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Plant water sources in the cold semiarid ecosystem of the upper Kherlen River catchment in Mongolia: A stable isotope approach

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Summary In the cold semiarid region of northeastern Mongolia, we used stable isotopes (^{18}O and D) to determine potential plant water sources during the 2003 growing season (June to September) in two habitats: montane forest and an elevation gradient from the forest to Kherlen river bank. The forest is dominated by larch (*Larix sibirica*) with patches of cinquefoil shrubs (*Potentilla fruticosa*). The latter also grow throughout the elevation gradient, while the larch grows only on the top slope. Poplar (*Populus* spp.) and willow (*Salix* spp.) trees grow only on the river bank. All plant and soil samples showed isotopic signatures similar to summer precipitation, which is isotopically heavier in summer than winter. In July and August, larch trees in the forest tended to shift their water uptake to shallow depths in response to recent rainfall, but during the remaining months (June and September), depths of water uptake were unclear. Further, both the larch trees and cinquefoil shrubs in the forest used water at similar depths, suggesting potential competition for water. Plants along the elevation gradient showed different patterns of water use: (1) in July, larch used recent rainfall only, but in other months, the pattern was unclear; (2) cinquefoil depended on rainfall from recent weeks (as in August), but sometimes used antecedent rainwater from one month prior; and (3) poplar and willow seemed to use water from the river (as in August) or from precipitation that fell a few weeks prior (as in

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September), but the factors controlling this unusual shift are unknown. This study contributes to our understanding of plant water use strategies in cold semiarid ecosystems, and provides baseline data for models designed to understand large-scale hydrological effects of global climate change.

Introduction

Water use strategies of plants and water transport in the soil—plant—atmosphere continuum are critical to understanding ecosystem functioning in arid and semiarid habitats where plant productivity is often limited by soil moisture (Noy-Meir, 1973; Webb et al., 1983). Moreover, they are intrinsically related to precipitation variability (Fischer and Turner, 1978; Breymeyer et al., 1996). Indeed, because precipitation is highly dependent on forest evapotranspiration (Salati et al., 1979; Savenije, 1995), deforestation and land cover changes will likely reduce precipitation, and thus, increase the risk of regional drought (Eltahir and Bras, 1994; Wang and Eltahir, 2000).

Isotopic compositions (D and ^{18}O) of different water pools in an ecosystem (soil, plant and atmospheric) can describe interactions between these water pools and biological and hydrological processes (Ehleringer and Dawson, 1992; Gat, 1996; Yakir and Sternberg, 2000; Dawson et al., 2002). For example, because, in general, plant roots do not discriminate against specific water isotopes during water uptake (exception: mangroves; see Lin and Sternberg, 1993), the isotopic composition of stem water can determine potential plant water sources (Wershaw et al., 1966; Ehleringer and Dawson, 1992; Brunel et al., 1995). Certain plants are thought to use different water sources in response to seasonal water availability (e.g. Ehleringer et al., 1991; Weltzin and McPherson, 1997; Jackson et al., 1999; Stratton et al., 2000), reducing competition for water and increasing the likelihood of plant survival during periods of water shortage (Noy-Meir, 1973; Ehleringer et al., 1991; Peñuelas et al., 2000).

Numerous studies have described plant water uptake in arid and semiarid habitats by applying isotope mixing models. For example, along the summer monsoon precipitation gradient in Arizona and Utah, USA, three dominant tree species in the pinyon-juniper community are known to use different water sources: *Pinus edulis* and *Juniperus osteosperma* were shown to use a large proportion of monsoon precipitation while *Quercus gambelii* used only deep soil water even in periods of recent substantial summer precipitation (Williams and Ehleringer, 2000). Moreover, in the semiarid Mu-Us desert, Inner Mongolia, China, native *Sabina vulgaris* and introduced *Salix matsudana* trees use relatively deep soil water as well as groundwater, whereas the shrub *Artemisia ordosica* uses shallow soil water only (Ohte et al., 2003). Afforestation in this desert area with *S. matsudana* might therefore cause irreversible groundwater loss because, compared to native plants, this exotic tree has relatively low water use efficiency (Ohte et al., 2003). In savanna communities, trees, shrubs, and grasses are able to coexist because, in general, trees and shrubs tend to use deep water sources while grasses tend to use shallow water; a pattern certainly related to the different root distribution patterns of these life forms (Noy-Meir, 1973; Walker et al., 1981; Sala et al., 1989; Le Roux et al., 1995; Scholes and Archer, 1997; Weltzin and McPherson, 1997; House et al., 2003; see Moreira et al., 2000, for an exception to this niche partitioning hypothesis).

The application of mixing models to estimates of plant water sources and their relative contributions has received both support (e.g. Brunel et al., 1995) and criticism (e.g. Thorburn and Ehleringer, 1995; Snyder and Williams, 2000; Phillips and Gregg, 2001; Phillips and Koch, 2002; Phillips and Gregg, 2003). Brunel et al. (1995), in a semiarid field situation, found that the total error involved in sampling, extraction and assumptions was <5‰ for D and <1‰ for ^{18}O, suggesting that these models are appropriate for determining potential plant water sources. However, mixing models do not provide information about the active root area or depths of plant water uptake; shortcomings recently overcome by Ogle et al. (2004) who proposed an algorithm for reconstructing the active root area and water uptake profiles, and by Romero-Saltos et al. (2005) who developed a model to estimate potential mean depths of plant water uptake from isotopic signatures of soil and stem water.

