



Short Communication

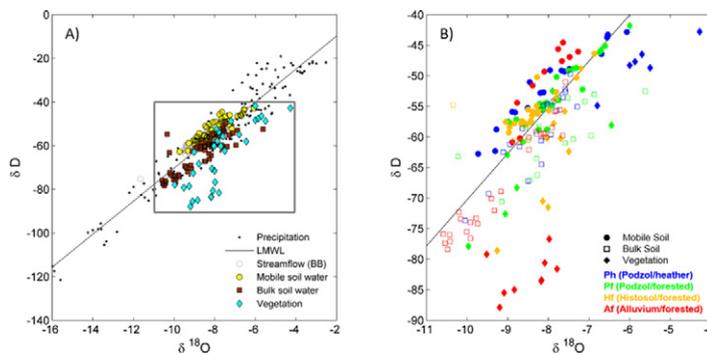
Spatial and temporal patterns of soil water storage and vegetation water use in humid northern catchments

Josie Geris^{a,*}, Doerthe Tetzlaff^a, Jeffrey J. McDonnell^{a,b}, Chris Soulsby^a^a Northern Rivers Institute, School of Geosciences, University of Aberdeen, Aberdeen, Scotland, United Kingdom^b Global Institute for Water Security, National Hydrology Research Centre, University of Saskatchewan, Saskatoon, Canada

HIGHLIGHTS

- Plant-soil-water interactions in the temperate humid North are relatively unknown.
- Stable isotopes of soil and vegetation water revealed spatio-temporal patterns.
- In contrast to other biomes, we found little separation between soil water sources.
- Vegetation sources were constant temporally, but variable with landscape position.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 1 February 2017

Received in revised form 26 March 2017

Accepted 30 March 2017

Editor: Jay Gan

Keywords:

Vegetation water use

Soil water storage

Isotopes

ABSTRACT

Using stable isotope data from soil and vegetation xylem samples across a range of landscape positions, this study provides preliminary insights into spatial patterns and temporal dynamics of soil-plant water interactions in a humid, low-energy northern environment. Our analysis showed that evaporative fractionation affected the isotopic signatures in soil water at shallow depths but was less marked than previously observed in other environments. By comparing the temporal dynamics of stable isotopes in soil water mainly held at suctions around and below field capacity, we found that these waters are not clearly separated. The study inferred that vegetation water sources at all sites were relatively constant, and most likely to be in the upper profile close to the soil/atmosphere interface. The data analyses also suggested that both vegetation type and landscape position, including soil type, may have a strong influence on local water uptake patterns, although more work is needed to explicitly identify water sources and understand the effect of plant physiological processes on xylem isotopic water signatures.

© 2017 Elsevier B.V. All rights reserved.

* Corresponding author at: St. Mary's Building, Elphinstone Road, University of Aberdeen, AB24 3UF, Scotland, United Kingdom.
E-mail address: j.geris@abdn.ac.uk (J. Geris).

1. Introduction

Characterizing the dynamics of plant water availability and the mechanisms whereby plants access available water sources remain key challenges in ecohydrology (Asbjornsen et al., 2011; McDonnell, 2014). Insights into these processes are crucial for our understanding how precipitation is partitioned back into the atmosphere through

evapotranspiration, or recharges ground water and generates runoff (Brooks et al., 2015; Tetzlaff et al., 2015). Many studies on the physical, chemical and biological aspects of plant, water and soil relations have advanced our understanding in previous decades (see e.g. reviews by Philip, 1966; Kramer and Boyer, 1995; Rodriguez-Iturbe and Porporato, 2004; Asbjornsen et al., 2011; Kirkham, 2014). Research from across a wide range of environments differing in climate, soil type and vegetation has shown that strong interactions between these properties (e.g. Jackson et al., 2000; Scott et al., 2000; Schwendenmann et al., 2015; Dai et al., 2015) ultimately control the temporal and spatial dynamics of plant water availability and uptake patterns. Stable isotope analyses of plant xylem water and various potential source waters have proved valuable in resolving some of the questions surrounding plant water uptake (e.g. Ehleringer and Dawson, 1992; Brooks et al., 2010; Goldsmith et al., 2012). Many of these studies have shown that plants can be highly opportunistic and adaptable in accessing water from the subsurface. For example, although not the general rule (Wei et al., 2013), it is well known that vegetation can switch from accessing shallower to deeper sources between seasons (e.g. Penna et al., 2013; White and Smith, 2015) or during periods of drought (Barbeta et al., 2015). Isotopically different vegetation water of co-existing species has also indicated niche segregation for water uptake in mixed stands (e.g. Rossatto et al., 2014; Comas et al., 2015; Schwendenmann et al., 2015).

Several recent studies have suggested that there may also be “ecohydrological separation” of distinct soil water pools (the “two water worlds” hypothesis) comprising plant-available water on one hand and water that drains to streams on the other (Brooks et al., 2010; Evaristo et al., 2015; Good et al., 2015a; Bowling et al., 2016). Physically, it has been proposed that this could represent water held at suctions greater than field capacity (in this context usually referred to as “plant available” water or “tightly bound” water) and waters held at suctions less than field capacity (mobile water), respectively (following e.g. Brooks et al., 2010; Orłowski et al., 2016a). The isotopic character of water held at these different suctions found to be distinctly different, with tree water resembling the more fractionated tightly bound water. While questions remain on how and why plants may use tightly-bound soil water when more mobile water is available to their roots (Bowling et al., 2016), most efforts have focussed on the conditions that drive soil water separation. Recent meta-analysis (Evaristo et al., 2015) and global remote sensing efforts (Good et al., 2015a, 2015b) have shown that ecohydrological separation is widespread globally. However, more detailed studies in diverse environments have provided a range of alternative interpretations in relation to these differences in isotopic signatures. In climates with strong seasonality, bulk water (including the tightly bound water) isotopically resembled that of the first rain (Brooks et al., 2010; Goldsmith et al., 2012) or snowmelt (Gierke et al., 2016) after the dry season. It was hypothesised that this first water entered the smaller pores when they were dry and got locked (or was more tightly bound) throughout the rest of the season without significant mixing with additional precipitation inputs. However, recent work by Hervé-Fernández et al. (2016) in a rainy temperate zone in Chile, and by McCutcheon et al. (2017) in a semi-arid, snow-dominated landscape in Idaho demonstrated that during wet periods when soils are replenished there (temporarily) was sufficient mixing of water stored in the larger and smaller pores of the soil to infer that soil water was not clearly separated into two compartments. Furthermore, while Evaristo et al. (2016) did clearly demonstrate a distinct separation of two subsurface reservoirs in an environment with less seasonality in precipitation (Puerto Rico), some preliminary analyses from sites across higher latitudes in Europe with less marked summer drying did not show strong evidence in support of this (Scotland, Geris et al. (2015a); Germany, Schmid et al. (2016)). Furthermore, following earlier work by Allison and Barnes (Allison, 1982; Allison and Barnes, 1983; Barnes and Allison, 1983), Sprenger et al. (2016) have postulated that distinct pools of water may only exist at shallow depths, characterised by the maximum evaporation

penetration depth, which depends on soil texture and the climatic conditions. They have further theorized that mixing of tightly bound evaporative fractionated water with newly introduced (mobile) water does occur and increases during the percolation process.

While disentangling the relative role and interplay of vegetation and soil properties on plant available water and the “(eco)hydrological partitioning” of subsurface water is a major focus of current work (Troch et al., 2013; McDonnell, 2014; Vereecken et al., 2015); low energy, humid northern regions have so far received relatively little attention (Tetzlaff et al., 2015), compared to e.g. (seasonally) high energy, water-limited ecosystems (Zeppel, 2013). In the former, water sources are often not limited (Rodriguez-Iturbe et al., 2007; Thompson et al., 2010). However, future climate projections include longer growing seasons and reductions in water availability (IPCC, 2013), so that increased knowledge on the soil-vegetation water interactions in these rapidly changing areas is urgently needed. Preliminary work in the Scottish Highlands failed to establish strong evidence in support of two separated soil water pools. Instead the results suggested that trees extract water from the uppermost part of the soil profile, which showed some evaporative fractionation effects in the summer months (Geris et al., 2015a). However, questions remain on how these interactions develop throughout the year and if these are consistent for different soil and vegetation types spatially distributed across the landscape.

