The Role of Plants in Site and Catchment Isotope Response

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HYDROLOGY

Introduction

For applications of the stable isotopes of water in hydrological modeling, it is often assumed, that plants do not strongly alter the isotopic composition of water, based on the observation that plants do not fractionate water isotopes while taking up water (Ziegler et al. 1976; White et al. 1985).

Literature review

A review of studies on plant physiology and plot scale plant hydrology indicates that several processes do affect the abundance of water isotopes deuterium (^2H) and oxygen-18 (^{18}O) through canopy effects, plant and cell water exchange down to root zone effects. This effects can be grouped into three and are classified as selection, redistribution, and uptake effects.

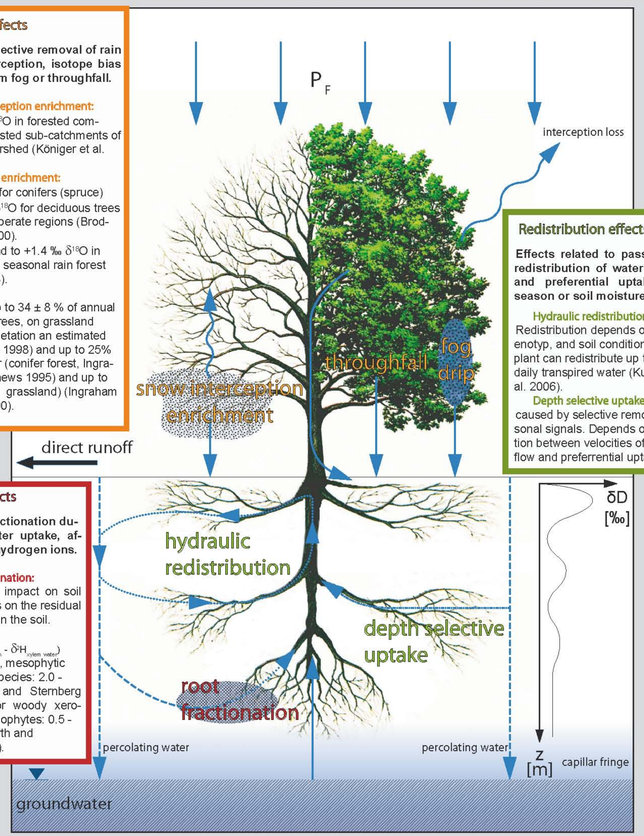
Selection effects

Effects by selective removal of rain or snow interception, isotope bias stemming from fog or throughfall.

Snow interception enrichment:
up to 2.0 ‰ $\delta^{18}O$ in forested compared to deforested sub-catchments of the same watershed (Königer et al. 2008)

Throughfall enrichment:
+0.38 ‰ $\delta^{18}O$ for conifers (spruce) and +0.36 ‰ $\delta^{18}O$ for deciduous trees (beech) in temperate regions (Broderson et al. 2000).
+5.5 ‰ δ^2H and to +1.4 ‰ $\delta^{18}O$ in natural tropical seasonal rain forest (Liu et al. 2008).

Fog drip:
can provide up to 34 ± 8 % of annual rainfall under trees, on grassland without tall vegetation an estimated 17 % (Dawson 1998) and up to 25% of groundwater (conifer forest, Ingraham and Matthews 1995) and up to 69 % (tussock grassland) (Ingraham and Marks 2000).



Redistribution effects

Effects related to passive (physical) redistribution of water and isotopes and preferential uptake by depth, season or soil moisture.

Hydraulic redistribution:
Redistribution depends on taxa, phaenotyp, and soil conditions. A single plant can redistribute up to 81 % of the daily transpired water (Kurz-Besson et al. 2006).

Depth selective uptake:
caused by selective removal of seasonal signals. Depends on the correlation between velocities of soil water flow and preferential uptake

Uptake effects

Effects by fractionation during root water uptake, affecting only hydrogen ions.

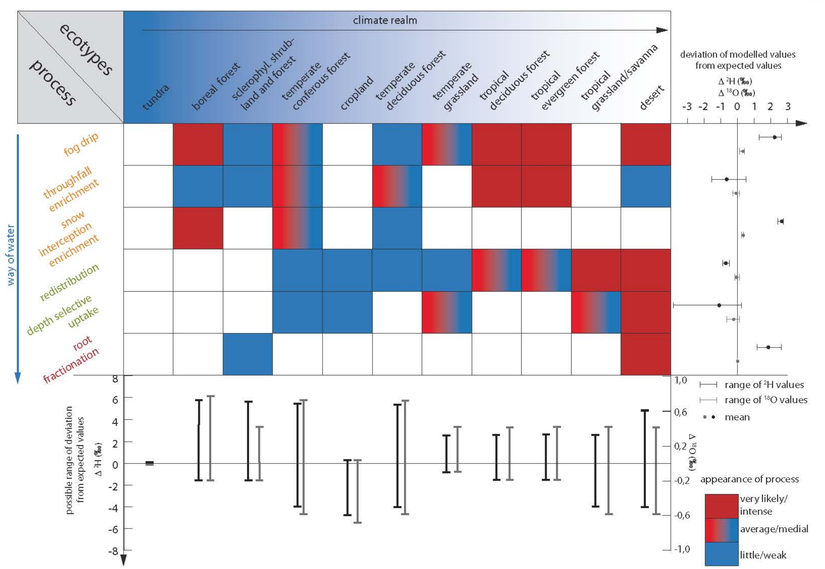
Root fractionation:
The observed impact on soil water depends on the residual water content in the soil.