In the cold semiarid environment of northeastern Mongolia, research on water sources of dominant plant species is just starting. In the Kherlen River catchment area, larch (*Larix sibirica* Ledeb.) taiga forest dominates and plays an important role in the eco-hydrological processes of the entire basin (Li et al., 2005; Sugita et al., this issue). In this montane forest, Li et al. (2006) showed that during the growing season, according to ^{18}O signatures of plant and soil water, larch trees use water from the top 30 cm of the soil after rainfall events, but water from deeper layers when the topsoil water becomes scarce. In this paper, we attempt to confirm this pattern of water use using the model of Romero-Saltos et al. (2005) to estimate potential mean depths of water uptake, using soil and stem signatures of not only ^{18}O, but also D. We also determine plant water sources during the growing season along an elevation gradient from the montane larch forest stand to the bank of the Kherlen River. For this gradient scenario, we test the following two postulates: (1) during the growing season, recently fallen rainwater is the main source of water for plants growing along the mountain slope, and (2) river water is the main source of water for plants growing on the river bank.

Materials and methods

Study area

The study was conducted at Mongonmorit, Tov province, Mongolia, in the mountain catchment area of the Kherlen River, near the tower of the Rangelands Atmosphere—Hydrosphere—Biosphere Interaction Study Experiment

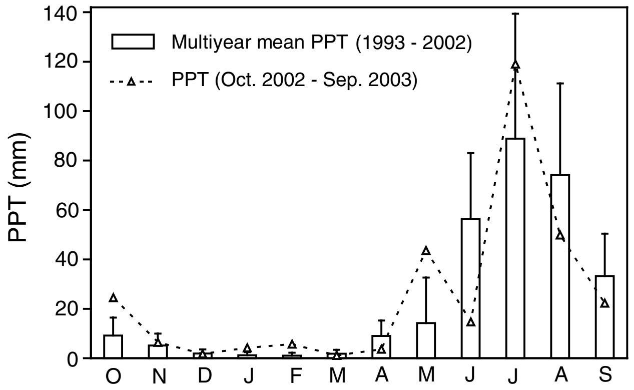

Figure 1 Precipitation (PPT) as measured at the Mongonmorit station of the Institute of Meteorology and Hydrology, Mongolia. Error bars denote 1 SD.

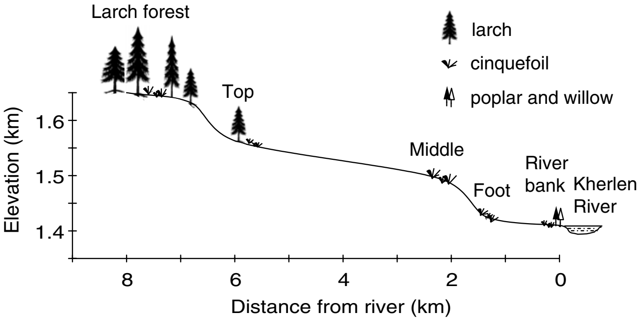

Figure 2 Elevation profile of the study area showing the relative location of the larch forest, the elevation gradient, and most common plant species sampled at these sites. The plants and river are not to scale.

(RAISE) (48°21.112′ N, 108°39.260′ E, 1630 m; Li et al., 2005; Sugita et al., this issue). The Kherlen River originates from the Khentii and Khyangan mountains in Mongolia (Tsevegmid, 1969). The climate in this area is classified as semiarid, cold continental.

According to the Mongonmorit meteorological station (25 km southwest of the RAISE tower) operated by the Institute of Meteorology and Hydrology, Mongolia, mean annual precipitation (PPT) is 296 mm, which is very close to the rainfall accumulated during the study period (299 mm from October 2002 to September 2003). At Mongonmorit, over 80% (249 mm) of PPT falls during the growing season from May through September (Fig. 1). In comparison, our RAISE tower site received 271 mm of rainfall during the growing season, 8.7% more. In general, monthly PPT distribution during the study period followed the multiyear pattern, except for unusually high rainfall in May 2003. The mean annual air temperature at Mongonmorit is −2.7 °C (1993—2002 average) with January being the coldest month (mean daily air temperature: −21.5 °C) and July the hottest (mean daily air temperature: 13.6 °C).

The mountain forest in this area is dominated by Siberian larch (*L. sibirica* Ledeb.) with scattered or patchy areas of white birch (*Betula platyphylla* Sukach.). The soil is classified as spodosol. Mean stand height is about 20 m, while the projected leaf area index of the canopy vegetation (larch) is 2.7, as estimated by the litter trap method (Li et al., 2005). The understory is dense and forms a distinct layer of grasses (e.g. sedges and Junegrass) and scattered shrubs, particularly cinquefoil (*Potentilla fruticosa* L.). Cinquefoil shrubs also occur along the elevation gradient from the forest stand to the river bank on the south-facing slope of the mountain (Fig. 2). This gradient includes a steppe where larch trees are absent or rare (Fig. 2). On the riverbank, poplar (*Populus* spp.) and willow (*Salix* spp.) trees are common; these species are immersed in the river when snow melts in the spring (late March to early May) and are therefore adapted to survive seasonal water logging.

Precipitation and river water sampling

Precipitation samples were routinely collected by Mongonmorit meteorological station throughout the year. Rainwater was collected with a funnel attached to a plastic tank containing a ping-pong ball to prevent evaporation. Snow was collected with a vat secured on the ground and later melted in an airtight container at room temperatures. Both daily rainwater and melted snow water samples were collected and stored in 100-mL plastic bottles. See Yamanaka et al. (this issue) for a detailed description of precipitation sampling. In this study, we used data collected by Mongonmorit station from October 2002 to September 2003 (Fig. 1). River water was collected and stored in 100-mL plastic bottles during the plant and soil sample collection periods.

Plant and soil sampling

During the 2003 growing season, we sampled representative plant species of the forest stand (larch and cinquefoil) surrounding the flux tower and along the elevation gradient from the forest stand to the river bank (larch, cinquefoil, poplar, and willow) (Fig. 2). Only larch was collected continuously throughout the growing season (June 16, 19—21 July, 19 August, and 30 September).