Here, we report the results of a preliminary investigation of stable isotope dynamics in xylem water and potential soil water sources (mobile and less mobile) in four soil-vegetation assemblages in the Scottish Highlands. Our specific objectives were to: (i) assess annual dynamics of water stored in the soil by evaluating the isotopic character and possible interactions between more mobile and tightly bound soil water; (ii) evaluate the annual patterns in vegetation water uptake in the context of these soil processes; and (iii) examine how i and ii vary spatially in different soil-vegetation units.

2. Data and methods

We monitored soil and xylem water dynamics in four characteristic ecosystems within the Girnock Burn catchment (30 km²) in the Scottish

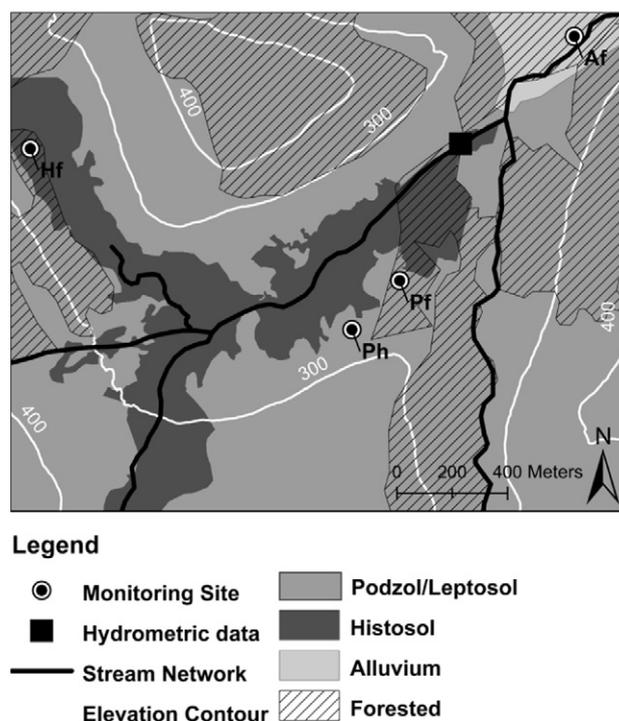


Fig. 1. Site overview showing the four sampling locations, the soil distribution and the forested areas.

Highlands (Fig. 1). The prevailing humid climate is characterised by low intensity precipitation (~950 mm per annum) which is spread relatively evenly throughout the year. There is a strong seasonality in energy fluxes, with potential evapotranspiration rates (~400 mm per annum) typically <0.5 mm per day in winter and up to 4 mm per day in summer. The Girnock drains a glaciated landscape through a widened valley bottom with thick peat deposits (histosols). Geology features granite, schists and other metamorphic bedrock, covered by drifts in the valley bottom which is also the parent material for dominant podzolic soils on the hillslopes. Vegetation cover reflects both soil type (bog vegetation, in particular *Sphagnum*, on the Histosols and the shrubs *Calluna vulgaris* and *Erica tetralix* on the podzols) and the effects of land management forming distinct soil-vegetation assemblages. The landscape has a long history of deforestation, a situation which is currently largely maintained by game shooting, in particular for Red Deer (*Cervus elaphus*) which inhibits tree regeneration through over-grazing. At present, forested areas are restricted to locations inaccessible to deer (i.e. behind deer fences and on steeper slopes). Fig. 1 shows the distribution of forested areas. While the dominant native tree species across the study site is Scots Pine (*Pinus sylvestris* L.), the stand in the north-eastern part is older than elsewhere and has a less dense, more open woodland vegetation structure. Rooting depth for both forest and heather in this type of environment is relatively shallow, with most of the fine root production and turnover typically occurring in the upper 20 cm of the soil (e.g. Bishop and Dambrine, 1995; Čermák et al., 2008), although the full rooting depth range does also depend on soil type and properties (Crow, 2005). For shallow and organic soils the rooting depth range is up to 0.5 m, while for more permeable, deep well drained soils (e.g. alluvium) this can be up to 4 m for forest stands (Crow, 2005). More detailed descriptions of the Girnock catchment area are provided elsewhere (e.g. Soulsby et al., 2007; Birkel et al., 2015).

Soil and vegetation water samples were extracted from the four main soil-vegetation units at four different times of the year, representing different hydroclimatological conditions during the growing season (Figs. 1, 2; Table 1). Typical for the Girnock and northern environments in more general terms, the four units involved podzolic soils with heather (Ph), and Scots Pine forest (Pf) vegetation, and two more Scots Pine sites on histosol (Hf) and alluvial (Af) soils. Sampling occurred at the end of the growing season (15th November 2012), the start of the following growing season in spring (18th April 2013), and

Table 1

Hydroclimatological conditions and average soil moisture of the top soil at the four sampling sites for the four sampling occasions. The catchment conditions include the daily antecedent precipitation for the previous seven (API_7) and 14 (API_{14}) days; discharge (Q), potential evapotranspiration (PET), and the mean normalised soil wetness index (MNSW) across the different soil types (see Geris et al., 2015a).

	Nov 12	Apr 13	Jun 13	Jul 13	
<i>Catchment conditions</i>					
API_7 (mm)	3.6	111.9	0.3	0	
API_{14} (mm)	7.1	117.1	9.2	0	
Q (mm d ⁻¹)	0.92	4.70	0.79	0.41	
PET (mm d ⁻¹)	0.57	1.88	1.86	3.19	
MNSW (-)	0.62	0.83	0.52	0.05	
<i>Site measurements</i>					
Soil moisture content [mean (stdev)] (%)	Ph	35.9 (9.7)	58.1 (11.5)	28.8 (11.8)	11.3 (6.2)
	Pf	37.9 (6.0)	54.9 (12.4)	46.1 (15.0)	12.1 (6.4)
	Hf	90.1 (6.0)	Saturated	92.7 (8.6)	76.2 (6.0)
	Af	23.6 (4.1)	39.4 (4.3)	18.1 (4.8)	5.6 (1.8)

at two dates as the summer growing season became increasingly dry (11th June 2013 and 22nd July 2013, respectively). The study occurred during a year with a relatively dry summer period (Geris et al., 2015c). The 2012–2013 winter also experienced an unusually long period with snow cover through to mid April (Dick et al., 2015). Although the temporal sampling resolution is still fairly coarse, Fig. 2 shows that the variability in hydroclimatological conditions at the four sampling occasions represents the full range of conditions during a whole hydrological year.

At each site, soil water was collected using both MacroRhizon suction cups and cryogenic vacuum distillation (West et al., 2006) of intact soil cores. These samples represent mobile water and include more tightly bound water respectively. Mobile water was collected with the MacroRhizon samples at 0.1, 0.3 and 0.5 m depth. Sampling at 0.1 m depth was inhibited at Hf and Af in November as a result of top soil frost. For the more freely draining podzol and alluvium sites (Pf and Af) no mobile soil water could be collected during July as a result of the exceptionally dry soils. Bulk soil water at Ph, Pf and Hf water was

