

Ecohydrological separation in wet, low energy northern environments? A preliminary assessment using different soil water extraction techniques

Journal:	<i>Hydrological Processes</i>
Manuscript ID:	HYP-15-0039.R1
Wiley - Manuscript type:	Special Issue Tracer Advances Review
Date Submitted by the Author:	27-May-2015
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Keywords:	Isotopes, Water Storage, Soil Water Extraction, Tree Water Use

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3 1 **Ecohydrological separation in wet, low energy northern environments? A**
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5 2 **preliminary assessment using different soil water extraction techniques**
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31
32 15 **Abstract**
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35 16 Ecohydrological studies in seasonally dry climatic regions have revealed isotopic separation
36
37 17 of the sources of water used by trees and those that generate stream flow, also referred to
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39 18 as the 'two water worlds' hypothesis. Here we investigated whether similar separation
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41 19 occurs in a wet, low energy northern (Latitude 57°) environment in Scotland. For two
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43 20 common soil types (Histosols and Podzols) at three soil depths, and at both forested (with
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45 21 Scots Pine (*Pinus sylvestris*)) and non-forested sites, we compared the stable isotope
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47 22 composition of soil water held at increasing soil water tensions. These were assessed by
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49 23 different soil water extraction techniques: Rhizon samplers (mobile water), centrifugation at
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51 24 different speeds (representing different tensions), and cryogenic extraction (bulk water).
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53 25 Sampling occurred during a relatively dry summer. Water that was held at increasing
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55 26 tensions appeared more depleted than more mobile water, consistent with older (winter)
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57 27 precipitation. This pattern was independent of soil type, vegetation cover, and time during
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59 28 the growing season, although there was a slight tendency towards less separation with soil
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29 depth. Nevertheless, soil waters in this generally wet, low energy environment exhibited

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3 30 only minor evaporative enrichment, limited to the upper soil profile only. Furthermore,
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5 31 stream water showed no deviation from the local meteoric water line. Preliminary sampling
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7 32 for tree xylem water suggested uptake of evaporated soil water from the near surface soil
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9 33 horizons (upper 10 cm) where fine root densities are concentrated. For Histosols in
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11 34 particular, tree water appeared lagged in its isotopic composition compared to the soil
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13 35 water time series. Although more work is needed to fully test the 'two water worlds'
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15 36 hypothesis, our initial analyses did not provide clear evidence to support this in wet, low
16
17 37 energy northern environments.

18 38 **Keywords:** isotopes; water storage; soil water extraction; tree water use
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22 23 40 **1. Introduction**

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25 41 Catchment water storage, mixing and flux processes usually have a strong influence on
26
27 42 stream flow generation and solute transport (Kirchner *et al.*, 2000; 2001; McDonnell *et al.*,
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29 43 2010; Rinaldo *et al.*, 2011). It has often been assumed that water in subsurface stores is well
30
31 44 mixed and that vegetation assimilates water that would have otherwise contributed to
32
33 45 groundwater recharge and stream flow. These assumptions are well embedded in most
34
35 46 (eco)hydrological models and conceptual frameworks. However, recent work has challenged
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37 47 this by suggesting that at least in seasonally warm and dry climatic regimes, vegetation uses
38
39 48 tightly bound water which is isotopically distinct from more mobile water that contributes
40
41 49 to streamflow (e.g. Brooks *et al.*, 2010, Goldsmith *et al.*, 2012). As such, these studies have
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43 50 speculated on the coexistence of two pools of water in the subsurface that do not mix, not
44
45 51 even during or after consecutive precipitation events. This 'two water worlds' hypothesis
46
47 52 (McDonnell, 2014) is supported by stable isotope (δD and $\delta^{18}O$) tracer analyses of
48
49 53 precipitation, soil, stream, and xylem water samples. Stable isotopes are useful tools to gain
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51 54 insights into hydrological processes (Kendall and McDonnell, 1998; Vitvar *et al.*, 2005) such
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53 55 as subsurface water storage, mixing and transport processes (e.g. Gazis and Feng, 2004;
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55 56 Mueller *et al.*, 2014; Tetzlaff *et al.*, 2014; Birkel and Soulsby, this volume), and also plant
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57 57 water use (e.g. Dawson and Ehleringer, 1991; Brandes *et al.*, 2007; Bertrand *et al.*, 2014). In
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59 58 the context of the 'two water worlds' hypothesis, the term 'ecohydrological separation' has
60
60 59 been used to describe instances where the vegetation is using water of a different (isotopic)

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2
3 60 character than that found draining freely through the soil profile and into the stream. In
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5 61 other words, the vegetation has been shown to preferentially draw water from a particular
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7 62 source, where several co-exist. Previous work (e.g. Brooks *et al.*, 2010, Goldsmith *et al.*,
8
9 63 2012) demonstrated a clear distinction between tightly bound water that has the signature
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11 64 of strong evaporative enrichment and which is used by the vegetation on the one hand, and
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13 65 more mobile waters with less enrichment and which recharges the stream on the other.

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15 66 It is well known that the chemical composition of extracted soil water may depend on the
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17 67 extraction techniques used (e.g. Walker *et al.*, 1994). This is related mostly to differences in
18
19 68 the matric tension exerted in the extraction so that water is drawn from different pore size
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21 69 distributions (Tiensing *et al.*, 2001). Secondary effects include, for example, soil type
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23 70 (Aragúas-Aragúas *et al.*, 1995), and extraction temperatures (Ingraham and Shadel, 1992;
24
25 71 Walker *et al.*, 1994). Traditional soil water extraction methods for stable isotope analyses
26
27 72 include lysimeter porous cups or samplers in the field, or soil core sampling for laboratory
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29 73 based cryogenic vacuum distillation, azeotropic distillation, centrifugation, and mechanical
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31 74 squeezing (see reviews by e.g. Barnes and Turner, 1998; Soderberg *et al.*, 2012). The key
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33 75 difference between these field *versus* lab techniques is that porous cups extract water that
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35 76 is held at low tensions (i.e. 'mobile' water at tensions less than 200 kPa), while most
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37 77 laboratory methods extract all water (down to 10-15 MPa) so that their chemical
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39 78 composition represents the bulk water (including more 'tightly bound' water) held by the
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41 79 soil (Landon *et al.*, 1999; Figuéroa-Johnson *et al.*, 2007; Zhao *et al.*, 2013). In this context,
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43 80 different techniques can therefore be used to extract water that is held at different soil
44
45 81 water tensions (i.e. in pores with increasingly smaller sizes). Several studies have
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47 82 demonstrated a clear distinction between the isotopic composition of mobile water
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49 83 extracted *via* lysimeters and bulk water extracted *via* cryogenic vacuum distillation (e.g.
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51 84 Brooks *et al.* (2010) in the USA, Goldsmith *et al.* (2012) in Mexico, and Zhao *et al.* (2013) in
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53 85 China).