Forest stand

For each sampling date (June 16, 19 July, 19 August, and 30 September), we collected a stem fully covered with periderm from each of five randomly selected adult larch trees ($N = 5$ stem samples per sampling date, total = 20 stems). In August and September, we also collected cinquefoil stem samples ($N = 3$ stem samples per sampling date, total = 6 stems). The bark of each stem was peeled off and the stem stored in 30-mL glass vials sealed with Teflon-lined caps. In order to determine changes in the depth of water uptake by larch trees during the 2003 growing season, soil samples from depths of 5, 10, 20, 30, 50, 70, and 100 cm were also collected on each sampling date by digging a 1 × 1 × 1 m pit. Soil samples were placed in 100-mL glass vials sealed with Teflon-lined caps.

Elevation gradient

On 16 June, 21 July and 19 August, larch stem samples were taken at the forest-steppe transitional region (top of the slope), where larch trees are widely scattered (Fig. 2). Cinquefoil stems were collected at the top of the slope on

19 August and 30 September, and from the middle and foot of the slope on 19 August only. On the river bank, stems were collected on 21 July (willow only), 19 August (cinquefoil, poplar, and willow) and 30 September (cinquefoil, poplar, and willow). Three replicates of each elevation gradient plant sample were collected ($N = 3$). No soil samples were taken along the elevation gradient because the aim was only to test whether summer rainfall is the main source of water for plants along the mountain slope, and whether river water is the main source of water for those on the river bank (see Section 1).

Lab analysis

Plant and soil samples were frozen and then thawed overnight before water was extracted using the cryogenic vacuum distillation method (Ehleringer and Osmond, 1989). The D and ^{18}O content of the stem, soil, precipitation and river water was measured using a Finnigan MAT252 isotope ratio mass spectrometer at the University of Tsukuba, Japan. ^{18}O content was determined with the H_2O—CO_2 equilibration method (Socki et al., 1999), while D content was determined with the gaseous H_2—H_2O equilibration technique (Coplen et al., 1991). Overall analytical precision of the spectrometer was ±0.1‰ for $\delta^{18}O$ and ±1‰ for δD.

Data analysis

The ^{18}O and D content of a water sample (δ_{sample}) was expressed in delta notation (‰) relative to the V-SMOW standard (Vienna Standard Mean Ocean Water):

$$\delta_{\text{sample}} = \left[\frac{R_{\text{sample}}}{R_{\text{SMOW}}} - 1\right] \times 1000, \quad (1)$$

where R represents the heavy-to-light isotope ratio ($^{18}O/^{16}O$ or D/H). $(^{18}O/^{16}O)_{\text{SMOW}} = (2005.20 \pm 0.45) \times 10^{-6}$ (Baertschi, 1976) and $(D/H)_{\text{SMOW}} = (155.95 \pm 0.08) \times 10^{-6}$ (De Wit et al., 1980).

Isotopic composition of precipitation

The isotopic composition of precipitation was analyzed by plotting monthly δD values against $\delta^{18}O$ values during the year of study (October 2002 to September 2003). Because this relationship tends to be linear, it is usually analyzed with linear regression (Craig, 1961). The best-fit line of this regression is the local meteoric water line (LMWL), which can be compared to the global meteoric water line (GMWL), the average of many LMWL across the world (Craig, 1961; Rozanski et al., 1993). In this study, the LMWL also helped distinguish the isotopic signatures of precipitation in the growing season (May to September, i.e. mid-spring to the beginning of fall) from those of the non-growing season.

Depth of water uptake by larch trees in the forest stand

Depth of water uptake by larch trees in the forest surrounding the flux tower (see Fig. 1) was obtained using the model developed by Romero-Saltos et al. (2005), which relates the soil isotopic concentrations at various depths with the isotopic concentration of the stem. The model is based on the axiom that the isotopic composition of stem water is equal to the sum of the isotopic composition of soil water absorbed at all depths used by the roots, weighted by the amount of water absorbed at these depths. To define the amount of water absorbed at different depths, the model assumes that water is absorbed from a vertical soil segment of a given length (defined by the user), following a normal distribution. The single value (depth of water uptake) acting as the model output is that at the center of the normal distribution, i.e., the mean (μ). Because in reality a plant does not uptake water from a single segment of soil following a normal distribution, the depth of water uptake produced by the model actually represents a *potential* mean (μ) depth of water uptake.

Depending on the length of the soil segment used and how convoluted the soil isotopic profile is, the model might sometimes, for a given plant at a given sampling date, produce no solution at all or multiple solutions (i.e., multiple potential depths of water uptake) (Romero-Saltos et al., 2005). In this case, it is up to the user to decide how to treat such data. In this study, we decided to first calculate the potential mean depths of water uptake for soil segments of different length (10, 25, 50, 75 and 100 cm), and then compare the solutions obtained, basically looking for consistency among solutions obtained with different soil segment lengths. In case of multiple solutions at a given soil segment length (for a given tree at a given sampling date), we found the most probable value of depth of water uptake by: (1) selecting the value that was most similar to *unique* values obtained when larger soil segments were analyzed; (2) when this was not possible, by calculating an average value for those solutions that were the most consistent when compared to other values obtained with different lengths of soil segment; and (3) when multiple solutions occurred only once (i.e., using only a given length of soil segment, and no solutions using other lengths), by selecting the value most similar to that obtained for a different larch tree on the same sampling date.

Finally, for each tree at a given sampling date, the ''single'' solutions obtained with each length of soil segment analyzed were averaged to obtain a potential depth of water uptake. For each sampling date, the values obtained for different trees were further averaged and a standard deviation calculated. Although we sampled five larch trees every month, the real number of replicates (depths of water uptake values) varied every month either because no solution was obtained at any length of soil segment (38% of cases for both the δD and $\delta^{18}O$ datasets) or because water could not be extracted successfully from the stem sample in the first place (seven unsuccessful water extractions out of 20 stem samples analyzed in total). In this study, we independently analyzed the δD and $\delta^{18}O$ datasets to see if the patterns of depth of water uptake obtained were similar independent of the stable isotope used.

