Modelling leaf water isotope composition

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a crossroad between plant physiology, fluid mechanics and applied mathematics

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I. RATIONALE

Why studying leaf water $^{18}O/^{16}O$ and D/H signals?

The $^{18}O/^{16}O$ and D/H ratios of leaf water are useful signals for studying the *carbon* and *water* budgets of terrestrial ecosystems as they:

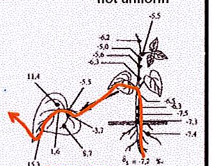
...impact the isotope ratio of plant material allowing:
- to determine changes in stomatal conductance and crop yield
- to do paleoclimate reconstructions by tree ring analysis

...affect atmospheric water vapour (^{18}O, D) allowing:
- to partition evaporation from transpiration
- to study water redistribution and recycling by plants

...affect atmospheric CO_2 (^{18}O) allowing:
- to partition respiration from photosynthesis (one day!)

...affect atmospheric O_2 (^{18}O) (Dole effect) allowing:
- paleo-reconstructions of terrestrial vs. marine productivity

The isotope ratio of plant water is not uniform



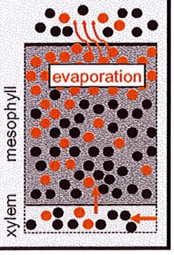
Plant water becomes more and more enriched as it approaches the leaf tip

Why leaf water is enriched relative to sap water?

Schematically, leaf water can be separated in two water reservoirs: the *xylem* and the *mesophyll*.

Water enters the leaf through the xylem and evaporates on the mesophyll 'walls'.

Light water molecules ($H_2{}^{16}O$) evaporate and diffuse more rapidly than heavy water molecules ($H_2{}^{18}O$ or HDO) which creates an isotopic enrichment in the mesophyll (see Figure).

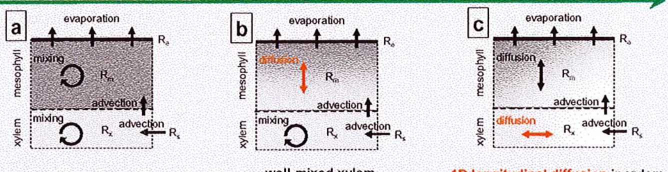


II. OBJECTIVES

Existing leaf water isotopic enrichment models

In all models the *advection* of water and isotopic enrichment through *evaporation* are accounted for but, depending on their degree of realism, the isotopic composition of leaf water in each reservoir may be uniform (complete *mixing*) or not (*diffusion*)

Increasing realism/complexity



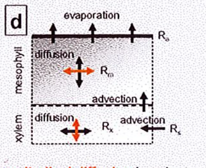
a: well-mixed xylem, well-mixed mesophyll (Bariac et al. 1991)

b: well-mixed xylem, 1D radial diffusion in mesophyll (Farquhar and Lloyd 1993)

c: 1D longitudinal diffusion in xylem, 1D radial diffusion in mesophyll (Farquhar and Gan 2003)

What is currently lacking

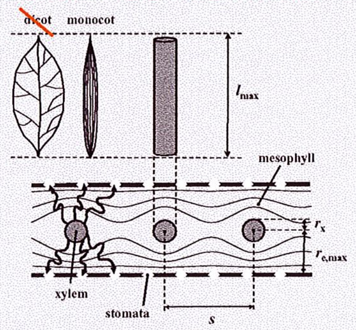
Current models are unable to reproduce the progressive leaf water and transpiration isotope enrichment observed in leaves. Accounting for radial diffusion in xylem or longitudinal diffusion in mesophyll might reduce the discrepancies.

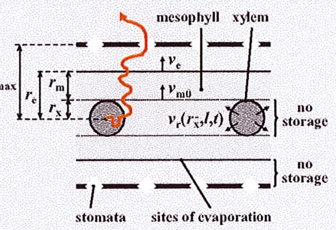


d: 2D radial/longitudinal diffusion in xylem, 2D radial/longitudinal diffusion in mesophyll

III. MODEL DESCRIPTION

Model leaf and model assumptions





Leaf xylem = parallel, cylindrical veins

Mesophyll = planar reservoir surrounding the leaf veins

2D advection/diffusion with cylindrical symmetry in xylem

2D advection/diffusion with planar symmetry in mesophyll

Tortuosity of water path in radial direction in both xylem and mesophyll

Model equations

In leaf xylem

$$\frac{\partial R}{\partial t}+\frac{\partial}{\partial l}\left(v_l R - D\frac{\partial R}{\partial l}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r v_r R - rD\kappa_x\frac{\partial R}{\partial r}\right)=0$$

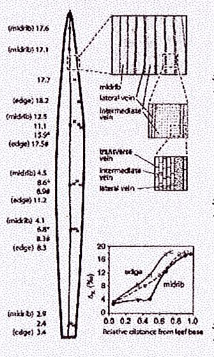
In mesophyll

$$\frac{\partial R}{\partial t}+\frac{\partial}{\partial r}\left(v_m R - D\kappa_m\frac{\partial R}{\partial r}\right) + \frac{\partial}{\partial l}\left(-D\kappa_m\frac{\partial R}{\partial l}\right)=0$$

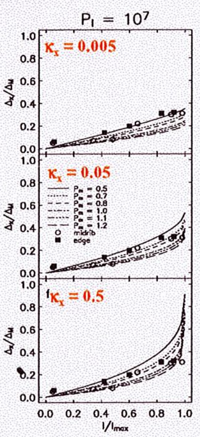
Boundary condition at $r = r_x$

$$2\pi r_x l_{max}\cdot\left(v_r R(r_x^-,l,t) - D\kappa_x\left.\frac{\partial R}{\partial r}\right|_{r_x^-,l,t}\right) = s l_{max}\cdot\left(v_r R(r_x^+,l,t) - D\kappa_m\left.\frac{\partial R}{\partial r}\right|_{r_x^+,l,t}\right)$$

IV. RESULTS

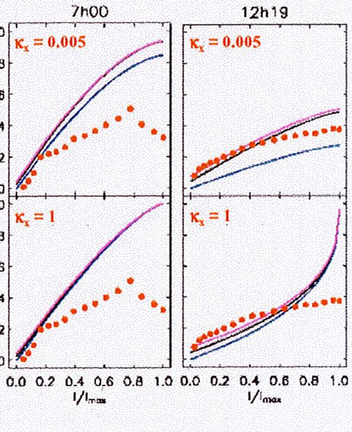


(data from Gan et al., 2003)



Accounting for a radial tortuosity factor in the leaf xylem (κ_x) enables to correctly repoduce the observed progressive isotope enrichment of xylem water along a maize leaf under steady environmental conditions

In the field with a naturally varying environment, non steady-state effects seem to dominate in the morning regardless of the value of the tortuosity factor in the leaf xylem or in the leaf mesophyll



V. CONCLUSIONS & PERSPECTIVES

We think that our formulation is promising when one tries to describe the isotopic composition of leaf water and transpiration in a naturally varying environment as it allows to account for both non steady-state and diffusive effects consistently. Yet this formulation is a simplification of what happens in monocot leaves but cannot be applied other than qualitatively to coniferous needles or dycotyledoneous leaves with their reticulate network of veins.

In the future we plan to 1/ explore the role of longitudinal diffusion in mesophyll, 2/ better characterize non steady-state effects, 3/ simplify the model equations for bulk leaf water in order to generalize the results to other leaf types (needles, dicotyledon leaves) and use them in terrestrial ecosystem models.

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