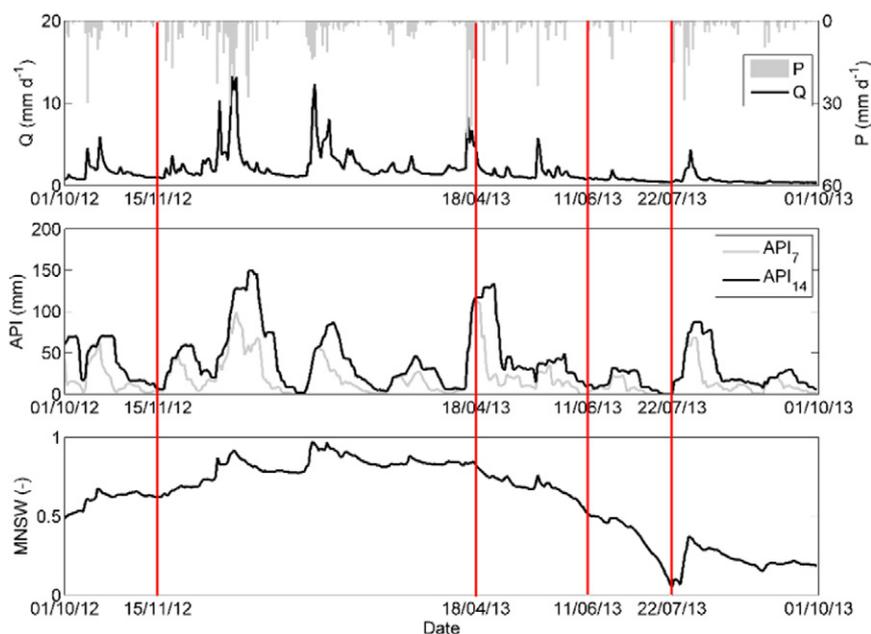


Fig. 2. Hydroclimatological conditions during the study year. The top plot shows daily precipitation (P) and discharge (Q); the middle plot shows daily antecedent precipitation for the previous seven (API_7) and 14 (API_{14}) days; and the bottom plot shows the mean normalised soil wetness index across the different soil types (see Geris et al., 2015a).

cryogenically extracted for the upper two soil depths, and for Af for all three depths. This reflects a balance between the need to capture the soil water stored in the rooting zone and high analytical costs for cryogenic extraction. For comparative purposes, soil moisture content at ground level for each site was determined by the average of ten replicate measurements using a *DeltaT* handheld time domain reflectometer. Vegetation water was also extracted cryogenically from Scots Pine xylem cores taken at 1.5 m (chest height) and from heather twigs. Where possible, sampling included up to three replicas for each water extraction technique. This was occasionally inhibited by incomplete extraction. Vegetation and soil water samples were cryogenically extracted for >2 h based on extraction time curves. Extraction efficiency was >0.99 for all samples presented. Cryogenic extraction was carried out at the Isotope Laboratory of the Global Institute for Water Security, University of Saskatchewan, following the procedure of West et al. (2006). Using the same set-up, a small selection of replicas was also analysed at the Surface Chemistry and Catalysis laboratory, University of Aberdeen. Comparisons between the analyses of these replicas revealed that results were within expected measurement error. Daily precipitation and stream water samples at a central location in the Girnock (Fig. 1) completed the sampling regime.

All water samples were analysed for both deuterium ($\delta^2\text{H}$) and oxygen-18 ($\delta^{18}\text{O}$) using a *Los Gatos* laser liquid water isotope analyser following standard protocols. Values are expressed in delta per mil (‰) relative to the Vienna Standard Mean Ocean Water standard. Isotope analyses of vegetation water samples and a subsample of soil water samples were also performed via the traditional isotope ratio mass spectrometry to test for the effects of organic contaminants (West et al., 2010) on the laser isotope ratio spectroscopy. This showed that all soil water samples analysed via the laser analyser were within the measurement precision (1‰ for $\delta^2\text{H}$ and 0.4‰ for $\delta^{18}\text{O}$).

The soil and vegetation water samples were evaluated using dual isotope plots via graphical xylem–soil water isotopic value comparison. It is assumed that the xylem water isotopic signature reflects the uptake-weighted average of $\delta^2\text{H}$ or $\delta^{18}\text{O}$ values of potential water sources on the basis that water is not fractionated during root uptake and evaporation from suberized stems is negligible (Ehleringer and Dawson, 1992), as such processes mainly occur in saline environments or in arid regions with little liquid water (Ellsworth and Williams, 2007). However, even if it may be assumed that roots predominantly take soil water from one depth zone (or pore space) at any given point in time, the soil water data collected here are not sufficient to unambiguously determine the exact water sources. Instead, here we

evaluate the similarities or differences between mobile and bulk soil water and how this relates to vegetation water isotopic signatures, including evidence of (evaporative) fractionation, to assess interactions between mobile and bulk soil water and plant–soil water. To allow for a further quantification of similarities or differences between various water sources and for comparison with data from other sites, we also determined the precipitation offset (via *lc*-excess (Eq. (1)) and *P*-excess, following Landwehr and Coplen, 2006 and Evaristo et al., 2015, respectively) for the bulk soil water. *P*-excess quantifies the deviation from the local meteoric water line and is a derivation of the *lc*-excess metric which takes into account the standard deviation laboratory procedure measurement uncertainty.

$$lc\text{-excess} = \delta D - a\delta^{18}\text{O} - b \tag{1}$$

3. Results and discussion

3.1. Spatio-temporal dynamics of mobile and bulk soil water

Across the sites and throughout the sampling periods, soil water data plotted within the scatter of annual precipitation data; and bulk soil water extracted cryogenically largely overlapped the stream and mobile soil water (Fig. 3A; Table 2). No major deviations from the local meteoric water line that could indicate significant evaporative fractionation effects were observed in the soil water samples. In general, this supports earlier findings that found limited evidence for the existence of ‘ecologically separated’ subsurface water pools in humid northern environments with little seasonality in precipitation (Geris et al., 2015a; Schmid et al., 2016). It also agrees with findings in semi-arid, snow dominated environments (McCutcheon et al., 2017).

However, the bulk soil water did appear to be consistently slightly more depleted and more likely to plot below the meteoric water line than mobile water (Fig. 3), which is in line with the general pattern in observations elsewhere (e.g. Brooks et al., 2010; Hervé-Fernández et al., 2016; Orłowski et al., 2016a). This is also reflected in the *lc*-excess values of the different soil water samples, which are more negative for the bulk water (Fig. 4, left panel). Figs. 3B and 4 show that these differences are most pronounced for site Af, absent for Hf, and while comparable for Ph and Pf, the latter bulk soil water samples show some limited effects of evaporative fractionation. Similar differences in soil water have been linked to mechanisms that could drive the apparent separation of subsurface water pools. These relate to different

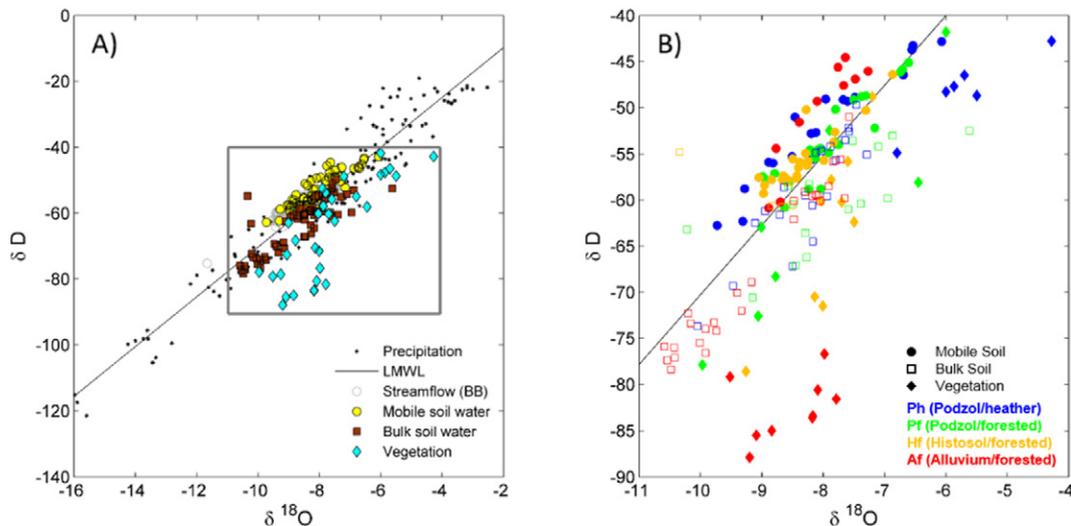


Fig. 3. Stable water isotopes of annual precipitation and streamflow, and all vegetation, mobile and bulk soil water samples across all four vegetation-soil units (A). The grey box in panel A indicates the scale of panel B, which shows the soil and vegetation stable water isotopes for each unit separately.