Δ^2H (= $\delta^2H_{soil\ solution}$ - $\delta^2H_{xylem\ water}$) for glycophytic, mesophytic salt-adapted species: 2.0 - 13.0 ‰ (Lin and Sternberg 1993). Δ^2H for woody xerophytes and halophytes: 0.5 - 9.0 ‰ (Ellsworth and Williams 2007).

Synopsis

The possible effect of plants on isotope content of runoff in catchments depends on local climate and associate biomes with their typical plant species and life form structure.

The effects can potentiate and cancel out each other in respect of deviation from expected isotopic values or can be mutually exclusive.
To propose a compilation of possible ranges in deviation, eleven biomes - representing the most common ecotypes worldwide - were used.



The graphic integrates

- The chance of appearance of a process in an ecotype
- obtained process value range of deviation (from model)
- value range for single ecotypes with regard to every possible process per ecotype

Results

cropland: clear deviation, depletion in respect to expected values prognosted

boreal forest and sclerophytic shrubland & forest: prognosted deviation towards heavier values

other processes: no clear direction of deviation; either depletion or enrichment possible

Model

The isotope balance was established using the equation:

$$\frac{d(V * \delta_V)}{dt} = \alpha * P * \delta_P - Q_{ETP} * \delta_{Q_{ETP}}$$

where α = percentage of precipitation reaching the soil, P = precipitation and δ_P = isotope ratio of precipitation, Q = outflow, δ_Q = isotope ratio of outflow, V = volumetric soil moisture and δ_V = isotopic composition of soil moisture.

The conceptual model used had:
- three reservoirs representing three soil layers
- properties of the soil layers are defined by pore volume and field capacity
- soil layer outflow (Q) regulated by an exponential coefficient
- isotopes weighted according to water volumes

All influencing processes were designed as modules, so they could be "switched" on or off

Selection effects

Throughfall enrichment:
Throughfall is influenting input in amount and isotopic value. The input was changed before entering the first reservoir.

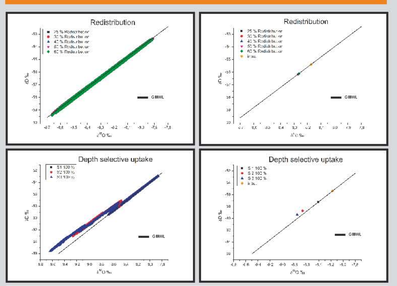
Net isotope effects are minor and range in the order of - 0.05 to +0.19 ‰ $\delta^{18}O$ and -1.54 to +0.43 ‰ $\delta^{18}O$.

Snow interception enrichment:
Based on the Throughfall enrichment module. Typical values for snow interception (30 - 40 %) were used.

model runs showed mean values of +2.6 ‰ δ^2H and +0.34 ‰ $\delta^{18}O$.

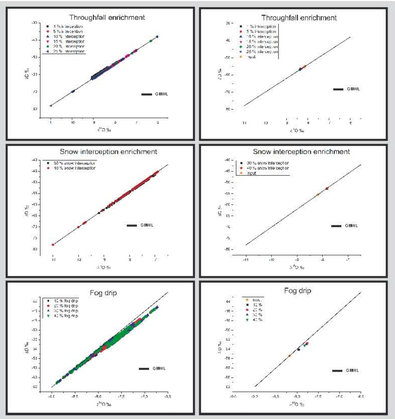
Fog drip:
Fog drip was treated like one more precipitation component and was simply added to the first reservoir.

model runs obtained enrichment values between +1.26 and +2.62 ‰ δ^2H and +0.21 to +0.42 ‰ $\delta^{18}O$



Uptake effects

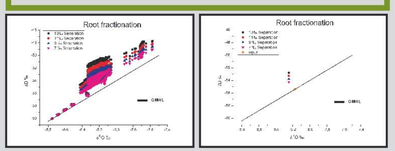
Root fractionation:
The root fractionating module is based on the transpiration module and can desinged variable.
Net isotope effects are major and lead to a selective δ^2H enrichment by about +5.0 ‰ δ^2H



Redistribution effects

Hydraulic redistribution:
Redistribution was realised as transfer of water from the reservoir with the highest water content to the reservoir with the lowest content.
Model runs indicate that redistribution has minor effects on isotope composition: amounting to 0.2 ‰ $\delta^{18}O$. Isotope effects show a complex dependency on climate regime, soil properties and plant transpiration regime.

Depth selective uptake:
Was realised with an uptake module. Every reservoir represented an uptake depth, which can designed variable through the year. In temperate regions bias it is mostly negative and can reach -3.97 ‰ δ^2H through selective removal of summer rain.



Results

Plant physiological procsses resulting in isotope effects on the water cycle can be grouped into three effect-groups. Their effects are documented to reach 2.0 ‰ $\delta^{18}O$ (snow interception enrichment, Königer et al. 2008) for catchments and up to 13 ‰ δ^2H for small scale plots (root fractionation, Lin & Sternberg 1993).

- Plants do have the potential to influence the isotopic composition of soil water, groundwater and runoff.
- Processes may enhance or cancel out.

- The range of deviation from expected values for a single ecotype is wide and net bias can exceed ranges of -3.97 - +5.39 ‰ δ^2H and -0.58 - +0.725 ‰ $\delta^{18}O$ in extreme cases.

Results

Model runs indicate that processes hitherto only documented for plot scale sites has also the potential to alter the isotopic content in catchment runoff. Obtained values ranged from -0.58 ‰ $\delta^{18}O$ (depth selective uptake) to +0.42 ‰ $\delta^{18}O$ (fog drip) and -3.97 ‰ δ^2H (depth selective uptake) to +2.62 ‰ δ^2H (fog drip and root fractionation).

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