54
55 86 The mechanisms that control subsurface isotopic separation in catchments are poorly
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57 87 understood (McDonnell, 2014). In relatively dry mineral soils with high clay content and
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59 88 consequently high cation exchange capacity, clay particles can interact with soil water to
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61 89 create "pools" of different waters with varying isotope compositions (Aragúas-Aragúas *et al.*,
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63 90 1995; Meißner *et al.*, 2013; Oerter *et al.*, 2014). However, a main factor controlling soil

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3 91 water separation may be a strong seasonality in climate (McDonnell, 2014); where
4
5 92 considerable soil drying might be required to allow for (evaporated) precipitation inputs to
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7 93 enter and be retained by the smaller pore spaces for prolonged periods of time (Brooks *et*
8
9 94 *al.*, 2010; Goldsmith *et al.*, 2012). When soils are dry and precipitation intensity and
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11 95 duration are low, Tang and Feng (2001) showed that new water could not effectively replace
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13 96 old water in a soil column. They argued that traces of old water could be present in the soil
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15 97 matrix for a long time or even throughout the entire growing season. However, it should
16
17 98 again be stressed that all studies that specifically explored the occurrence of separation
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19 99 based on isotopic signatures have been conducted at sites with strongly seasonal patterns in
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21 100 precipitation and high evaporative losses. To further understand the wider relevance of
22
23 101 these isotopic implications for soil water storage and flow partitioning, there is a pressing
24
25 102 need to explore contrasting environments across different hydroclimates (in particular less
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27 103 seasonal in precipitation inputs) and in different soil types (McDonnell, 2014; Tetzlaff *et al.*,
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29 104 this volume).

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31 105 In this paper we explore soil water storage and evidence for ecohydrological separation in a
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33 106 low energy, wet northern catchment. In these humid, boreal environments, there is usually
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35 107 limited seasonality in precipitation inputs, energy for evapotranspiration is relatively low,
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37 108 and soil water storage is persistently high (Tetzlaff *et al.*, 2014; Geris *et al.*, 2015a),
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39 109 particularly when compared to the more seasonal and drier climates in previous studies. We
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41 110 hypothesise that in such wetter environments, soil water stored in smaller pores is more
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43 111 likely to exchange or mix with more mobile water. We investigated this hypothesis for
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45 112 various soil-vegetation units in the eastern Scottish Highlands, UK, by comparing the stable
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47 113 isotope composition of soil water held at different tensions by using various extraction
48
49 114 techniques: porous Rhizon samplers (inferred matric tension of < 200 kPa), centrifugation
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51 115 (inferred tension of ~200, ~700, and ~1100 kPa) and cryogenic extraction (up to 15 MPa).
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53 116 We compared soil water that was sampled during a growing season in a 10 year return
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55 117 period drought (Geris *et al.*, 2015b), assuming that if separation of soil waters would exist, it
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57 118 would be most marked during such a period with relatively high evapotranspiration. Our
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59 119 specific questions were:

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120 (1) Can any different pools of soil water in northern environments be identified by
121 comparing the stable isotope composition of soil water held at different tensions?

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3 122 (2) If so, how might differences in soil type affect these patterns?
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5 123 (3) How does the water use of vegetation, as identified by the xylem isotope
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7 124 composition, compare to the measured soil water isotope composition of water
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9 125 under different tensions?
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12 127 **2. Study area**

14 128 This study was carried out in the Bruntland Burn (3.2 km²) experimental catchment in the
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16 129 Cairngorms National Park, Northern Scotland, UK (Figure 1) where forests are part of the
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18 130 boreal forest biome of the upper latitudes of the Northern hemisphere. The prevailing wet
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20 131 climate has fairly cool summers (June average temperature = 15.8 °C), cold winters
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22 132 (February average temperature = -0.7 °C), and 1100 mm of annual precipitation which is
23
24 133 relatively evenly distributed throughout the year. Annual runoff (700 mm) greatly exceeds
25
26 134 potential evapotranspiration estimates (400 mm). Elevations range from 248 to 539 m a.s.l.
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28 135 (mean 351 m a.s.l.) and the mean slope is ~13°. The catchment is predominantly underlain
29
30 136 by metamorphic (54 %) and granite (46 %) bedrock. The geology gives rise to low base status
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32 137 soils and the landscape is characterised by a strong glacial legacy. The widened valley
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34 138 bottom has thick glacial drift deposits up to 40 m deep (Birkel *et al.*, 2015). These are
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36 139 covered by thick (>1 m) waterlogged peat soils in the valley bottom, which gradually thins to
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38 140 shallow peats (0.5 m) on the lower hillslopes. These Histosols cover 21% of the catchment.
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40 141 The dominant soil types on the hillslopes are humus-iron Podzols (Spodosols, 36% of the
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42 142 catchment area), which thin to Leptosols (Entisols, 14%) and bedrock outcrops (29%) at
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44 143 slopes >25°. The Podzols have a ~0.2 m O- horizon that overlies the mineral sub-soil.

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46 144 The hydrology has an important control on the spatial distribution of water storage and
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48 145 fluxes. The poorly draining Histosols in the riparian zone are permanently wet and have high
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50 146 total water storage. Hence, the dynamic storage differences are small and runoff generation
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52 147 is predominantly through near surface runoff flow pathways. The Podzols on the hillslopes
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54 148 experience distinct wetting and drying cycles that coincide with precipitation events
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56 149 (Tetzlaff *et al.*, 2014). In these more freely draining soils, the dynamic storage changes are
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58 150 larger and there is more recharge to deeper flow pathways (Birkel *et al.*, 2015). The spatial
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60 151 distribution of vegetation shows a strong connection with soil type. The Histosols are
152 characterised by *Sphagnum spp*, *Molina caerulea* and *Myrica gale* dominated peat bogs. The

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3 153 most widespread vegetation on the hillslopes is heather (*Calluna* and *Erica* species)
4 154 vegetation. Trees, mainly native Scots Pine (*Pinus sylvestris*), are able to grow on all main
5 155 soil types, but after centuries of widespread deforestation their distribution is now limited
6 156 to steeper areas (20% of the catchment) generally inaccessible to deer grazing. During
7 157 relatively dry conditions, there is some indication that tree cover can affect hydrological
8 158 responses, e.g. through increasing evapotranspiration and exacerbating soil water storage
9 159 drawdown trends (Geris *et al.*, 2015a; 2015b), although these effects are small at the
10 160 catchment scale. Tracer studies have indicated that, in general, stream flow has a strong
11 161 connection to soil water stored in the Histosols and that the riparian zone contributes the
12 162 majority of water in the stream (Tetzlaff *et al.*, 2014). Direct groundwater contributions (as a
13 163 separate source compared to soil water contributions) are in the order of 25-35% of annual
14 164 stream flow (Soulsby *et al.*, 2007).
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27 166 3. Methods

