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Partitioning evapotranspiration in a temperate grassland ecosystem: Numerical modeling with isotopic tracers

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To partition evapotranspiration (ET) into soil evaporation (E) and vegetation transpiration (T), a new numerical Iso-SPAC (coupled heat, water with isotopic tracer in soil–plant–atmosphere-continuum) model was developed and applied to a temperate-grassland ecosystem in central Japan. Several models of varying complexity have been tested with the aim of obtaining the close to the true value for the isotope composition of leaf water and transpiration flux. The agreement between model predictions and observations demonstrated that the Iso-SPAC model with a steady-state assumption for transpiration flux can reproduce seasonal variations of all the surface energy balance components as well as isotope data (canopy foliage and ET flux). Uncertainties/errors for T/ET and each end members in assigned model parameters and measured input variables were discussed quantitatively. The T/ET increased with grass growth, and the sharp reduction caused by clear cutting was well reflected. The transpiration fraction ranged from 0.02 to 0.99 during growing seasons, and the mean value was 0.75 with a standard deviation of 0.24. Results indicate that SPAC model is a promising tool for integrating the isotopic fractionation processes with separate E and T in multispecies terrestrial ecosystems and has the advantage of enabling long-term assessment of ET partitioning as well as isotopic enrichment output at soil–plant–atmosphere interface. Our study reemphasize that isotope tracer approach is useful for evaluating quantitatively the relationships among hydrological components.

1. Introduction

Evapotranspiration (ET) emphasizes the combined flux associated with two different pathways (soil evaporation (E) and plant transpiration (T)) of water vaporization in terrestrial ecosystems (Katul et al., 2012). It is important to improve our knowledge of its components, as they provide abundant information about water and heat transfer through the whole soil–plant–atmosphere continuum. Most research has focused on ET as an aggregated process, but more recently, emphasis has been placed on the importance of distinguishing between and quantifying the two major components of ET. This partitioning is one of the most significant ecohydrological challenges and has important implications not only for water budget but also for understanding feedback between vegetation dynamics and water as well as biogeochemical cycles (Newman et al., 2006).

Stable water isotopes are natural tracers of ecosystem processes and can be used for partitioning at the ecosystem level. This concept has been applied by many studies on diverse regions worldwide (Moreira et al., 1997; Yakir and Sternberg, 2000; Williams et al., 2004; Yepez et al., 2003, 2005; Tsujimura et al., 2007; Wang et al., 2010; Good et al., 2014). The T/ET can be estimated by

$$\frac{T}{\mathrm{ET}} = \frac{\delta_{\mathrm{ET}} - \delta_E}{\delta_T - \delta_E} \tag{1}$$

where δ is the isotope composition (δ^{18}O or δD), and the subscripts ET, E and T denote the evapotranspiration, evaporation and transpiration fluxes, respectively. On the other hand, the SPAC model, which can estimate/predict evaporation and transpiration flux separately (e.g., Shuttleworth and Wallace, 1985; Kustas and Norman, 2000; Brenner and Incoll, 1997; Reynolds et al., 2000; Wang and Yamanaka, 2014), is another useful tool. In particular, SPAC models involving isotopic tracers (i.e., Iso-SPAC models) are expected to