Table 2

Water isotope (see Fig. 3) and Ic -excess values (Fig. 4) for all precipitation, stream, mobile soil, bulk soil and vegetation water samples. Range values show min, max (mean).

Water samples	n	δD range	$\delta^{18}\text{O}$ range	Ic -excess range
Precipitation	149	−121.4, −19.1 (−67.3) ^a	−16.0, −2.5 (−9.5)	
Stream	311	−75.2, −42.2 (−60.5)	−11.7, −7.0 (−9.1)	−4.8, 14.9 (1.5)
Mobile soil	76	−62.8, −42.8 (−53.8)	−9.7, −6.1 (−8.1)	−3.4, 7.8 (2.4)
Bulk soil	67	−78.4, −49.7 (−60.2)	−10.6, −5.6 (−8.3)	−15.4, 18.1 (−3.0)
Vegetation xylem	32	−87.9, −41.8 (−65.2)	−10.0, −4.3 (−7.7)	−28.0, 1.9 (−12.8)

^a Weighted mean $\delta\text{D} = -59.1$.

conditions under which evaporation of water in the two soil spaces occurs, resulting in differential fractionation processes and thus different isotopic signatures. Evaporation of mobile water occurs under equilibrium (first-stage evaporation (Or et al., 2013)), while non-equilibrium evaporation conditions (second-stage evaporation, associated with increased drying) of more tightly bound adsorbed water in soil particles results in a deviation from the meteoric water line (Phillips, 2010; Sprenger et al., 2016). Even though the soils at the study site experienced marked drying in the study year (Fig. 2; Table 1), it is unclear whether sufficient drying occurred in this relatively wet environment at all of the sites to initiate such stage two evaporation. When more depleted bulk soil water was observed earlier for summer data only, Geris et al. (2015a) previously hypothesised that this could also reflect winter precipitation moving more slowly through the small pore spaces. Overall, depleted winter precipitation is the main source of recharge soil rewetting under high duration precipitation events. The results from this study suggest that some effects of evaporative processes are also likely, because a) the bulk samples mainly plot slightly below the local meteoric water line and the mobile water samples on or above, and b) this observation is consistent throughout the year (Figs. 3, 5). We acknowledge that the effects reported here may be so relatively small because the uppermost soil sampling depth was 10 cm and this may miss the upper (0–10 cm) profile where evaporation could be evident. For example, for the same environment Sprenger et al., 2017c demonstrated that water in the upper 5 cm of the soil profile was much more strongly fractionated than at 15–20 cm depth.

Nonetheless, recent work suggested that there may be effects of the soil water extraction techniques (Sprenger et al., 2015; Orłowski et al., 2016a) that may explain the observed patterns. For example, several studies have demonstrated that the isotopic values of cryogenically extracted soil water may be affected by extraction time (i.e. resulting in incomplete extraction (Koeniger et al., 2011)), clay content (Aragúas-Aragúas et al., 1995; Oerter et al., 2014), and especially at low soil water contents (Meißner et al., 2014). Such effects are unlikely here as clay content was low, extractions were complete, and soil water content relatively high. It has also been suggested that $\delta^2\text{H}$ and $\delta^{18}\text{O}$ values become progressively lighter with increasing organic carbon content (CO_2 emissions; e.g. Orłowski et al., 2016b). However,

Sprenger et al. (2017a) more recently demonstrated that this has no influence on the isotope analyses for our soils so that it is unlikely that the naturally high organic matter content of the histosols and top layers of the other soils directly affected the results.

Further investigations into the role of soil properties and extraction techniques are required to fully establish the drivers of the differences observed here, but compared to findings reported in other studies, the similarities of samples representing ‘mobile’ and ‘more tightly bound’ water are the most striking. P-excess values, used to quantify deviations in soil water from precipitation sources, further highlight the subtlety of this. The median P-excess value for cryogenically extracted soil water across the sites here was -3.0 (mean -2.6), which indicates an offset less than those reported by Evaristo et al. (2015) for 5 major biomes across the world (ranging from -9.3 in the tropics, to around -5.2 in temperate zones, and to -3.7 in arid zones). While our work is one site, compared to the global-in-scale work of Good et al. (2015a, 2015b) and the multi-biome meta-analysis (Evaristo et al., 2015), it does suggest that there are some places that fall outside of the ecohydrological separation framework.

Temporal dynamics in soil water isotopes are apparent in Fig. 5. For the November to June period, the soil water across the sites is more depleted in winter than in summer, which reflects the main season in precipitation input and streamflow output signals (Tetzlaff et al., 2014). The analysis also showed that there is overall more temporal variability in the isotope dynamics in the freely draining soils on the one hand (Ph, Pf, Af) than the more poorly draining Histosol (Hf) on the other, though such variability decreases with depth (Geris et al., 2015b). Although consistently more depleted as described above, the general temporal variability in the bulk soil water is consistent with that of the mobile soil water for all sites. This suggests that the water storage dynamics in different pore spaces are more likely connected (with both pore spaces reflecting the variability in precipitation input) rather than fully separated.

There are two key exceptions to such general observations, which further highlight the spatial variability in soil water isotopes and may reflect differences in the hydrogeology in different landscape positions. Firstly, Fig. 5 indicates that those minor deviations from the meteoric water line (in particular for Pf, second row in Fig. 5) were apparent

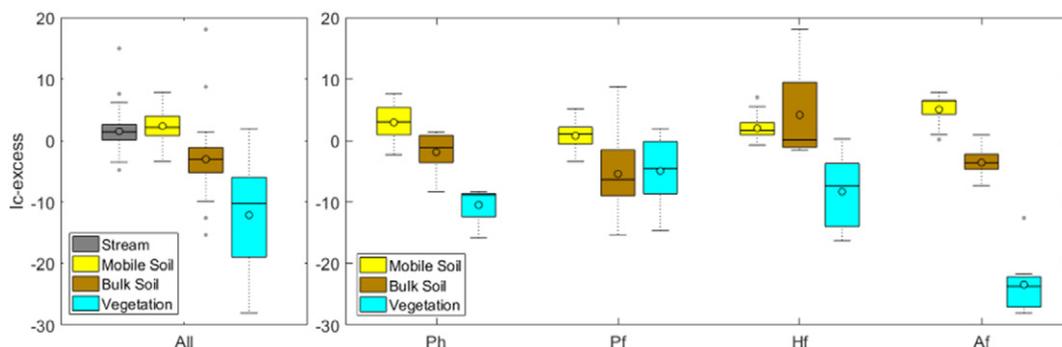


Fig. 4. Ic -excess value boxplots for all stream, mobile soil, bulk soil and vegetation water across the sites (left panel) and soil and vegetation water for each site individually (right panel). The tops and bottoms of each box are the 25th and 75th percentiles of the samples, respectively. The line and circle in each box are the sample median and mean, respectively. Outliers are defined as 1.5 times the interquartile range away from the top or bottom of the box.