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30 167 To examine soil water storage and flow separation in low energy, wet environments, we
31 168 compared hydrometric data and stable isotope composition of precipitation, stream water,
32 169 xylem water, and different soil waters for four soil-vegetation units in the Bruntland Burn
33 170 catchment (Figure 1). The main study period reported here spanned the growing season of
34 171 2013 (May – August), though basic hydrometric and isotope monitoring of precipitation and
35 172 stream flow is part of a longer term study. As April still experienced significant snow cover
36 173 on the ground (Geris *et al.*, 2015a), the start of the 2013 growing season was defined at the
37 174 beginning of May. We focussed on the summer growing season, as long residence times of
38 175 water in the trees can decouple isotopic signals of xylem and soil source water in winter
39 176 (Brandes *et al.*, 2007). The four soil-vegetation units are broadly representative of the
40 177 dominant soil and vegetation units in such boreal environments and include two Histosol
41 178 sites with Sphagnum (Hs) and Scots pine forest (Hf) cover, and two Podzol sites with
42 179 Heather (Ph) and Scots pine forest (Pf) cover, respectively (Figure 1). For a detailed
43 180 description of these four sites and the soil physical characteristics, the reader is referred to
44 181 Geris *et al.*, 2015a.
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3 182 Hydrometric data included daily catchment precipitation and stream flow. Further
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5 183 climatological data were available from a nearby automatic meteorological station located 1
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7 184 km west of the Bruntland Burn. These were used to estimate daily potential
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9 185 evapotranspiration rates using a simplified version of the Penman-Monteith Equation (cf.
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11 186 Dunn and Mackay, 1995). Furthermore, at the four study sites, 15 min soil moisture data
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13 187 were collected at three different monitoring depths (10, 30, and 50 cm), which largely
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15 188 coincide with the main soil horizons (*Geris et al.*, 2015a). At each of these monitoring depths,
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17 189 volumetric soil moisture (VSM) content was measured with *Campbell Scientific* 650-VS time
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19 190 domain reflectometry (TDR) probes. Average values of two replicate probes are presented
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21 191 here. VSM data were collected for each of the three depths for the Podzol sites. For the
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23 192 Histosol sites, VSM was attained at 0.1 m depth only, as the lower soil layers (0.2 m and
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25 193 beyond) were permanently saturated.

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27 194 During the full duration of the study period, daily precipitation and stream water samples
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29 195 were collected via *ISCO* automatic water samples for stable isotope analyses. In addition,
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31 196 fortnightly soil water samples were collected via *Rhizosphere Research Products*
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33 197 MacroRhizon moisture samplers to assess the dynamics of mobile water. These are small
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35 198 porous Rhizon samplers (*Di Bonito et al.*, 2008) that sample water under vacuum. Vacuum
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37 199 was obtained via 30mL syringes with retainers to hold the vacuum. After initial flushing of
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39 200 the system, the vacuum was held for 10-30 minutes until at least 10mL of soil water was
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41 201 collected. The vacuum is assumed to have tension strengths smaller than 200 kPa. Two
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43 202 hundred kPa is the bubble point of the Rhizon samplers and it also represents the lowest
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45 203 inferred tension exerted using any of the other extraction methods used in this study.

46
47 204 In the middle of the growing period when conditions were unusually dry, two more
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49 205 extensive sampling campaigns (Table 1) were carried out where soil water was further
50
51 206 extracted using other techniques. These represent water that is held at a range of soil water
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53 207 tensions (Table 2). In addition to the Rhizon mobile water collection, the second method
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55 208 involved centrifugation of intact soil cores at various speeds that represent different matric
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57 209 tensions. During the two extensive sampling campaigns, 12 soil cores from each of the three
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59 210 horizons at each site were extracted and transferred into centrifuge tubes (each 2 mL max
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211 volume) with 0.45 μ m pore size filters. The filtration unit was embedded within the
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centrifuge tube. These tubes were immediately sealed with parafilm and refrigerated until

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3 213 analyses. A temperature controlled (5 °C) *Thermo Scientific* Fresco 21 Microcentrifuge was
4 214 used to avoid isotopic fractionation effects as a result of the centrifugation. Samples were
5 215 split into three groups (n = 4 for each group) and spun for 1 hr at different speeds to
6 216 represent water that is held at inferred matric tensions up to ~200, ~700, and ~1100 kPa.
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8 217 Initial tests showed that centrifugation times of 1 hr were sufficient, after which no more
9 218 water would be extracted at a particular speed. Relative centrifugal force was converted to
10 219 soil water tensions using transformations based on simple soil physics (Edmunds and Bath,
11 220 1976). Samples with water extracted up to ~200 kPa were spun again at a speed
12 221 representing ~1100 kPa to sample water held between ~ 200 and 1100 kPa.

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15 222 The third extraction method involved cryogenic vacuum distillation. Two soil samples of
16 223 each horizon were collected in 40 mL vials, sealed with parafilm, and frozen until analyses.
17 224 Cryogenic extraction was carried out in the Surface Chemistry and Catalysis laboratory,
18 225 University of Aberdeen, following the procedure of West *et al.* (2006). Due to relatively high
19 226 water content, extraction times were long (>2 hr), which limited the analyses to 2 samples
20 227 for each horizon and for the upper two soil depths only. After extraction, samples were
21 228 oven dried (105°C) for 24 hrs. Pre and post drying weight was compared to determine
22 229 extraction efficiency. Full extraction efficiency (no difference in pre and post drying weight)
23 230 was achieved for all samples.

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26 231 For the forested sites, xylem samples were collected from three mature trees using an
27 232 increment borer during the two more extensive soil sampling campaigns. Trees were
28 233 selected based on their vicinity to the soil water sampling site (Figure 1). Storage and
29 234 cryogenic extraction followed the same procedure as the soil samples. One xylem water
30 235 sample for the Podzolic soil did not achieve full extraction efficiency. The stable isotope
31 236 analysis result of this sample was therefore excluded from the analyses here.