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Notation

C	Molar concentration of water, equal to 55.5×10^3 mol m^{-3}
C_p	Heat capacity of dry air, J kg^{-1} K^{-1}
D	Diffusivity of $^{18}O–H_2O$ or $HD^{16}O$ in water, m^2 s^{-1}
E	Soil evaporation rate, mm h^{-1}
ET	Evapotranspiration rate, mm h^{-1}
f	Fraction of water at evaporating site to bulk leaf water, dimensionless
G	Ground heat flux density, W m^{-2}
g_{st}	Leaf-scale stomatal conductance, mm s^{-1}
H	Sensible heat flux density, W m^{-2}
h^*	Relative humidity of the ambient air reference to T_L or T_G, %
h_a	Relative humidity at the reference level, %
LAI	Leaf area index, m^{-2} m^{-2}
L_d	Downward long-wave radiation, W m^{-2}
L_{eff}	Scaled effective "radial" length in Péclet number, m
lET	Latent heat flux, W m^{-2}
P	Air pressure at the reference level, hPa
$\wp$	Péclet number, dimensionless
q_a	Specific humidity at reference height, kg kg^{-1}
r_a	Aerodynamic resistance above the vegetation canopy, s m^{-1}
r_{aV}	Aerodynamic resistance in the canopy air layer, s m^{-1}
r_b	Canopy-scale boundary layer resistance, s m^{-1}
r_c	Canopy-scale stomata resistance, s m^{-1}
R_n	Net solar radiation, W m^{-2}
r_{ss}	Soil resistance, s m^{-1} or m^2 s mol^{-1}
r_{st}	Leaf-scale stomata resistance, s m^{-1}
r_{st_min}	Minimum stomata resistance, s m^{-1}
r_{st_max}	Maximum stomata resistance, s m^{-1}
r_t	Canopy-scale total resistance to water vapor and heat from canopy surface to reference height, s m^{-1}
S_d	Downward short-wave radiation, W m^{-2}
S_i	Sensitivity coefficient, dimensionless
T	Plant transpiration rate, mm h^{-1}
T_a	Air temperature at the reference level, K
T_G	Ground soil temperature, K
T_L	Leaf canopy temperature, K
T_{soil}	Soil surface temperature at a depth Z_{soil} (m), °C
u	Wind speed at the reference level, m s^{-1}
u_c	Wind speed inside the conopy, m s^{-1}
u_v	Wind speed at vegetation height, m s^{-1}
W	Leaf water content (mass of water per unit ground area at the canopy scale), kg m^{-2}
w_i	Mole fraction of (light) water vapor in the intercellular spaces, mol mol^{-1}
Z_h	The height of temperature and humidity measurement, m
Z_m	The height of wind speed measurement, m
Z_{soil}	Depth of ground heat flux measurement, m
Z_v	Vegetation height, m
α	Surface albedo, dimensionless
α^+	Equilibrium fractionation factor for water (>1), dimensionless
α_G	Albedo of ground surface, dimensionless
$\alpha_G{}^+$	Equilibrium fractionation factor for water (>1) at ground surface temperature, dimensionless
α_k	Kinetic fractionation factor for water vapor (>1), dimensionless
α_{kG}	Kinetic fractionation factor for water vapor (>1) at ground surface temperature, dimensionless
α_{kL}	Kinetic fractionation factor for water vapor (>1) at leaf temperature, dimensionless
$\alpha_L{}^+$	Equilibrium fractionation factor for water (>1) at leaf temperature, dimensionless
α_V	Albedo of vegetation canopy, dimensionless
δ	Isotope composition of sample water relative to a standard, ‰
δD	Staple isotope composition of hydrogen in water, ‰
$\delta^{18}O$	Stable isotope composition of oxygen in water, ‰
δ_E	δ of evaporation flux, ‰
δ_{ET}	δ of evapotranspiration flux, ‰
$\delta_{L,b}$	δ of bulk leaf water, ‰
$\delta_{L,bs}$	Steady state value of $\delta_{L,b}$, ‰
$\delta_{L,e}$	δ at evaporative site in leaf, ‰
$\delta_{L,es}$	Steady state values of $\delta_{L,e}$, ‰
δ_S	δ of liquid soil water, ‰
δ_T	δ of plant transpiration flux, ‰
δ_V	δ of water vapor, ‰
δ_X	δ of xylem water, ‰
ϵ^+	Isotopic equilibrium fractionation factor between liquid water and vapor, ‰
ϵ_k	Isotopic kinetic fractionation factor between liquid water and vapor, ‰
θ	Volumetric soil water content, m^{-3} m^{-3}
λ_{ss}	Thermal conductivity of surface soil, W m^{-1} K^{-1}
ρ_a	Density of moisture air, kg m^{-3}

be more reliable for this purpose (e.g., Braud et al., 1995, 2005a,b; Riley et al., 2002).

However, some previous studies have raised doubt about the steady-state assumption (SSA) that the $\delta^{18}O$ and δD of transpiration flux (δ_T) is assumed to equal to that of xylem water (δ_X) (Yepez et al., 2005; Lai et al., 2006; Welp et al., 2008) when using isotope approaches. Although several models of isotopic enrichment of leaf water with the SSA or without (Cuntz et al., 2007; Dongmann et al., 1974; Farquhar and Cernusak, 2005; Ogée et al., 2007) have been proposed, it remains unclear which one is the best under field conditions. On the other hand, the SPAC model is a powerful tool for integrating the isotopic fractionation processes with H_2O exchange in terrestrial ecosystems and has the advantage of enabling long-term assessment of ET partitioning as well as isotopic enrichment output at the plant-atmosphere interface. Xiao et al. (2010) developed a large leaf isotopic model (SiLSM) to investigate the controlling factors of the isotopic exchange of $^{18}O–H_2O$ and $C^{18}OO$ between the agroecosystem and the atmosphere; however, the contribution from the soil evaporation was neglected. Numerous land surface models with isotopic tracers have been developed (e.g., Braud et al., 2005a,b,b; Riley et al., 2002; Yoshimura et al., 2006). However, how to integrate and simulate the dynamic variation in the isotope composition of plant transpiration and soil evaporation remains challenge. Few Iso-SPAC models have been developed or sufficiently validated by appropriate isotopic observation. In general, the isotopic variation in SPAC models should be well understood based on field observation and modeled in a sophisticated manner.

The transpiration fraction (T/ET), which is indicative of ET partitioning, reflects the influence of vegetation on the hydrological cycle and provides an important insight into biological feedbacks for predicting climate changes (Wang et al., 2014). The objectives of the present study were as follows: (1) to couple the isotopic fractionation process and parameterization schemes in a SPAC