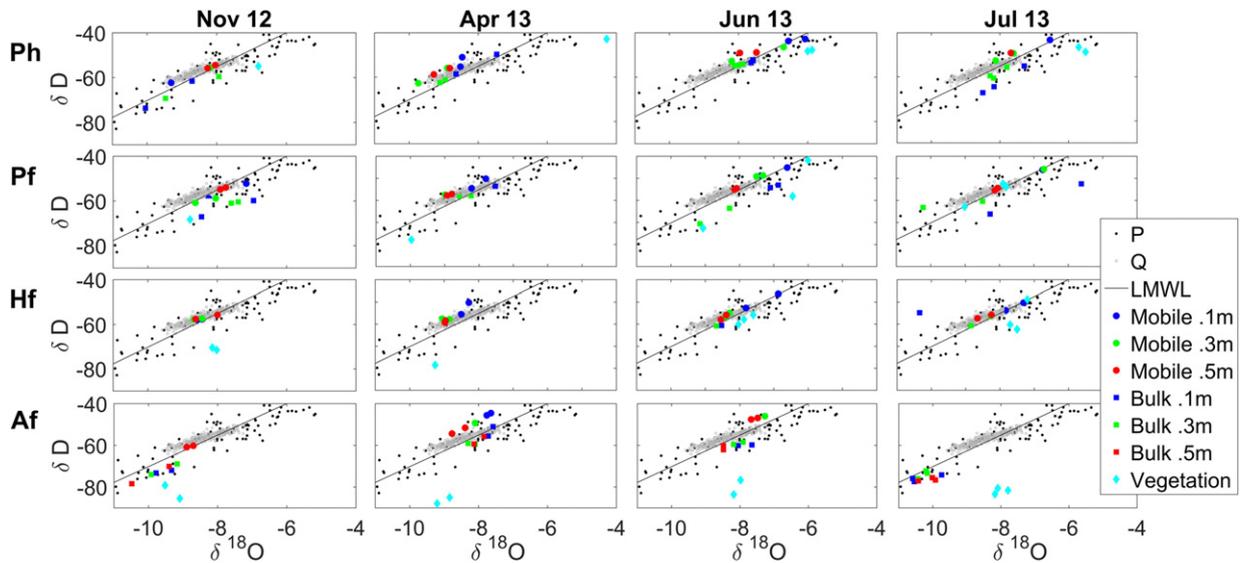


Fig. 5. Stable isotope results for mobile (circles) and bulk (squares) soil water for three different depths, and cryogenically extracted xylem water for the four different sampling locations and the four different times throughout the year. Daily precipitation and stream water for the whole study year are also shown.

only in the upper soil layers. This indicates that evaporative fractionation effects of soil water were only apparent near the surface, and likely not at deeper depths because of mixing processes during percolation through the soil profile. Secondly, the dynamics at the alluvial site were most different from those in the other soil-vegetation units. Here, the more depleted nature of the bulk soil water isotopes appears to be most consistent. As this is the most freely draining site, soil moisture conditions were the lowest (Table 1) so that bulk soil water samples may have comprised a higher proportion of tightly bound water that had been subjected to evaporation. Furthermore, contrary to the patterns observed at the other sites, the Af bulk water samples are most depleted in July (and similar to the November sampling campaign). Unfortunately, soil dryness inhibited mobile soil water extraction for comparison in temporal patterns. The more depleted nature of the soil water samples at Af may also be related to the site location in the riparian zone of the main stem of the Girnock stream. Previous studies have shown that the isotope signatures of stream water from the Girnock (with higher altitudes) are more depleted than those of the smaller subcatchment in which the other three sites are located (Birkel et al., 2011; Tunaley et al., 2017).

3.2. Spatio-temporal dynamics of vegetation water

Although there are clear spatial differences in vegetation water (Fig. 3B), for the majority of the sites (Ph, Pf, Hf; see Fig. 5) the winter xylem samples were more depleted than the summer samples. This again reflects the general seasonality in precipitation and soil water and shows that there is no clear lag in the vegetation uptake, at least at the coarse temporal resolution of the sampling employed here. Recent sapflow measurements at the study site have since revealed that tree water at the sampling height of 1.5 m most likely reflects water uptake of around one week previously during summer (Wang et al., 2017). As energy is much more limited from October to March (see e.g. Birkel et al., 2015), water will be stored in the trees for much longer during these winter months, which could explain the more depleted xylem than soil samples at Pf and Hf during November and April, which agrees with observations in Scots Pine elsewhere (Brandes et al., 2007). The signs of fractionation for winter vegetation water at Hf in particular may be attributed to uptake of snow meltwater, since snow lying at this site was more extensive than in other parts of the study area (Geris et al., 2015b). Higher temporal resolution data would be needed

to gain further insights into water uptake, in particular to consider the response to rapid variations in different potential vegetation water sources, e.g. associated with rainfall events (Volkman et al., 2016; Werner and Dubbert, 2016).

Although the xylem samples (as for the soil water data) largely plot along the meteoric water line and within the precipitation data scatter (Figs. 3, 5), the deviations are more marked for vegetation water (see also Fig. 4). As for most bulk soil water samples, the vegetation data all plot on or below the meteoric water line, and not above as the majority of mobile and some stream water samples do. The closer resemblance of vegetation water to bulk soil water (Figs. 3, 4) is in agreement with observations elsewhere (see e.g. Brooks et al., 2010; Evaristo et al., 2015). However, there is a marked contrast with vegetation in most of these other studies, which exhibited consistently more fractionated water in the xylem samples. The data here therefore suggest that the source water generally showed more limited effects of evaporative fractionation, although there is insufficient data to unambiguously determine the vegetation water sources specifically. The bulk water observed at the three soil depths sampled here alone is likely inadequate for constraining dominant vegetation water sources water for humid northern environments with shallow organic-rich soils. It has previously been proposed that water uptake in these regions may occur from the upper-most soil horizons, at shallower depths than the 0.1 m used here (Geris et al., 2015a). Evaporative fractionation effects are most evident at and near the surface (Sprenger et al., 2017b, 2017c), so this soil water (tightly bound and mobile water when soils are near saturation) is most affected, as well as by re-equilibration of water isotopic signatures at the soil/atmosphere interface. The results from Sprenger et al. (2017c) would suggest that the upper 5 cm of the soil is therefore a plausible source of the low (i.e. most negative) $\delta^{18}O$ -excess vegetation water, in particular for sites where rooting depth is most shallow (i.e. at site Ph for heather vegetation and at Hf for the Scots Pine at consistently wet Histosols; Fig. 4, right panel).

Fig. 5 shows that a site by site comparison through time reveals more complex differences in the isotopic composition of xylem water compared to soil water. The observed patterns can be grouped into three classes, which suggests that both vegetation, soil properties and location in the landscape play an important role in the water sources utilised by vegetation. First, the heather vegetation is consistently more enriched than the Scots pine xylem samples (top row Fig. 5). As heather has a much shallower rooting system than Scots Pine (typically <5 cm

deep), the evaporative effects on soil water might be most evident. Second, despite dissimilarities in soil properties, the Scots Pine xylem data show fairly similar temporal behaviour at Hf and Pf, with much more depleted isotopic signatures in winter than in summer. Third, the vegetation data from the forested Alluvium site (Af) are most dissimilar to the other sites (Figs. 3–5). This water has most negative $\delta^{18}\text{O}$ -excess values (Fig. 4) and plots consistently in the same space, which sits clearly below the meteoric water line (Fig. 5). Furthermore, its source must have been highly depleted, even more so than the bulk water sampled in November and July at this site. These differences at Af may reflect a combination of three factors. Firstly, owing to the nature of the soil and vegetation properties themselves, the evaporative fractionation and diffusion effects are expected to be strongest at this site. For example, it is known that dense vegetation covers can diminish evaporative fractionation processes in soil water (e.g. Burger and Seiler, 1992; Dubbert et al., 2013). The open woodland vegetation structure at Af (the least dense of the four sites) could have therefore contributed to stronger fractionation of the plant available water. Secondly, as suggested above for the more depleted nature of bulk soil water, there may also be a relation to the site location in the riparian zone of the main stem of the Girnock stream, which is characterised by more depleted precipitation inputs. Thirdly, the trees at this site were taller and older than at Pf and Hf. It has been shown that such properties may affect tree water uptake as reflected in the xylem isotopic signature (Goldsmith et al., 2012). For this site, a deeper tree root system accessing water not sampled in the shallow soil may therefore provide an alternative explanation.