Water sources along the elevation gradient

In any given month, potential water sources of the species growing along the elevation gradient were determined by the closeness of their average δD—$\delta^{18}O$ signatures to those of the potential water sources (river water or precipitation). This visual comparison is done through a scatter plot of δD values against $\delta^{18}O$ values (Ehleringer et al., 1991; Ehleringer and Dawson, 1992; Brunel et al., 1995). The $\delta^{18}O$ values of PPT ($\delta^{18}O_{\text{PPT}}$) were weighted by the amount of each PPT >1.5 mm (i.e., $\delta^{18}O_{PPT} = \sum PPT_i \times \delta^{18}O_{PPT_i} / \sum PPT_i$) over the sampling intervals (May 14—June 15, June 19—July 17, July 22—August 16, and August 20—September 29). This is based on the assumption that plant water use is connected to rainwater that fell before sample collection or during the intersampling period rather than thereafter.

Results and discussion

Isotopic composition of precipitation

There was strong seasonal variation in the oxygen isotopic composition of precipitation ($\delta^{18}O_{PPT}$), ranging from −27.8‰ in January (winter) to −7.8‰ in June (summer) (Fig. 3). Correspondingly, the hydrogen isotopic composition of precipitation (δD_{PPT}) ranged from −201.2‰ in January to −59.9‰ in June (Fig. 3). Therefore, precipitation during the winter and fall (*ca.* October to March) is significantly more depleted of heavy isotopes (more negative $\delta^{18}O_{PPT}$ and δD_{PPT} values) compared to spring and summer precipitation (*ca.* May to September, the growing season). The variation in the isotopic composition of precipitation in eastern Mongolia is discussed in Yamanaka et al. (this issue). The findings clearly define the variation in isotopic precipitation signatures throughout the year, facilitating identification of those plants that use precipitation as their main water source, either as recently fallen rainfall or as melted winter snow (Li et al., 2006).

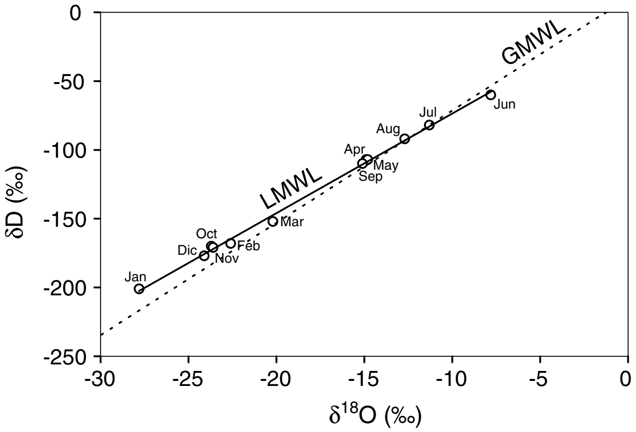

Figure 3 The local meteoric water line (LMWL) in the study area showing the linear relationship between the δD and $\delta^{18}O$ isotopic signatures in local precipitation from October 2002 to September 2003 ($\delta D_{PPT} = 7.23 \times \delta^{18}O_{PPT} - 1.29$). The global meteoric water line (GMWL) is shown for comparison ($\delta D_{PPT} = 8.17 \times \delta^{18}O_{PPT} + 10.35$).

Despite the large complexity of global hydrological processes, Craig (1961) found that stable isotope ratios of hydrogen and oxygen in monthly precipitation correlate on a global scale by a linear relationship known as the global meteoric water line (GMWL): $\delta D_{PPT} = 8 \times \delta^{18}O_{PPT} + 10$. Rozanski et al. (1993) refined the GMWL as: $\delta D_{PPT} = 8.17 \times \delta^{18}O_{PPT} + 10.35$. On a local scale, both the slope and intercept of this linear relationship vary depending on seasonal and geographical variability in local climatic conditions (Gibson et al., 2002). The local meteoric water line (LMWL) at Mongonmorit is described as: $\delta D_{PPT} = (7.23 \pm 0.12) \times \delta^{18}O_{PPT} - (1.29 \pm 2.23)$ ($N = 12$, adjusted $r^2 = 0.997$, $P < 0.001$). Therefore, the slope and intercept of the LMWL were about 12% and 112% lower, respectively, than those of the refined GMWL (Rozanski et al., 1993). This deviation from the GMWL is mainly due to evaporation-induced kinetic fractionation effects (Merlivat and Jouzel, 1979; Jacob and Sonntag, 1991; Zimmermann et al., 1967) and Rayleigh fractionation in the closed system (Jouzel et al., 1997; Kendall and Caldwell, 1998).