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33
34 237 Precipitation, stream and soil water samples were analysed for stable isotope composition
35 238 with a *Los Gatos* DLT-100 laser liquid water isotope analyser following standard protocols.
36 239 Data are provided in the δ -notation (‰) relative to the Vienna Standard Mean Ocean Water
37 240 (VSMOW) and the precision of measurements is $\pm 0.6\text{‰}$ for δD and $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$. It is
38 241 known that water extracted from both soil and vegetation samples may contain organic
39 242 contaminants which can interfere with the laser isotope ratio spectroscopy (West *et al.*,

2010). This is typically strong for vegetation samples (e.g. Zhao *et al.*, 2011), while often minor for soil water samples (Schultz *et al.*, 2011). *Los Gatos* software was used to identify any sample contamination (cf. Schultz *et al.*, 2011; West *et al.*, 2011). For the samples in this study, we found that only vegetation samples were contaminated by small organic components. We therefore treated these with activated charcoal to reduce the concentration of organics from the water samples (c.f. West *et al.*, 2010) and analysed them using traditional isotope ratio mass spectrometry, to avoid laser contamination effects. These samples were analysed at the Scottish Universities Environmental Research Centre (SUERC) Mass Spectrometry Facility Laboratory in East Kilbride. The precision of these stable isotope measurements is $\pm 2.0\text{‰}$ for δD and $\pm 0.5\text{‰}$ for $\delta^{18}\text{O}$.

To identify differences between different soil and xylem waters across the four monitoring sites, their isotope signatures were compared against their location with respect to the global and local meteoric water line. This was also used to test for any evaporative fractionation effects in any of the source waters. Furthermore, the results of the two extensive field sampling campaigns were evaluated within the longer term context of precipitation, stream and mobile soil water time series.

4. Results

4.1 Hydroclimatological conditions

The study period included an unusually dry and warm summer with relatively little precipitation, high evapotranspiration and low discharge rates (Figure 2). Compared to long term hydroclimatological averages, similar dry periods have an estimated return period of 1 in 10 years (NHMP, September 2013; Geris *et al.*, 2015b). When analysed for the total study period, precipitation inputs (240 mm) were low compared to stream discharge (120 mm) and potential evapotranspiration (333 mm) outputs, resulting in a considerable decline in catchment average storage. Figure 2 shows that there were two distinct periods with no precipitation (9 days in early June and 18 days during early to late July). This is atypical for the eastern Scottish Highlands which are generally characterised by year-round low intensity but frequent precipitation. The isotope composition of precipitation inputs during the study period was enriched (weighted δD mean = -52.0‰ ; standard deviation = 17.7‰) in comparison to long term averages (weighted δD mean = -59.1‰ ; standard deviation =

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3 273 21.1 ‰), but in line with expected seasonality. Stream water isotope signatures
4
5 274 demonstrate considerable damping, suggesting significant mixing of event and old
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7 275 precipitation water before it enters the stream.
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9
10 276 Table 1 shows the hydroclimatological conditions during the two extensive soil and tree
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12 277 xylem sampling campaigns on June 11th and July 22nd. These were specifically targeted to
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14 278 coincide with the end of the two periods with low precipitation. Although the conditions
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16 279 were relatively dry during both days, July 22nd experienced higher air temperatures and
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18 280 potential evapotranspiration rates than June 11th. In addition, the second day was later in
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20 281 the growing season and the catchment was generally drier (Table 1; Figures 2-3).

21 282 **4.2 Soil water storage**

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23 283 Considering the dry summer 2013 conditions, the dynamic soil water storage changes in the
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25 284 Histosols were relatively small (Figure 3). Compared to the Histosols, the Podzols
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27 285 experienced stronger drying. This resulted in reduced extractable water availability for
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29 286 sampling, particularly in July. In general, the storage changes in the upper soil profiles were
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31 287 most marked, and also more variable for the Podzols than in the Histosols. However, as a
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33 288 result of the two exceptionally dry periods, the VSM content during the extensive sampling
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35 289 days was, although overall still high, relatively dry for these four specific soil-vegetation
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37 290 units, mainly in July (see also Figure 3). In particular for the tree cover sites, the upper soil
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39 291 horizons (as measured at the 0.1 m depth) VSM readings were as low as 0.47 for the
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41 292 Histosol (Hf) and 0.16 for the Podzol (Pf) during the July sampling campaign.

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43 293 The soil water isotope time series in mobile waters extracted from lysimeters showed that
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45 294 for most soil horizons, but particularly the surface horizons, there was a general shift
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47 295 towards more enriched samples up until the end of July, after which more depleted samples
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49 296 were observed (Figure 3). This can be directly related to a high input of relatively depleted
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51 297 precipitation at the end of July and beginning of August (Figure 2). Overall, there was more
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53 298 variability in the isotope signatures of the drier, freely draining Podzols in response to
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55 299 precipitation inputs than in the wetter Histosols. The mobile water at all sites was most
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57 300 enriched during the two extensive sampling campaigns, in the context of the study period
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59 301 timeseries at a particular site (Figure 3). This was not the case for the Hf site, where the
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3 302 isotopic composition of the July sample was slightly more depleted than the earlier summer
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5 303 samples, although these differences were small.

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7 304 There are four main observations on the soil water isotope signatures from the different
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9 305 extraction techniques. Firstly, overall, water that was held at higher inferred tensions was
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11 306 more depleted than the more mobile water (Table 2; Figures 4-5), suggesting some degree
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13 307 of separation. This was observed when comparing the results from the three extraction
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15 308 techniques (porous Rhizon samplers > centrifugation > cryogenic extraction). However,
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17 309 there was no clear difference between water samples obtained by extraction at different
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19 310 centrifugation speeds. In addition, the analyses indicated that separation was strongest in
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21 311 the upper soil profile at 0.1 m.

22 312 Secondly, the patterns observed are consistent for all four soil-vegetation units, with the
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24 313 caveat that the relatively dry conditions of the Podzols, and the rather small soil core
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26 314 sampling size, limited the water that could be extracted via the centrifugation method.
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28 315 Nevertheless, the overall patterns are similar across the four sites, even in the absence of
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30 316 centrifugation data. This suggests that any isotopic separation appeared to be independent
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32 317 of soil type as well as vegetation cover. However, in general the Podzolic soil waters were
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34 318 more enriched than those of the Histosols and therefore reflected more recent precipitation
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36 319 inputs. This observation could be related simply to the more freely draining nature of the
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38 320 Podzols, with lower moisture content available for mixing and shorter residence times in
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40 321 general.

41 322 Thirdly, Figure 5 demonstrates that the June and July sampling trips both showed similar
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43 323 separation patterns. Moreover, there was no clear difference between specific samples (i.e.
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45 324 the July samples are in general not more or less enriched than the June samples). This may
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47 325 imply that the separation was consistent during the monitoring period and provides a
48
49 326 justification for bulking of June and July samples in all other Figures and Tables.