4. Conclusion

This work evaluated spatial and temporal patterns in soil water storage and vegetation water use in humid northern environments. The interactions between soil and plant water were considered for four different soil/vegetation units, comprising podzol soils with heather and scots pine trees (Ph and Pf, respectively), as well as scots pine forested histosol and alluvium soils (Hf and Af, respectively). Although soil and xylem stable water isotope data across these units revealed general patterns in their temporal dynamics, there were marked differences between the different vegetation units. In general, comparisons between the stable isotopic character of mobile and bulk soil water at three different depths (10, 30 and 50 cm) revealed that although the bulk water was slightly more depleted, the temporal dynamics appeared to be in sync with those of mobile water, and both were determined by (seasonal) variations in precipitation inputs. Evaporative fractionation affected the isotopic signatures in soil water at shallow depths but compared with other environments/climates, these effects were small. Our results did not clearly indicate any preferential vegetation water uptake from either mobile or tightly bound soil water. Overall, it appears that the most likely main water source for the vegetation at all sites (in particular for the heather vegetation at Ph) was consistently at or near the soil/atmosphere interface. As such, the source water appeared to be time-invariable, even though the isotopic character of these source waters was variable for most sites. For those sites with time-variable isotopic xylem water, these variations were consistent with the variability in the respective potential source. Differences in soil water were most marked for the relatively dry alluvium soil at Af. The xylem water also indicated a different vegetation water source not sampled here. The limited number of vegetation samples dictate that further work is needed to unambiguously constrain vegetation water sources across the sites. However, efforts are also required to test the assumptions that isotopic signatures of source water are not affected during water uptake and within tree transport. Diffusion through tree bark (Dawson and Ehleringer, 1993) and or exchange between phloem and xylem water (Cernusak et al., 2005) may just be two exemplary processes to challenge this. The impacts of other physiological plant properties should also be reviewed.

Acknowledgements

We are thankful for the assistance of Audrey Innes (University of Aberdeen) and Kim Janzen (University of Saskatchewan) with soil and vegetation laboratory sample preparation and analyses. We would like to thank the European Research Council (ERC, project GA 335910 VeWa) for funding. The comments from two reviewers greatly improved an earlier version of the manuscript, for which we are highly grateful.

References

- Allison, G.B., 1982. The relationship between ^{18}O and deuterium in water in sand columns undergoing evaporation. *J. Hydrol.* 55:163–169. [http://dx.doi.org/10.1016/0022-1694\(82\)90127-5](http://dx.doi.org/10.1016/0022-1694(82)90127-5).
- Allison, G.B., Barnes, C.J., 1983. Estimation of evaporation from non-vegetated surfaces using natural deuterium. *Nature* 301:143–145. <http://dx.doi.org/10.1038/301143a0>.
- Araguas-Araguas, L., Rozanski, K., Gonfiantini, R., Louvat, D., 1995. Isotope effects accompanying vacuum extraction of soil water for stable isotope analyses. *J. Hydrol.* 168, 159–171.
- Asbjornsen, H., Goldsmith, G.R., Alvarado-Barrientos, M.S., Rebel, K., van Osch, F.P., Rietkerk, M., Chen, J., Gotsch, S., Tobón, C., Geissert, D.R., Gómez-Tagle, A., Vache, K., Dawson, T.E., 2011. Ecological advances and applications in plant–water relations research: a review. *J. Plant Ecol.* 4:3–22. <http://dx.doi.org/10.1093/jpe/rtr005>.
- Barbeta, A., Mejía-Chang, M., Ogaya, R., Voltas, J., Dawson, T.E., Peñuelas, J., 2015. The combined effects of a long-term experimental drought and an extreme drought on the use of plant-water sources in a Mediterranean forest. *Glob. Chang. Biol.* 21:1213–1225. <http://dx.doi.org/10.1111/gcb.12785>.
- Barnes, C.J., Allison, G.B., 1983. The distribution of deuterium and ^{18}O in dry soils: 1. Theory. *J. Hydrol.* 60:141–156. [http://dx.doi.org/10.1016/0022-1694\(83\)90018-5](http://dx.doi.org/10.1016/0022-1694(83)90018-5).
- Birkel, C., Soulsby, C., Tetzlaff, D., 2011. Modelling catchment-scale water storage dynamics: reconciling dynamic storage with tracer-inferred passive storage. *Hydrol. Process.* 25: 3924–3936. <http://dx.doi.org/10.1002/hyp.8201>.
- Birkel, C., Soulsby, C., Tetzlaff, D., 2015. Conceptual modelling to assess how the interplay of hydrological connectivity, catchment storage and tracer dynamics controls nonstationary water age estimates. *Hydrol. Process.* 29:2956–2969. <http://dx.doi.org/10.1002/hyp.10414>.
- Bishop, K., Dambrine, E., 1995. Localization of tree water uptake in Scots pine and Norway spruce with hydrological tracers. *Can. J. For. Res.* 25:286–297. <http://dx.doi.org/10.1139/x95-033>.
- Bowling, D.R., Schulze, E.S., Hall, S.J., 2016. Revisiting streamside trees that do not use stream water: can the two water worlds hypothesis and snowpack isotopic effects explain a missing water source? *Ecohydrology* <http://dx.doi.org/10.1002/eco.1771> (Early View).
- Brandes, E., Wenzinger, J., Koeniger, P., Schindler, D., Rennerberg, H., Leibundgut, C., Mayer, H., Gessler, A., 2007. Assessing environmental and physiological controls over water relations in a Scots pine (*Pinus sylvestris* L.) stand through analyses of stable isotope composition of water and organic matter. *Plant Cell Environ.* 30:113–127. <http://dx.doi.org/10.1111/j.1365-3040.2006.01609.x>.
- Brooks, R.J., Barnard, H.R., Coulombe, R., McDonnell, J.J., 2010. Ecohydrologic separation of water between trees and streams in a Mediterranean climate. *Nat. Geosci.* 3:100–104. <http://dx.doi.org/10.1038/NGE0722>.
- Brooks, P.D., Chorover, J., Fan, Y., Godsey, S.E., Maxwell, R.M., McNamara, J.P., Tague, C., 2015. Hydrological partitioning in the critical zone: Recent advances and opportunities for developing transferable understanding of water cycle dynamics. *Water Resour. Res.* 51:6973–6987. <http://dx.doi.org/10.1002/2015WR017039>.
- Burger, H.-M., Seiler, K.-P., 1992. Evaporation from soil water under humid climate conditions and its impact on deuterium and ^{18}O concentrations in groundwater. In: IAEA (Ed.), *Isotope Techniques in Water Resources Development: Proceedings of an International Symposium on Isotope Techniques in Water Resources Development Organized by the International Atomic Energy Agency in Co-operation With the United Nations*, 319th ed. IAEA and UNESCO, Vienna, pp. 674–678.
- Čermák, J., Nadezhdina, N., Meiresonne, L., Ceulemans, R., 2008. Scots pine root distribution derived from radial sap flow patterns in stems of large leaning trees. *Plant Soil* 305:61–75. <http://dx.doi.org/10.1007/s11104-007-9433-z>.
- Cernusak, L.A., Farquhar, G.D., Pate, J.S., 2005. Environmental and physiological controls over oxygen and carbon isotope composition of Tasmanian blue gum, *Eucalyptus globulus*. *Tree Physiol.* 25, 129–146.
- Comas, C., del Castillo, J., Voltas, J., Ferrio, J.P., 2015. Point processes statistics of stable isotopes: analysing water uptake patterns in a mixed stand of Aleppo pine and Holm oak. *For. Syst.* 24. <http://dx.doi.org/10.5424/fs/2015241-05846> (p.e009).
- Crow, P., 2005. *The Influence of Soils and Species on Tree Root Depth*. Forestry Commission information note. Surrey, UK, p. 8.
- Dai, Y., Zheng, X., Tang, L., Li, Y., 2015. Stable oxygen isotopes reveal distinct water use patterns of two Haloxylon species in the Gurbantonggut Desert. *Plant Soil* 389:73–87. <http://dx.doi.org/10.1007/s11104-014-2342-z>.
- Dawson, T.E., Ehleringer, J.R., 1993. Isotopic enrichment of water in the “woody” tissues of plants: implications for plant water source, water uptake, and other studies which use the stable isotopic composition of cellulose. *Geochim. Cosmochim. Acta* 57:3487–3492. [http://dx.doi.org/10.1016/0016-7037\(93\)90554-A](http://dx.doi.org/10.1016/0016-7037(93)90554-A).
- Dick, J.J., Tetzlaff, D., Birkel, C., Soulsby, C., 2015. Modelling landscape controls on dissolved organic carbon sources and fluxes to streams. *Biogeochemistry* 122:361. <http://dx.doi.org/10.1007/s10533-014-0046-3>.
- Dubbert, M., Cuntz, M., Piayda, A., Maguás, C., Werner, C., 2013. Partitioning evapotranspiration - testing the Craig and Gordon model with field measurements of oxygen isotope ratios of evaporative fluxes. *J. Hydrol.* 496:142–153. <http://dx.doi.org/10.1016/j.jhydrol.2013.05.033>.
- Ehleringer, J.R., Dawson, T.E., 1992. Water uptake by plants: perspectives from stable isotope composition. *Plant Cell Environ.* 15:1073–1082. <http://dx.doi.org/10.1111/j.1365-3040.1992.tb01657.x>.