Monthly variation in depths of water uptake by larch trees in the forest stand

The isotopic content of soil water at different depths changed abruptly from month to month (Fig. 4), reflecting a very dynamic process of soil evaporation and rainfall percolation (see Li et al., 2006, for a detailed description and probable explanations of this process). The commonly observed pattern of accumulation of heavy isotopes in the topsoil as a result of soil evaporation was observed in June, July and September, but not August (Fig. 4). This peculiar August

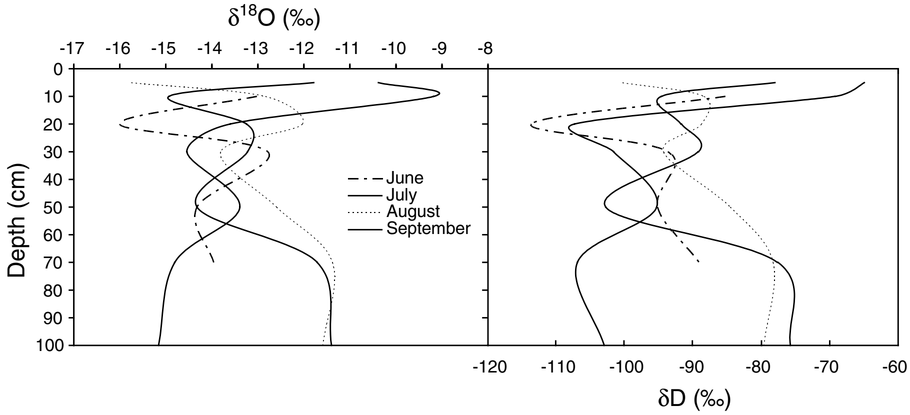

Figure 4 Profiles of the soil water isotopic concentration during the growing period in the larch forest stand (1630 m altitude, see Fig. 2).

pattern could be explained by the large amount of rainfall that fell during the July—August intersampling period, which probably diminished the soil evaporative enrichment process (Li et al., 2006).

The depth of water uptake can easily be estimated when stem water has an isotopic concentration that matches the unique isotopic concentration of soil water at a given depth. However, for every month of the growing season (June—September), soil water isotopic signatures of very different depths were very similar (Fig. 4), making it complicated to determine a single potential depth of water uptake for a given stem sample. Analysis of soil water content (SWC) at different depths might help overcome this problem if it is assumed that most water is absorbed from depths of relatively high SWC (as in Li et al., 2006). In other words, of depths with a similar isotopic content, those that show a relatively low SWC are excluded as potential depths of water uptake. This approach assumes that root function parallels SWC distribution (i.e., more functional roots where the SWC is high), which is probably true most of the time. In this study, however, we did not assume any SWC-root functionality correlation, but simply analyzed the depth of water uptake solutions obtained by the model of Romero-Saltos et al. (2005). Details on how these solutions were analyzed are explained in Section 2.5.2.

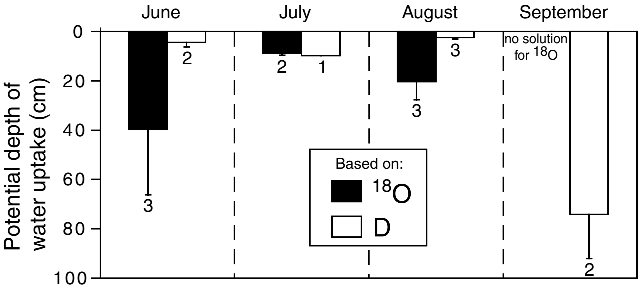

Figure 5 Potential mean depths of water uptake (±1 SD) by the larch trees in the forest stand during the 2003 growing season according to the δD and δ^{18}O isotopic content of soil water and larch stem water. Depths were calculated using the model of Romero-Saltos et al. (2005). Numbers below error bars indicate the actual sample size (i.e., number of solutions obtained by the model out of 3—5 water stem samples analyzed each month).

With the same sample, the depth of water uptake model often calculated different solutions depending on the isotope or parameters used (i.e., length of soil segment, see Section 2.5.2). In fact, for a given sampling date, some δD—δ^{18}O paired values differed from the typical linear relationship described by the rest of the samples. Despite these drawbacks, it is clear that during July and August, months with large precipitation input (Fig. 1), larch trees used water from the top 30 cm of soil, according to both ^{18}O and D signatures (Fig. 5). This confirms the conclusions obtained by Li et al. (2006) who visually compared soil and stem ^{18}O isotopic data together with SWC and detailed rainfall data from the intersampling periods. According to the ^{18}O signatures, larch trees in June used water from a depth below 30 cm, while in September no depth of water uptake solution was obtained by the model. This also coincides with the conclusions of Li et al. (2006), although they noted that the δ ^{18}O stem signatures in September closely matched the δ^{18}O signature of a small rainfall event (2 mm) a few days before the sampling date. This is evidence that during the growing season larch trees in this forest apparently respond quickly to recent rainfall events, which increase the SWC in the topsoil from where water is then absorbed. Similarly, Sugimoto et al. (2002) found that *Larix gmelinii*, another species of larch, in east Siberia mainly used recent precipitation water during a wet summer but could use thawing permafrost water during a drought summer. The D-based results of June and September do not coincide with those of Li et al. (2006) using ^{18}O. This could be an artifact of the data analysis procedure (see Section 2.5.2) or related to natural processes we cannot explain with the data collected. To solve these inconsistencies, we suggest a deuterium pulse-chase experiment, in which a label of deuterium-enriched water is irrigated around the trees at the beginning of the growing season, and then periodically followed in the soil and stem water throughout the growing season (see Romero-Saltos et al., 2005). For further detailed discussion on how rainfall during the intersampling periods affected depth of water uptake patterns by larch trees during the 2003 growing season, please refer to Li et al. (2006).