50 327 Finally, there is very limited evidence to suggest strong evaporative fractionation of any of
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52 328 the soil water samples. Although mobile waters sampled with the Rhizon samplers were
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54 329 more enriched than the more tightly bound waters, there was little to no major deviation
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56 330 from the meteoric water line at most sites (Figure 5). The strongest indication of such
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3 331 fractionation effects is evident for the forested Podzol (Pf) site, in the upper soil profile at
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5 332 0.1 m depth in the O Horizon.
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10 334 **4.3 Water stores and vegetation water sources**

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12 335 Like the previous plots, Figure 6 demonstrates that there is a vertical profile in the isotope
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14 336 signatures of the mobile soil waters for all sites, showing the most depleted waters at
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16 337 greater depths. There is also a strong overlap between the soil water, in particular for the
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18 338 Histosols in the riparian zone, and stream water as indicated by their respective isotope
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20 339 compositions. Figure 6 shows the soil waters of forested sites only, but data (not shown
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22 340 here) demonstrated similar overlaps for the non-forested sites (see also Tetzlaff *et al.*, 2014;
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24 341 Geris *et al.*, 2015a). Both summer (May-August 2013) and the previous winter (November
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26 342 2012-April 2013, from Geris *et al.*, 2015a) mobile soil data were included to assess potential
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28 343 tree water sources and account for any delay in water uptake. The summer soil water data
29
30 344 also include the results from the centrifuged and cryogenically extracted samples. Overall,
31
32 345 all of these summer soil water data largely plot in the same space as the stream data (Figure
33
34 346 6). This indicates there is no strong evidence to suggest that there is a marked isotopic
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36 347 separation between the water stored in the soils available for vegetation uptake and that
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38 348 reaching the stream.

39
40 349 The space in which the isotope composition of Scots Pine xylem waters plotted was similar
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42 350 to the soil and stream water, but different for the two soil types. Xylem samples in cores
43
44 351 taken from trees growing on the Histosol site (Hf) generally plotted slightly below the
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46 352 meteoric water line and in a different space from stream water as well as summer soil
47
48 353 waters sampled there (Figure 6), though the depleted deuterium values were more similar
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50 354 to winter soil waters (open symbols in Figure 6). They also did not plot directly on the
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52 355 evaporative line of any of the soil waters. For the trees growing on the Podzolic soil (Pf),
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54 356 most xylem samples plotted directly on the meteoric water line and within the space of
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56 357 both soil and stream water. However, one sample showed some evaporative fractionation
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58 358 effects and plotted in the space of soil water samples that were extracted using
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60 359 centrifugation and cryogenic extraction (i.e. potentially representing water held at higher
360 360 tensions) from the upper profile.

361

362 **5 Discussion**363 **5.1 Soil water storage and flow partitioning for different soil types**

364 The results of the various extraction techniques indicated that water held in the smaller
365 pores was generally more depleted than the mobile soil water. Although a different climate
366 regime and set of soil types, these results are consistent with previous studies using
367 different extraction techniques to determine soil water isotopes (e.g. Landon *et al.*, 1999;
368 Figuéroa-Johnson *et al.* 2007; Brooks *et al.*, 2010). The results could suggest that for all four
369 soil-vegetation units, and for a prolonged period of time (> 1 month), the mass transfer
370 between mobile and less mobile subsurface pores was low, as indicated by the isotopically
371 distinct soil water pools. The more depleted bulk water samples appeared to reflect older
372 winter precipitation inputs and be less affected by summer evaporation. Consistent with
373 basic soil physics, this suggested that the water held at high tensions is older than that held
374 at lower tensions, and it is less mobile. However, although the soils in this study experienced
375 drying, the moisture content remained relatively high throughout the study period, apart
376 from in the forested Podzol. In particular during the June sampling campaign, VSM data
377 were still comparable to conditions during wetter winter periods at most sites (see Tetzlaff
378 *et al.*, 2014). Several previous laboratory and field investigations have shown that
379 particularly at lower water contents, soils have greater fractions of immobile water and
380 slower mass transfer between the mobile and immobile regions (Padilla *et al.*, 1999; Tang
381 and Feng, 2001; Zhao *et al.*, 2013). Our results suggest that in humid, low energy
382 environments, similar effects are evident even when soils still remain relatively wet. The
383 difference is that our study was set in an energy limited system, rather than a water limited
384 system as reported elsewhere.

385 It has recently been identified that soil chemical properties (in particular high clay cation
386 exchange capacities, CEC) could also cause isotopic separation in soil waters (Aragúas-
387 Aragúas *et al.*, 1995; Meißner *et al.*, 2013; Oerter *et al.*, 2014). Although we do not have
388 data on cation exchange capacity and clay content, the soil parent material is generally
389 glacial drift comprised of silty-sand and larger clasts. The clay content is usually low in
390 mineral horizons and very low in organic horizons, where cation exchange sites will be on

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3 391 organic substances. At three nearby sites with similar soils, Barton *et al.* (1999) found CEC
4 392 values in the order of 1-5 mmol/kg. Furthermore, the study by Oerter *et al.* (2014) indicated
5 393 that such cation exchange capacity effects were only strong for VSM on the order of 0.05
6 394 and significantly decreased at 0.30. In this context, water content in this study was relatively
7 395 high, in particular for the June sampling campaign, and clay content was generally low.
8 396 Hence, this would suggest that any soil property effects related to clay content cation
9 397 exchange were small. This is further supported by similar separation occurring across the
10 398 different soil-vegetation units. However, we recognise that, in order to fully understand the
11 399 mechanisms that drive soil water storage and flow separation at our site and at any other,
12 400 further testing that considers pH, temperature, microbiological activity and other factors
13 401 that could potentially affect the isotope composition of soil water would be required.

14 402 The isotopic differences between the three extraction techniques were relatively small. The
15 403 maximum difference in δD between mobile and bulk water was on the order of 10‰, and
16 404 often less (Table 2). This is less than half the δD range observed annually in highly damped
17 405 stream water (around 25‰, varying between extremes of -75.2‰ to -49.6‰, see Geris *et al.*,
18 406 2015a). In addition, the 10‰ difference was observed only between extraction techniques
19 407 that sampled water held at tensions to the most extreme, while little to no differences were
20 408 found between water extracted at the different centrifuge rotations. Furthermore, the
21 409 depletion in the bulk soil water was also still far less than the observed range of
22 410 precipitation in the previous winter, which is up to -142.9‰ (Geris *et al.*, 2015a).
23 411 Multifactorial experiments with suitable statistical analyses could establish the significance
24 412 of actual differences between the results from different extraction techniques and soil
25 413 water depths. However, the limited data collected here are too small a sample size to meet
26 414 the underlying criteria needed for rigorous statistical testing. Although the results here do
27 415 indicate certain patterns as described above, further sampling would be required to fully
28 416 confirm or refute differences between soil water sampling techniques.