- Ellsworth, P.Z., Williams, D.G., 2007. Hydrogen isotope fractionation during water uptake by woody xerophytes. *Plant Soil* 291:93–107. <http://dx.doi.org/10.1007/s11104-006-9177-1>.
- Evaristo, J., Jasechko, S., McDonnell, J.J., 2015. Global separation of plant transpiration from groundwater and streamflow. *Nature* 525, 91–94 (DOI: 1038/nature14983).
- Evaristo, J., McDonnell, J.J., Scholl, M.A., Buijzeel, L.A., Chun, K.P., 2016. Insights into plant water uptake from xylem-water isotope measurements in two tropical catchments with contrasting moisture conditions. *Hydrol. Process.* 30:3210–3227. <http://dx.doi.org/10.1002/hyp.10841>.
- Geris, J., Tetzlaff, D., McDonnell, J., Anderson, J., Paton, G., Soulsby, C., 2015a. Ecohydrological separation in wet, low energy northern environments? A preliminary assessment using different soil water extraction techniques. *Hydrol. Process.* 29:5139–5152. <http://dx.doi.org/10.1002/hyp.10603>.
- Geris, J., Tetzlaff, D., McDonnell, J.J., Soulsby, C., 2015b. The relative role of soil type and tree cover on water storage and transmission in northern headwater catchments. *Hydrol. Process.* 29:1844–1860. <http://dx.doi.org/10.1002/hyp.10289>.
- Geris, J., Tetzlaff, D., Soulsby, C., 2015c. Resistance and resilience to droughts: hydrogeological controls on catchment storage and run-off response. *Hydrol. Process.* 29:4579–4593. <http://dx.doi.org/10.1002/hyp.10480>.
- Gierke, C., Newton, B.T., Phillips, F.M., 2016. Soil-water dynamics and tree water uptake in the Sacramento Mountains of New Mexico (USA): a stable isotope study. *Hydrogeol. J.* 24: 805–818. <http://dx.doi.org/10.1007/s10040-016-1403-1>.
- Goldsmith, G.R., Muñoz-Villiers, L.E., Holwerda, F., McDonnell, J.J., Asbjornsen, H., Dawson, T.E., 2012. Stable isotopes reveal linkages among ecohydrological processes in a seasonally dry tropical montane cloud forest. *Ecohydrology* 5:779–790. <http://dx.doi.org/10.1002/eco.268>.
- Good, S.P., Noone, D., Bowen, G., 2015a. Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science* 349:175–177. <http://dx.doi.org/10.1126/science.1259311>.
- Good, S.P., Noone, D., Kurita, N., Benetti, M., Bowen, G.J., 2015b. D/H isotope ratios in the global hydrologic cycle. *Geophys. Res. Lett.* 42:5042–5050. <http://dx.doi.org/10.1002/2015GL064117>.
- Hervé-Fernández, P., Oyarzún, C., Brumbt, C., Huygens, D., Bodé, S., Verhoest, N.E.C., Boeckx, P., 2016. Assessing the “two water worlds” hypothesis and water sources for native and exotic evergreen species in south-central Chile. *Hydrol. Process.* <http://dx.doi.org/10.1002/hyp.10984> (Early View).
- IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (1535 pp).
- Jackson, R.B., Sperry, J.S., Dawson, T.E., 2000. Root water uptake and transport: using physiological processes in global predictions. *Trends Plant Sci.* 5, 482–488.
- Kirkham, M.B., 2014. *Principles of Soil and Plant Water Relations*. second ed. Academic Press, Elsevier (598 pp).
- Koerner, P., Marshall, J.D., Link, T., Mulch, A., 2011. An inexpensive, fast, and reliable method for vacuum extraction of soil and plant water for stable isotope analyses by mass spectrometry. *Rapid Commun. Mass Spectrom.* 25:3041–3048. <http://dx.doi.org/10.1002/rcm.5198>.
- Kramer, P.J., Boyer, J.S., 1995. *Water Relations of Plants and Soils*. Academic Press (495 pp).
- Landwehr, J.M., Coplen, T.B., 2006. Line-conditioned excess: a new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems. *International Conference on Isotopes in Environmental Studies*. IAEA, Vienna, pp. 132–135.
- McCutcheon, R.J., McNamara, J.P., Kohn, M.J., Evans, S.L., 2017. An evaluation of the ecohydrological separation hypothesis in a semiarid catchment. *Hydrol. Process.* 31: 783–799. <http://dx.doi.org/10.1002/hyp.11052>.
- McDonnell, J.J., 2014. The two water worlds hypothesis: ecohydrological separation of water between streams and trees? *WIREs Water* 1:323–329. <http://dx.doi.org/10.1002/wat2.1027>.
- Meißner, M., Köhler, M., Schwendenmann, L., Hölischer, D., Jens Dyckmans, J., 2014. Soil water uptake by trees using water stable isotopes ($\delta^2\text{H}$ and $\delta^{18}\text{O}$)—a method test regarding soil moisture, texture and carbonate. *Plant Soil* 376:327–355. <http://dx.doi.org/10.1007/s11104-013-1970-z>.
- Oerter, E., Finstad, K., Schaefer, J., Goldsmith, G.R., Dawson, T., Amundson, R., 2014. Oxygen isotope fractionation effects in soil water via interaction with cations (Mg, Ca, K, Na) adsorbed to phyllosilicate clay minerals. *J. Hydrol.* 515:1–9. <http://dx.doi.org/10.1016/j.jhydrol.2014.04.029>.
- Or, D., Lehmann, P., Shahraeeni, E., Shokri, N., 2013. Advances in soil evaporation physics—a review. *Vadose Zone J.* 12. <http://dx.doi.org/10.2136/vzj2012.0163>.
- Orlowski, N., Pratt, D.L., McDonnell, J.J., 2016a. Intercomparison of soil pore water extraction methods for stable isotope analysis. *Hydrol. Process.* 30:3434–3449. <http://dx.doi.org/10.1002/hyp.10870>.
- Orlowski, N., Breuer, L., McDonnell, J.J., 2016b. Critical issues with cryogenic extraction of soil water for stable isotope analysis. *Ecohydrology* 9:1–5. <http://dx.doi.org/10.1002/eco.1722>.
- Penna, D., Oliviero, O., Assendelft, R., Zuecco, G., van Meerveld, H.J., Anfodillo, T., Carraro, V., Borgia, M., Dalla Fontana G., 2013. Tracing the water sources of trees and streams: isotopic analysis in a small pre-alpine catchment. *Procedia Environ. Sci.* 19:106–112. <http://dx.doi.org/10.1016/j.proenv.2013.06.012>.
- Philip, J.R., 1966. Plant water relations: some physical aspects. *Annu. Rev. Plant Physiol.* 17: 245–268. <http://dx.doi.org/10.1146/annurev.pp.17.060166.001333>.
- Phillips, F., 2010. Soil-water bypass. *Nat. Geosci.* 178:162–175. <http://dx.doi.org/10.1016/j.pepi.2009.10.001>.
- Rodríguez-Iturbe, I., Porporato, A., 2004. *Ecohydrology of Water-controlled Ecosystems: Soil Moisture and Plant Dynamics*. Cambridge University Press, Cambridge, UK, p. 442.