Cinquefoil shrubs were also sampled in the forest stand in August and September. In both months, they showed average δ^{18}O and δD values similar to the average isotopic composition of adult larch trees (Table 1). This suggests potential competition for water between these two plant species; the competition effect is probably stronger with

Table 1 Average (±1 SD) δ^{18}O and δD values of stem water from larch trees and cinquefoil shrubs in the forest stand in August and September 2003

Species	δ^{18}O August	δ^{18}O September	δD August	δD September
Larch	−13.2 ± 0.2 (N = 3)	−10.5 ± 0.5 (N = 5)	−113.3 ± 5.5 (N = 3)	−73.6 ± 12.1 (N = 5)
Cinquefoil	−12.7 ± 0.4 (N = 3)	−10.4 ± 1.2 (N = 3)	−91 ± 13.5 (N = 3)	−80.7 ± 9.1 (N = 5)
P value	0.400	1.000	0.111	0.556

Sample sizes (# water samples extracted and analyzed) are shown in parentheses. The Mann—Whitney U-test (Sokal and Rohlf, 1995) showed that during the whole study period, no statistically significant differences were found between the isotopic signatures of larch and cinquefoil stem water at a significance level of α = 0.05.

larch seedlings, which need plenty of water to establish. Competition among these species has probably been intensified in the last decade because this forest has been frequently lumbered, and thus, subjected to significant recruitment of pioneer shrubs (incl. cinquefoil) and grasses. Indeed, during the study period, we found no larch seedlings in the forest. Another possible explanation for the absence of larch seedlings could be non-optimal light conditions for seedling recruitment, which is also related to the frequent logging activities in this forest.

Precipitation, river water or a mixture of both? Water sources along the elevation gradient

Average δ^{18}O and δD signatures of stem water along the elevation gradient (top slope, mid-slope, mountain foot and river bank) during the growing season (June—September) were, in general, located along the LMWL (Fig. 6), providing evidence that summer precipitation is readily used by these plants. Note that, because of logistic limitations in the field, not all plant species were sampled every month and the river water (consistently depleted of heavy isotopes compared to rainfall or stem water) was not sampled in June. It is also important to realize that while larch only occurred on the top slope and poplar and willow grew only on the river bank, cinquefoil was widely distributed in all habitats (see Section 2.1).

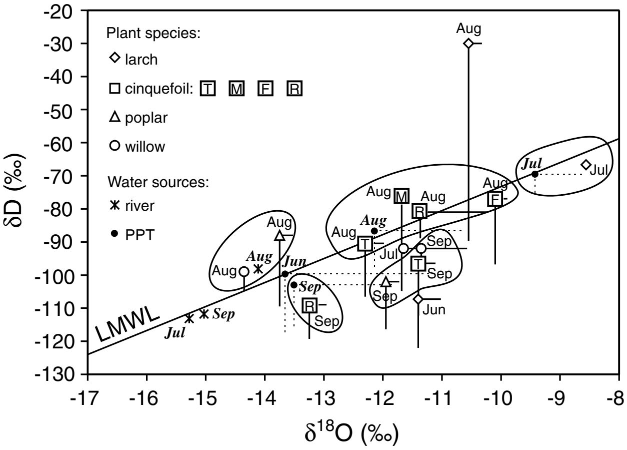

Figure 6 The relationship between δD and δ^{18}O in stem water of various species growing along the elevation gradient (larch, cinquefoil, poplar, and willow, see Fig. 2), and their potential water sources (precipitation and river water, in *italics*) during the 2003 growing season (June—September). The δ^{18}O values of precipitation were weighted by the amount of precipitation (see Section 2.5.3). Because of logistic reasons, not all plant species were sampled every month and river water was not sampled in June. Each point represents the average isotopic content (see Section 2.3). Because cinquefoil is widely distributed, a letter was assigned to identify the habitat of origin: **T** for top slope, **M** for mid-slope, **F** for mountain foot and **R** for river bank. To increase readability, error bars (±1 SD) have been drawn with different designs, only on one side of the *x* and *y* axes (not as crosses) and only if greater than the relative size of the symbol. The LWML for the growing season is shown for reference (see Fig. 3). Encircled are those cases where the water source used of the plants could be more or less visibly determined.

Although there was considerable monthly variation in average isotopic signatures of stem water of the different plant species examined, we were still able to distinguish some obvious patterns regarding their potential water sources during the growing season (Fig. 6): (1) in July, larch trees (on the top slope) clearly used that month's rainfall; (2) in August, cinquefoil shrubs along the elevation gradient and on the river bank used that month's rainfall or a mixture of July and August's precipitation; (3) also in August, poplar and willow trees on the river bank used river water only, suggesting that changes in water table depth (varying concomitantly with the river level) might affect growth of these trees; (4) in September, cinquefoil shrubs on the river bank continued to use current precipitation only, but those on the top slope possibly continued to use August precipitation (by this time, probably at relatively deeper soil levels because of percolation); and (5) also in September, poplar and willow trees on the river bank stopped using river water (September's river water signature was not near that of any of the plant samples collected) and apparently started using precipitation with an isotopic signature similar to August rainfall, an interesting phenomenon that we cannot easily explain at present. Indeed, to better explain the observed water use patterns, future studies should describe the root structure of the different plant species, characterize the physical characteristics of the soil (e.g., water percolation rates), monitor changes in the water table, and intensify the sampling frequency of both soil and plant species in the different habitats.

Conclusions

This study had two main objectives. First, to confirm the monthly variation in depths of water uptake by larch trees growing in the mountain forest originally described by Li et al. (2006), using not only ^{18}O (as Li et al. did) but also D signatures in a model for estimating potential depths of water uptake (Romero-Saltos et al., 2005). Second, to identify water sources during the growing season along an elevation gradient from the forest stand to the bank of the Kherlen River, assuming that plants along the mountain slope would use recently fallen summer rain, and that those on the river bank would mostly use river water. In general, we confirmed the depth of water uptake patterns originally described by Li et al. (2006); however, regarding water sources along the elevation gradient, we concluded that they vary temporally and spatially. A number of environmental factors not characterized in this study are necessary to explain the water use patterns at a given time. Nevertheless, the data provided is likely to be useful input for hydrological models designed to determine the large-scale effect of climate change on the sensitive semiarid ecosystem of northeastern Mongolia.

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References

Baertschi, P., 1976. Absolute ^{18}O content of standard mean ocean water. Earth and Planetary Science Letters 31, 341–344.