29 417 Apart from the upper soil profile of Pf, we did not find strong evaporative fractionation in
30 418 the bulk soil water, contrary to what was observed in earlier studies by Brooks *et al.* (2010)
31 419 and Goldsmith *et al.* (2012). One explanation is that soil evaporation is much more limited in
32 420 energy-limited hydroclimatic regimes where soils remain wet (Barnes and Turner, 1998).
33 421 Previous work at the same site over a 2 year period less affected by drought than in the

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2
3 422 current study also found very limited evaporative fractionation effects in mobile soil water
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5 423 and only under the driest conditions (Geris *et al.*, 2015a). An alternative explanation is that
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7 424 such fractionation in the bulk water has a limited effect on the isotopic composition as the
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9 425 soil water content is relatively high and only a small proportion of the total water which is
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11 426 held in the larger, more aerated pores in the upper profile, is affected. However, in this case
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13 427 we might have expected to find fractionation effects in the soil water samples that were
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15 428 centrifuged twice. Our results did not indicate that this was the case. In general though, our
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17 429 comparative results agree with other studies that found less difference between mobile and
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19 430 more tightly bound water for wetter soils and at greater depths (e.g. Zhao *et al.*, 2013).

20 431 **5.2 Vegetation water use**

21
22 432 When compared with the isotopic composition of potential water sources, xylem water can
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24 433 provide insights into the water assimilated by trees. Assuming no fractionation at the time
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26 434 of uptake or during transport within the trees (Ehrlinger and Dawson, 1992), plant xylem
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28 435 water should have the same isotope ratios as subsurface water which will ultimately reach
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30 436 stream networks, assuming complete mixing of subsurface water occurs. However, the
31
32 437 studies by Brooks *et al.* (2010) and Goldsmith *et al.* (2012) showed strong isotopic
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34 438 separation between xylem water on the one hand and mobile and stream water on the
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36 439 other, which was consistent throughout the season. In addition, they found that the xylem
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38 440 water also indicated strong fractionation effects from evaporative processes and mostly
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40 441 resembled bulk water that was extracted via cryogenic extraction. This suggested that tree
41
42 442 water uptake was preferentially sourced from tightly bound subsurface soil water. Earlier
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44 443 work by Dawson and Ehrlinger (1991) also demonstrated that riparian trees did not use
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46 444 water from the stream but from deeper groundwater sources, although their study was
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48 445 limited by the use of $\delta^{18}\text{O}$ alone. Only when both stable isotopes are compared against the
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50 446 meteoric water line, can different water stores and evaporative enrichment be explored in
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52 447 greater depth.

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54 448 Our preliminary vegetation water analyses showed that most samples plotted in the same
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56 449 meteoric water line space as the soil water samples, although others not. There were
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58 450 contrasting results between different soil-vegetation units and also within one unit (notably
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60 451 the forested Podzol site, Pf). However, in all cases, the space in which the xylem isotope

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3 452 composition data plotted was different in comparison to results of earlier studies, which
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5 453 showed a 'below the meteoric water line' grouping between bulk soil waters and xylem
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7 454 waters (Brooks *et al.*, 2010; Goldsmith *et al.*, 2012). We did not find strong connections
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9 455 between these two, neither between xylem water and any of the sampled soil or stream
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11 456 water.

12
13 457 There are multiple working hypotheses to explain the observed xylem water data. For the
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15 458 Podzol site, most xylem samples did actually plot on the meteoric water line (MWL) and in
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17 459 the same MWL space as soil and stream water. These data could indicate that trees do not
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19 460 use water from a distinct subsurface water pool and hence, the lack of evidence for isotopic
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21 461 separation at this site. However, one or two samples do show some effects of evaporative
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23 462 fractionation and plot in a similar MWL space to the more tightly bound water in the upper
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25 463 10 cm of the soil profile. Several studies across northern environments have demonstrated
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27 464 that for Scots Pine most of the fine root production and turnover is in the humus layer (i.e.
28
29 465 upper few cm) and upper 0.1 m (Roberts, 1976; Persson, 1980; Bishop and Dambrine, 1995;
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31 466 Čermák *et al.* 2008). This is above the uppermost sampling depth, though this is also where
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33 467 evaporation is highest (as hinted in the July Pf 0.1 m isotope samples). As the soils never
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35 468 dried out during the study period, moisture in the 0 – 0.1 m depth was still likely to be plant
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37 469 available, but also likely to have been fractionated due to soil surface evaporation.
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39 470 Moreover, the soil atmosphere would have been increasingly aerated as the soil dried,
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41 471 which may have allowed the soil water to start to re-equilibrate with the air as well. Thus, a
42
43 472 possible hypothesis for the evaporated signal in some plant water samples is that the upper
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45 473 0-10 cm could be the source of the majority of tree water in summer when the xylem
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47 474 samples were collected. However, this does not imply that the trees preferentially take up
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49 475 water from either tightly bound or mobile water, as was previously argued in the context of
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51 476 the 'two water worlds' hypothesis. Although sampling tree root distributions was beyond
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53 477 the scope of this work, the location of the majority of fine roots in the upper 10 cm of the
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55 478 soil is consistent with the literature on Scots Pine (Roberts, 1976; Persson, 1980; Bishop and
56
57 479 Dambrine, 1995; Čermák *et al.* 2008).

58
59 480 While this hypothesis would be the most likely explanation for the evaporated xylem waters
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481 of the trees at the Podzol site, the xylem data for the trees on Histosols largely do not lie
482 within any evaporative MWL of near surface soil water as observed during the study period.

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3 483 However, highly depleted winter isotopes were observed at site Ht (Geris *et al.*, 2015a;
4 484 Figure 6), from which the Ht xylem water could have been sourced, although also subject to
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6 485 some evaporative fractionation. In addition to the processes described above, this might
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8 486 imply that the apparent slight separation between xylem and soil/stream water could have
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10 487 been exacerbated by slower tree water uptake influencing its isotopic composition
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12 488 compared to the soil water. Long residence times of water transport in trees, in
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14 489 combination with suppressed transpiration during and just after rainfall events could cause
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16 490 such delays (Brandes *et al.*, 2007; Penna *et al.*, 2013). Scots Pine growth rates in Scotland
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18 491 are low, especially on acidic Histosols which are waterlogged and nutrient poor. Sapflow
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20 492 values in the literature suggest that water movement in Scots Pines is relatively slow in the
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22 493 order of 1 to 6 mm d⁻¹ (Köstner *et al.*, 1996; Brandes *et al.*, 2007). Moreover, a very cold
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24 494 spring preceded the warm, dry summer with temperatures well below average well into
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26 495 May which could have delayed the onset of transpiration in this particular year.

