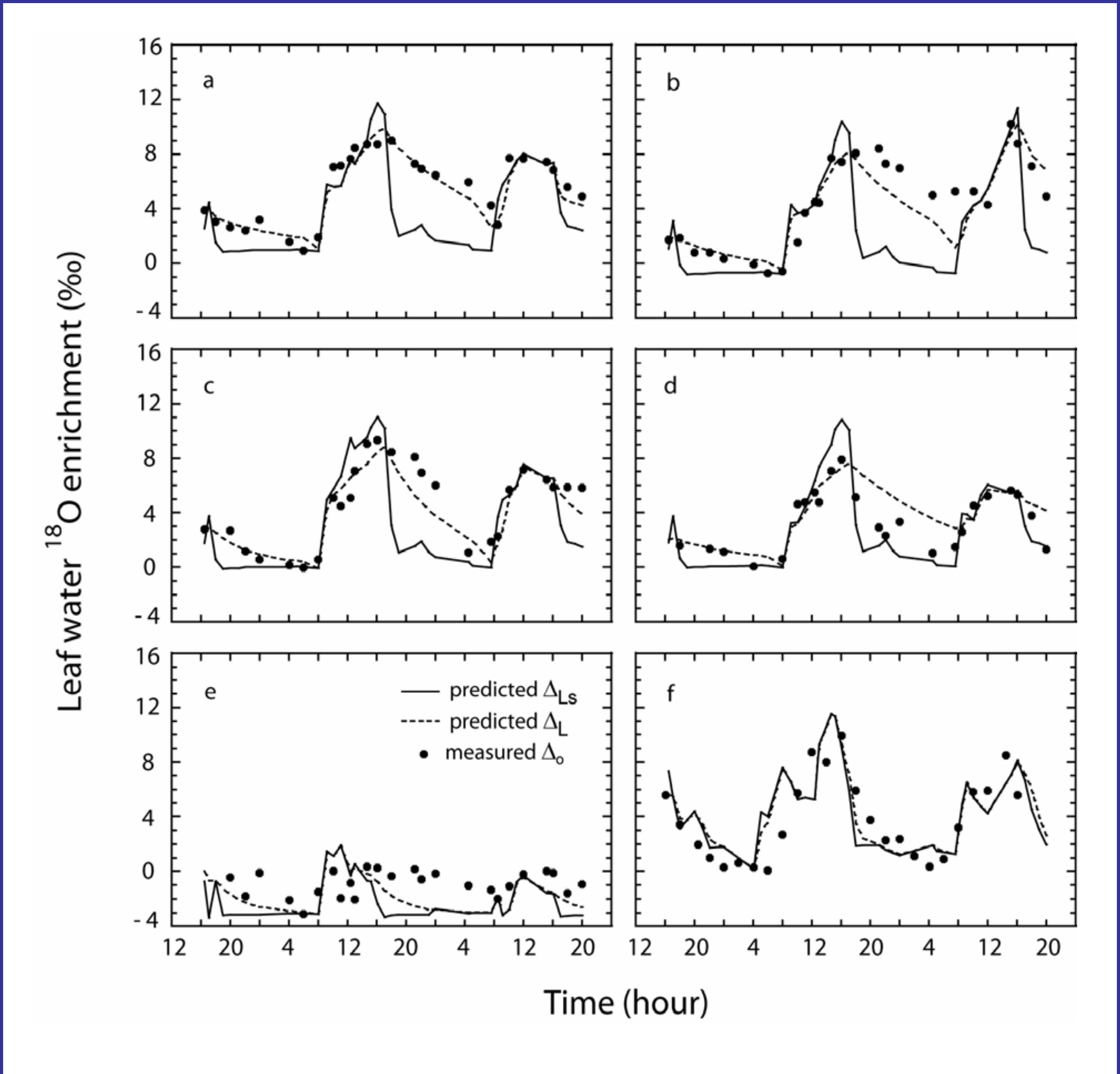
Model results are greatly improved after considering NSS and Péclet effects



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