Breymeyer, A.I., Hall, D.O., Melillo, J.M., Ågren, G.I., 1996. Global Change: Effects on Coniferous Forests and Grasslands (Scope 56). John Wiley & Sons, New York, 459 pp.

Brunel, J.P., Walker, G.R., Kennett-Smith, A.K., 1995. Field validation of isotopic procedures for determining sources of water used by plants in a semi-arid environment. Journal of Hydrology 167, 351–368.

Coplen, T.B., Wildman, J.D., Chen, J., 1991. Improvements in the gaseous hydrogen–water equilibration technique for hydrogen isotope ratio analysis. Analytical Chemistry 63, 910–912.

Craig, H., 1961. Isotopic variations in meteoric waters. Science 133, 1702–1703.

Dawson, T.E., Mambelli, S., Plamboeck, A.H., Templer, P.H., Tu, K.P., 2002. Stable isotopes in plant ecology. Annual Review of Ecology and Systematics 33, 507–559.

De Wit, J.C., Van der Straaten, C.M., Mook, W.G., 1980. Determination of the absolute D/H ratio of VSMOW and SLAP. Geostandards Newsletter 4, 33–36.

Ehleringer, J.R., Dawson, T.E., 1992. Water uptake by plants: perspectives from stable isotopes. Plant, Cell and Environment 15, 1073–1082.

Ehleringer, J.R., Osmond, C.B., 1989. Stable isotopes. In: Pearcy, R.W., Ehleringer, J.R., Mooney, H.A., Rundel, P.W. (Eds.), Plant Physiological Ecology. Chapman and Hall, London, pp. 281–299.

Ehleringer, J.R., Phillips, S.L., Schuster, W.S.F., Sandquist, D.R., 1991. Differential utilization of summer rains by desert plants. Oecologia 88, 430–434.

Eltahir, E.A.B., Bras, R.L., 1994. Sensitivity of regional climate to deforestation in the Amazon basin. Advances in Water Resources 17, 101–115.

Fischer, R.A., Turner, N.C., 1978. Plant productivity in the arid and semiarid zones. Annual Review of Plant Physiology 29, 277–317.

Gat, J.R., 1996. Oxygen and hydrogen isotopes in the hydrological cycle. Annual Reviews in Earth Planetary Sciences 24, 225–262.

Gibson, J.J., Aggrawal, P., Hogan, J., Kendall, C., Martinelli, L.A., Stichler, W., Rank, D., Goni, I., Choudury, M., Gat, J., Bhattacharya, S., Sugimoto, A., Fekete, B., Pietroniro, A., Maurer, T., Panarello, H., Stone, D., Seyler, P., Maurice-Bourgoin, L., Herzceg, A., 2002. Isotope studies in large river basins: a new global research focus. EOS 83 (52), 613–617.

House, J., Archer, S., Breshears, D.D., Scholes, R.J., the NCEAS Tree–grass Interactions Participants, 2003. Conundrums in mixed woody-herbaceous plant systems. Journal of Biogeography 30, 1763–1777.

Jackson, P.C., Meinzer, F.C., Bustamante, M., Goldstein, G., Franco, A., Rundel, P.W., Caldas, L., Igler, E., Causin, F., 1999. Partitioning of soil water among tree species in a Brazilian Cerrado ecosystem. Tree Physiology 19, 717–724.

Jacob, H., Sonntag, C., 1991. An 8 year record of the seasonal variation of ^{2}H and ^{18}O in atmospheric water vapor and precipitation at Heidelberg, Germany. Tellus 43B, 291–300.

Jouzel, J., Fröhlich, K., Schotterer, U., 1997. Deuterium and oxygen-18 in present-day precipitation: data and modeling. Hydrological Sciences Journal 42, 747–764.

Kendall, C., Caldwell, E.A., 1998. Fundamentals of isotope geochemistry. In: Kendall, C., McDonnell, J.J. (Eds.), Isotope Tracers in Catchment Hydrology. Elsevier Science B.V., Amsterdam, The Netherland, pp. 51–86.

Le Roux, X., Bariac, T., Mariotti, A., 1995. Spatial partitioning of the soil water resource between grass and shrub components in a West African humid savanna. Oecologia 104, 147–155.

Li, S.-G., Asanuma, J., Kotani, A., Eugster, W., Davaa, G., Oyunbaatar, D., Sugita, M., 2005. Year-round measurements of net ecosystem CO_2 flux over a montane larch forest in Mongolia. Journal of Geophysical Research 110, D09303. doi:10.1029/2004JD00545.

Li, S.-G., Tsujimura, M., Sugimoto, A., Sasaki, L., Yamanaka, T., Davaa, G., Oyunbaatar, D., Sugita, M., 2006. Seasonal variation in oxygen isotope composition of waters for a montane larch forest in Mongolia. Trees – Structure and Function 20, 122–130.

Lin, G., Sternberg, L. da S.L., 1993. Hydrogen isotopic fractionation during water uptake in coastal wetland plants. In: Ehleringer, J., Hall, A., Farquhar, G. (Eds.), Stable Isotopes and Plant Carbon–Water Relations. Academic Press, San Diego, pp. 497–510.

Merlivat, L., Jouzel, J., 1979. Global climatic interpretation of the deuterium–oxygen 18 relationship for precipitation. Journal of Geophysical Research 84 (C), 5029–5033.

Moreira, M.Z., Sternberg, L., Nepstad, D.C., 2000. Vertical patterns of soil water uptake by plants in a primary forest and an abandoned pasture in the eastern Amazon: an isotopic approach. Plant and Soil 222 (1–2), 95–107.

Noy-Meir, I., 1973. Desert ecosystems: environment and producers. Annual Review of Ecology and Systematics 4, 25–51.

Ogle, K., Wolpert, R.L., Reynolds, J.F., 2004. Reconstructing plant root area and water uptake profiles. Ecology 85, 1967–1978.