27 496 Another hypothesis to explain evaporated plant water signals could be related to internal
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29 497 physiological processes within the tree. Several field and laboratory studies have
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31 498 demonstrated that no isotopic fractionation takes place at the time of uptake or during
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33 499 transport within the trees until the water reaches the leaves where transpiration from the
34
35 500 leaf surface causes isotopic enrichment of leaf water (Ehrlinger and Dawson, 1992; Brunel *et al.*,
36
37 501 1994). However, a few studies have demonstrated some isotopic enrichment of xylem
38
39 502 water that could be linked with either stem cuticular evaporation (Dawson and Ehleringer,
40
41 503 1993), although this is most common for young deciduous trees, and/or xylem-phloem
42
43 504 exchange (Cernusak *et al.*, 2005; Bertrand *et al.*, 2014), and only under water stress. Neither
44
45 505 possibility can be ruled out, but given the soil moisture content, the mature Scots Pine trees
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47 506 in this study were unlikely to have experienced severe water stress.

48 507 Finally, we recognise that there are relatively limited numbers of xylem samples in this study
49
50 508 and clearly more data are needed to fully understand the interactions between water use,
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52 509 fractionation effects, and the apparent isotopic separation of soil water for some sites.
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54 510 Moreover, because of the large potential variability between trees within and between sites,
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56 511 a greater sample size is needed to characterise this heterogeneity. Although we aimed to
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58 512 sample trees of similar age, diameter and height, subtle differences between these tree
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60 513 characteristics are known to cause additional natural variability in xylem isotope data

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3 514 between trees, and for this reason sample sizes of at least one order of magnitude larger
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5 515 than deployed here might be advised (Goldsmith *et al.*, 2012).
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10 517 **5.3 Implications and future directions**
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12 518 Although the exact mechanisms remain unclear and are likely to be different from those in
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14 519 drier and more seasonal climates, this study has shown that soil waters in wet, low energy
15
16 520 northern catchments extracted under different tensions exhibit some minor isotopic
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18 521 differences. This could be associated with variations in fractions of immobile water and
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20 522 mass transfer between mobile and immobile regions. However, overall, there was no
21
22 523 marked separation from the stream water or the local meteoric water line, as has been
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24 524 reported previously. Furthermore, Scots Pine xylem water isotope data largely
25
26 525 demonstrated that there was minimal difference between the tree, soil, and stream water,
27
28 526 although some xylem samples suggested water uptake from evaporated near surface soil
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30 527 water. This study has not provided evidence that ecohydrological separation, consistent
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32 528 with the 'two water worlds' hypothesis occurs in wet, northern climates and further work is
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34 529 needed to explore the exact mechanisms that drive such processes. In addition, this study
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36 530 focussed specifically on a relatively dry period, assuming that if separate water pools' in the
37
38 531 soil and vegetation water would exist, it would be most extreme under these conditions. In
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40 532 comparison to the previous studies in wet Mediterranean climates, the isotopic separation
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42 533 found here was relatively small and did not show any effects of evaporative fractionation
43
44 534 despite the relatively high local evapotranspiration rates. As the study period experienced
45
46 535 an exceptionally dry growing season, it seems improbable that much stronger evaporative
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48 536 fractionation processes than those observed here are common at this site. It is therefore
49
50 537 unlikely that more marked isotopic separation in support of the 'two water worlds'
51
52 538 hypothesis would occur during wetter summers.

53
54 539 However, repeated sampling in wetter and colder conditions should be used to further test
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56 540 hypotheses regarding the extent and duration of the separation between mobile and bulk
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58 541 water as observed between June and July 2013. This is one of the first studies that
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60 542 specifically investigated such soil water storage and isotope separation in highly organic
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544 543 soils in higher latitude regions. As such, this study provides an important first step towards a

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3 544 better understanding of subsurface storage and transport, as well as tree water use. In
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5 545 particular, we showed that sampling of both mobile and bulk water may be needed to fully
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7 546 understand soil water hydrological processes. Additionally, because of the time scales
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9 547 involved in tree water transport, long term sampling of potential source water may be
10
11 548 needed to fully evaluate tree water use via xylem water isotopic composition. Future studies
12
13 549 will focus on further exploring the driving forces that could potentially separate tree and soil
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15 550 water.
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18 19 552 **6. Conclusion**

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21 553 We investigated soil water storage and flow separation in a humid, low energy boreal
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23 554 (Latitude 57°) environment in Scotland. We considered four representative soil-vegetation
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25 555 units that included forested (with Scots Pine (*Pinus sylvestris*)) and non-forested sites, and
26
27 556 two widespread soil types (Histosols and Podzols). Firstly, we examined whether subsurface
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29 557 soil water isotopic separation could be identified by comparing stable isotopes of soil water
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31 558 held at different soil water tensions. The isotope analyses showed that water that was held
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33 559 at increasing tensions was slightly more depleted than the more mobile water, and could
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35 560 therefore have been influenced by older (winter) precipitation. These patterns were
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37 561 independent of soil type, vegetation cover, and time during the growing season, although
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39 562 there was a slight tendency towards less separation with soil depth. However, no strong
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41 563 evidence of evaporative fractionation was found, apart from some minor effects in the
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43 564 upper soil profile of the forested Podzol site. Secondly, we explored how water use of
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45 565 vegetation, as identified by the xylem isotope composition, compared to the soil water
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47 566 stable isotopes. Overall, these data showed that xylem water was largely on the meteoric
48
49 567 water line and similar to soil and stream water. This suggests that there was no marked
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51 568 separation between these pools and no evidence to support the 'two water worlds'
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53 569 hypothesis. However, for the two soil types we found contrasting results which, for the
54
55 570 Podzol implied uptake of evaporated water from the near surface (upper 10cm) soil
56
57 571 horizons where fine root densities are concentrated. The trees of the Histosol site seemed
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59 572 to further exhibit a delayed response in their isotopic composition of xylem water compared
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573 to the soil water, possibly suggesting low rates of water uptake.

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575 **Acknowledgements**

576 The constructive comments and suggestions from two anonymous reviewers greatly
577 improved an earlier version of this manuscript. Jon Dick, Jason Lessels and Jane Bang
578 Poulsen are thanked for assistance with data collection; Audrey Innes for sample
579 preparation and assistance with the cryogenic extraction of water samples; Paula Craib for
580 glassware design; Colleagues in Prof. J. Anderson's lab for day-to-day assistance in cryogenic
581 extraction; Todd Dawson and Nathalie Schultz for providing information on extraction
582 techniques and the analysis of vegetation water; Hedda Weitz for help with the
583 centrifugation of soil samples; and Iain Malcolm and colleagues at the Marine Scotland
584 Freshwater Lab for providing meteorological data. We thank Jason Newton and the Scottish
585 Universities Environmental Research Centre (SUERC) Mass Spectrometry Facility Laboratory
586 in East Kilbride for the isotopic analyses of the xylem water samples. The European Research
587 Council ERC (project GA 335910 VEWA) is thanked for funding.