- Rodríguez-Iturbe, I., D’Odorico, P., Laio, F., Ridolfi, L., Tamea, S., 2007. Challenges in humid land ecology: interactions of water table and unsaturated zone with climate, soil, and vegetation. *Water Resour. Res.* 43, W09301. <http://dx.doi.org/10.1029/2007WR006073>.
- Rossato, D.R., Silva, L.C.R., Sternberg, S.L.S., Franco, A.C., 2014. Do woody and herbaceous species compete for soil water across topographic gradients? Evidence for niche partitioning in a Neotropical savanna. *South African Journal of Botany*—S. Afr. J. Bot. 91:14–18. <http://dx.doi.org/10.1016/j.sajb.2013.11.011>.
- Schmid, B., Dubbert, M., Werner, C., Hopp, L., 2016. Two Water Worlds in Temperate Forests? Partitioning of Water Sources in Two Forested Headwater Catchments in Germany (Abstract EGU2016-14748 presented at 2016 General Assembly, EGU, Vienna, Austria, 17–22 April).
- Schwendenmann, L., Pendall, E., Sanchez-Bragado, R., Kunert, N., Hölischer, D., 2015. Tree water uptake in a tropical plantation varying in tree diversity: interspecific differences, seasonal shifts and complementarity. *Ecohydrology* 8:1–12. <http://dx.doi.org/10.1002/eco.1479>.
- Scott, R.L., Shuttleworth, W.J., Goodrich, D.C., Maddock, T., 2000. The water use of two dominant vegetation communities in a semiarid riparian ecosystem. *Agric. For. Meteorol.* 105: 241–256. [http://dx.doi.org/10.1016/S0168-1923\(00\)00181-7](http://dx.doi.org/10.1016/S0168-1923(00)00181-7).
- Soulsby, C., Tetzlaff, D., van den Bedem, N., Malcolm, I.A., Bacon, P.J., Youngson, A.F., 2007. Inferring groundwater influences on surface water in montane catchments from hydrochemical surveys of springs and streamwaters. *J. Hydrol.* 333, 199–213.
- Sprenger, M., Herbstritt, B., Weiler, M., 2015. Established methods and new opportunities for pore water stable isotope analysis. *Hydrol. Process.* 29:5174–5192. <http://dx.doi.org/10.1002/hyp.10643>.
- Sprenger, M., Leistert, H., Gimbel, K., Weiler, M., 2016. Illuminating hydrological processes at the soil-vegetation-atmosphere interface with water stable isotopes. *Rev. Geophys.* <http://dx.doi.org/10.1002/2015RG000515>.
- Sprenger, M., Tetzlaff, D., Soulsby, C., 2017a. No influence of CO₂ on stable isotope analyses of soil waters with OA-ICOS. *Rapid Commun. Mass Spectrom.* <http://dx.doi.org/10.1002/rcm.7815>.
- Sprenger, M., Tetzlaff, D., Soulsby, C., 2017b. Stable isotopes reveal evaporation dynamics at the soil-plant-atmosphere interface of the critical zone. *Hydrol. Earth Syst. Sci. Discuss.* <http://dx.doi.org/10.5194/hess-2017-87> (In review).
- Sprenger, M., Tetzlaff, D., Tunaley, C., Dick, J., Soulsby, C., 2017c. Evaporation fractionation in a peatland drainage network affects stream water isotope composition. *Water Resour. Res.* 53. <http://dx.doi.org/10.1002/2016WR019258>.
- Tetzlaff, D., Birkel, C., Dick, J.J., Geris, J., Soulsby, C., 2014. Storage dynamics in hydrogeological units control hillslope connectivity, runoff generation, and the evolution of catchment transit time distributions. *Water Resour. Res.* 50:969–985. <http://dx.doi.org/10.1002/2013WR014147>.
- Tetzlaff, D., Buttle, J., Carey, S.K., van Huijgevoort, M.H.J., Laudon, H., McNamara, J.P., Mitchell, C.P.J., Spence, C., Gabor, R.S., Soulsby, C., 2015. A preliminary assessment of water partitioning and ecohydrological coupling in northern headwaters using stable isotopes and conceptual runoff models. *Hydrol. Process.* 29:5153–5173. <http://dx.doi.org/10.1002/hyp.10515>.
- Thompson, S.E., Harman, C.J., Heine, P., Katul, G.G., 2010. Vegetation–infiltration relationships across climatic and soil type gradients. *J. Geophys. Res.* 115, G02023. <http://dx.doi.org/10.1029/2009JG001134>.
- Troch, P.A., Carrillo, G., Sivapalan, M., Wagener, T., Sawicz, K., 2013. Climate-vegetation-soil interactions and long-term hydrologic partitioning: signatures of catchment co-evolution. *Hydrol. Earth Syst. Sci.* 17:2209–2217. <http://dx.doi.org/10.5194/hess-17-2209-2013>.
- Tunaley, C., Tetzlaff, D., Soulsby, C., 2017. Scaling effects of riparian peatlands on stables isotopes in runoff and DOC mobilization. *J. Hydrol.*
- Vereecken, H., Huismans, J.A., Hendricks Franssen, H.J., Bruggemann, N., Bogena, H.R., Kollet, S., Javaux, M., van der Krug, J., Vanderborght, J., 2015. Soil hydrology: recent methodological advances, challenges, and perspectives. *Water Resour. Res.* 51:2616–2633. <http://dx.doi.org/10.1002/2014WR016852>.
- Volkman, T.H.M., Haberger, K., Gessler, A., Weiler, M., 2016. High-resolution isotope measurements resolve rapid ecohydrological dynamics at the soil–plant interface. *New Phytol.* 210:839–849. <http://dx.doi.org/10.1111/nph.13868>.
- Wang, H., Tetzlaff, D., Soulsby, C., 2017. Environmental controls on transpiration in a low energy boreal Scots pine plantation. *Agric. For. Meteorol.*
- Wei, Y.F., Fang, J., Liu, S., Zhao, X.Y., Li, S.G., 2013. Stable isotopic observation of water use sources of *Pinus sylvestris* var. *mongolica* in Horqin Sandy Land, China. *Trees* 27:1249–1260. <http://dx.doi.org/10.1007/s00468-013-0873-1>.
- Werner, C., Dubbert, M., 2016. Resolving rapid dynamics of soil–plant–atmosphere interactions. *New Phytol.* 210:767–769. <http://dx.doi.org/10.1111/nph.13936>.
- West, A.G., Patrickson, S.J., Ehleringer, J.R., 2006. Water extraction times for plant and soil materials used in stable isotope analysis. *Rapid Commun. Mass Spectrom.* 20:1317–1321. <http://dx.doi.org/10.1002/rcm.2456>.
- West, A.G., Goldsmith, G.R., Brooks, P.D., Dawson, T.E., 2010. Discrepancies between isotope ratio infrared spectroscopy and isotope ratio mass spectrometry for the stable isotope analysis of plant and soil waters. *Rapid Commun. Mass Spectrom.* 24:1848–1954. <http://dx.doi.org/10.1002/rcm.4597>.
- White, J.C., Smith, W.K., 2015. Seasonal variation in water sources of the riparian tree species *Acer negundo* and *Betula nigra*, southern Appalachian foothills, USA. *Botany* 93:519–528. <http://dx.doi.org/10.1139/cjb-2015-0003>.
- Zeppel, M., 2013. Convergence of tree water use and hydraulic architecture in water-limited regions: a review and synthesis. *Ecohydrology* 6, 889–900.