Ohte, N., Koba, K., Yoshikawa, K., Sugimoto, A., Matsuo, N., Kabeya, N., Wang, L., 2003. Water utilization of natural and planted trees in the semi-arid desert of Inner Mongolia, China. Ecological Applications 13, 337–351.

Peñuelas, J., Filella, I., Lloret, F., Piñol, J., Siscart, D., 2000. Effects of a severe drought on water and nitrogen use by *Quercus ilex* and *Phillyrea latifolia*. Biologia Plantarum 43, 47–53.

Phillips, D.L., Gregg, J.W., 2001. Uncertainty in source partitioning using stable isotopes. Oecologia 127, 171–179.

Phillips, D.L., Gregg, J.W., 2003. Source partitioning using stable isotopes: coping with too many sources. Oecologia 136, 261–269.

Phillips, D.L., Koch, P.L., 2002. Incorporating concentration dependence in stable isotope mixing models. Oecologia 130, 114–125.

Romero-Saltos, H., Sternberg, L. da S.L., Moreira, M.Z., Nepstad, D.C., 2005. Rainfall exclusion in an eastern Amazonian forest alters soil water movement and depth of water uptake. American Journal of Botany 92 (3), 443–455.

Rozanski, K., Araguds-Araguds, L., Gonfiantini, R., 1993. Isotopic patterns in modem global precipitation. In: Swart, P.K., Lohman, K.C., McKenzie, J., Savin, S. (Eds.), Climate Change in Continental Isotopic Records – Geophysical Monograph 78. American Geophysical Union, Washington DC, pp. 1–36.

Sala, O.E., Golluscio, R.A., Lauenroth, W.K., Soriano, A., 1989. Resource partitioning between shrubs and grasses in the Patagonian steppe. Oecologia 81, 501–505.

Salati, E., Dall'Olio, A., Gat, J., Matsui, E., 1979. Recycling of water in Amazon Basin: an isotope study. Water Resources Research 15, 1250–1258.

Savenije, H.H.G., 1995. New definitions for moisture recycling and the relationship with land-use changes in the Sahel. Journal of Hydrology 167, 57–78.

Scholes, R.J., Archer, S.R., 1997. Tree—grass interactions in savannas. Annual Review of Ecology and Systematics 28, 545—570.

Snyder, K., Williams, D.G., 2000. Water sources used by riparian trees varies among stream types on the San Pedro river, Arizona. Agricultural and Forest Meteorology 105, 227—240.

Socki, R.A., Romanek, C.S., Gibson Jr., E.K., 1999. On-line technique for measuring stable oxygen and hydrogen isotopes from microliter quantities of water. Analytical Chemistry 71, 2250—2253.

Sokal, R.R., Rohlf, F.J., 1995. Biometry: The Principles and Practice of Statistics in Biological Research. W.H. Freeman, New York, pp. 887.

Stratton, L.C., Goldstein, G., Meinzer, F.C., 2000. Temporal and spatial partitioning of water resources among eight woody species in a Hawaiian dry forest. Oecologia 124, 309—317.

Sugimoto, A., Yanagisawa, N., Naito, D., Fujita, N., Maximov, T.C., 2002. Importance of permafrost as a source of water for plants in east Siberian taiga. Ecological Research 17, 493—503.

Sugita, M., Asanuma, J., Tsujimura, M., Mariko, S., Lu, M., Kimura, F., Azzaya, D., Adyasuren, Ts., this issue. An overview of the rangelands atmosphere—hydrosphere—biosphere interaction study experiment in northeastern Asia (RAISE). Journal of Hydrology.

Thorburn, P.J., Ehleringer, J.R., 1995. Root water uptake of field-growing plants indicated by measurements of natural-abundance deuterium. Plant and Soil 177, 225—233.

Tsevegmid, S.H., 1969. Geography of Mongolia. Mongolian Ministry for Nature and Environment, Ulaanbaatar, 401 pp.

Walker, B.H., Ludwig, D., Holling, C.S., Peterman, R.M., 1981. Stability of semi-arid savanna grazing systems. Journal of Ecology 69, 473—498.

Wang, G.L., Eltahir, E.A.B., 2000. Ecosystem dynamics and the Sahel drought. Geophysical Research Letters 27, 795—798.

Webb, W.L., Lauenroth, W.K., Szarek, S.R., Kinerson, R.S., 1983. Primary production and abiotic controls in forests, grasslands, and desert ecosystems of the United States. Ecology 64, 134—151.

Weltzin, J.F., McPherson, G.R., 1997. Spatial and temporal soil moisture resource partitioning by trees and grasses in a temperate savanna, Arizona, USA. Oecologia 112, 156—164.

Wershaw, R.L., Friedman, I., Heller, S.J., Frank, P.A., 1966. Hydrogen isotopic fractionation of water passing through trees. In: Hobson, G.D., Speers, G.S. (Eds.), Advances in Organic Geochemistry. Pergamon Press, New York, pp. 55—67.

Williams, D.G., Ehleringer, J.R., 2000. Intra- and inter-specific variation for summer precipitation use in pinyon-juniper woodlands. Ecological Monographs 70, 517—537.

Yakir, D., Sternberg, L.D.L., 2000. The use of stable isotopes to study ecosystem gas exchange. Oecologia 123, 297—311.

Yamanaka, T., Tsujimura, M., Oyunbaatar, D., Davaa, G., this issue. Isotopic variation of precipitation over eastern Mongolia and continental-scale atmospheric water cycle. Journal of Hydrology.

Zimmermann, U., Ehhalt, D., Munnich, K.O., 1967. Soil—water movement and evaporation: changes in isotopic composition of the water. In: Knippner, M. (Ed.), Proceedings of the Symposium on Isotopes in Hydrology. IAEA, Vienna, pp. 567—584.