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For Peer Review

Table 1. Hydroclimatological and soil moisture conditions during the extensive soil and vegetation water sampling campaigns during the growing season

Hydroclimatological Conditions							
	Units	11 June 2013			22 July 2013		
Mean Air Temperature	°C	9.76			14.94		
Potential Evapotranspiration	mm d ⁻¹	1.86			3.19		
Discharge	mm d ⁻¹	0.79			0.41		
Precipitation	mm d ⁻¹	0.32			0		
Precipitation in Previous 3 days	mm	0			0		
Precipitation in Previous 7 days	mm	0			0		
Precipitation in Previous 14 days	mm	9.53			0		
Volumetric Soil Moisture Conditions (Daily Mean)							
	Units	11 June 2013			22 July 2013		
Depth (m)		-0.1	-0.3	-0.5	-0.1	-0.3	-0.5
Hs (Histosol/Sphagnum)	-	0.81			0.78		
Hf (Histosol/Scots Pine)	-	0.54			0.47		
Ph (Podzol/Heather)	-	0.31	0.26	0.25	0.23	0.22	0.21
Pf (Podzol/Scots Pine)	-	0.36	0.32	0.22	0.16	0.18	0.15

Table 2 Observed deuterium ranges in vegetation and soil water for all sites during the two extensive sampling campaigns during the growing season. Range values show min, max (mean). June and July samples are bulked.

Sampling		Hs		Hf		Ph		Pf	
		n	range	n	range	n	range	n	range
Vegetation		0	NA	6	-62.4,-48.8 (-57.3)	0	NA	5	-62.9,-41.8 (-53.6)
0.1 m Depth	Mobile	4	-49.8,-45.1 (-47.4)	4	-53.8,-46.4 (-50.8)	3	-43.7,-42.8 (-43.3)	3	-48.8,-45.1 (-46.7)
	< 200kPa	5	-58.3,-54.5 (-56.3)	5	-56.9,-54.0 (-55.6)	0	NA	0	NA
	< 700kPa	6	-57.7,-55.1 (-56.3)	7	-56.7,-53.9 (-55.2)	2	-44.3,-44.0 (-44.1)	1	-38.6
	< 1100kPa	7	-57.6,-54.2 (-56.5)	7	-57.2,-53.3 (-55.2)	3	-45.4,-44.2 (-44.7)	1	-39.3
	200 - 1100kPa	2	-56.1,-55.7 (-55.9)	2	-56.7,-55.8 (-56.3)	0	NA	0	NA
	Bulk	2	-59.6,-59.4 (-59.5)	2	-60.6,-54.8 (-57.7)	2	-55.1,-53.5 (-54.3)	2	-53.1,-52.5 (-52.8)
0.3 m Depth	Mobile	4	-58.2,-57.8 (-58.1)	4	-56.5,-54.9 (-55.9)	4	-52.8,-46.4 (-49.6)	3	-49.1,-48.7 (-48.9)
	< 200kPa	6	-59.4,-55.9 (-57.6)	5	-56.7,-54.3 (-55.2)	0	NA	0	NA
	< 700kPa	7	-58.0,-55.6 (-56.8)	7	-58.1,-53.1 (-55.9)	2	-46.2,-44.6 (-45.4)	1	-47.7
	< 1100kPa	6	-59.1,-55.5 (57.2)	7	-53.8,-53.3 (-56.3)	2	-45.8,-45.1 (-45.5)	1	-47.0
	200 - 1100kPa	3	-56.4,-55.7 (-56.0)	2	-56.7,-55.8 (-56.3)	0	NA	0	NA
	Bulk	2	-61.8,-59.5 (-60.6)	2	-60.8,-60.7 (-60.7)	2	-55.7,-54.7 (-55.2)	2	-63.6,-60.4 (-62.0)
0.5 m Depth	Mobile	0	NA	4	-57.9,-55.8 (-56.8)	2	-49.1,-48.9 (-49.0)	2	-55.1,-54.5 (-54.8)
	< 200kPa	8	-58.7,-55.9 (-57.4)	7	-58.0,-53.5 (-55.9)	0	NA	0	NA
	< 700kPa	8	-58.7,-56.9 (-57.9)	7	-57.6,-52.5 (-55.8)	2	-47.3,-46.9 (-47.1)	1	-53.4
	< 1100kPa	8	-60.1,-57.0 (-58.4)	8	-56.8,-54.1 (-55.7)	2	-48.2,-46.9 (-47.5)	1	-51.8
	200 - 1100kPa	3	-57.5,-56.0 (-56.6)	1	-56.3	0	NA	0	NA

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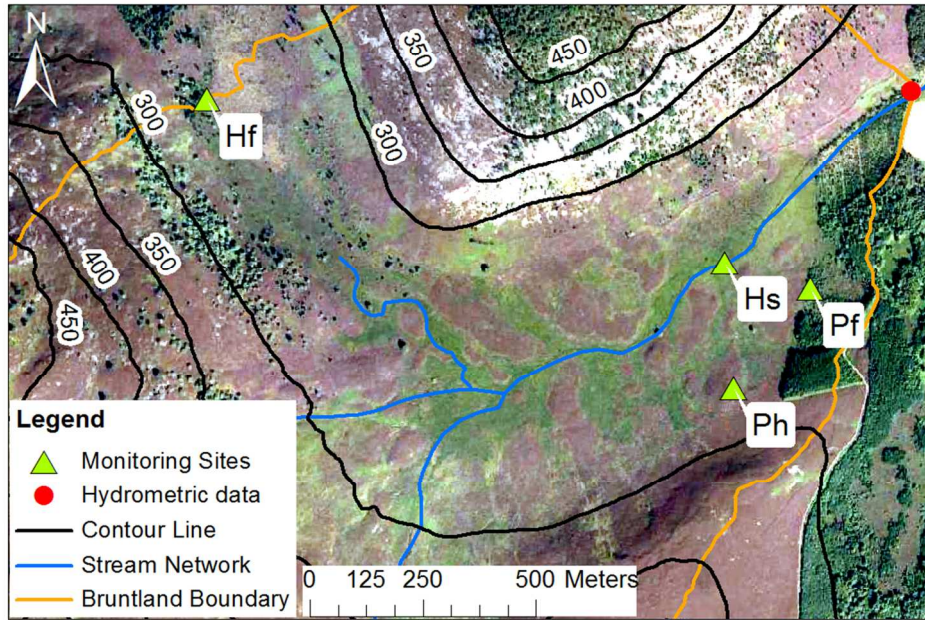


Figure 1 Bruntland Burn study area, showing the four monitoring sites, the topography, and vegetation distribution, where light green areas are peat bog, purple heather vegetation on freely draining soils, and dark green areas are forested.
190x142mm (300 x 300 DPI)

Review

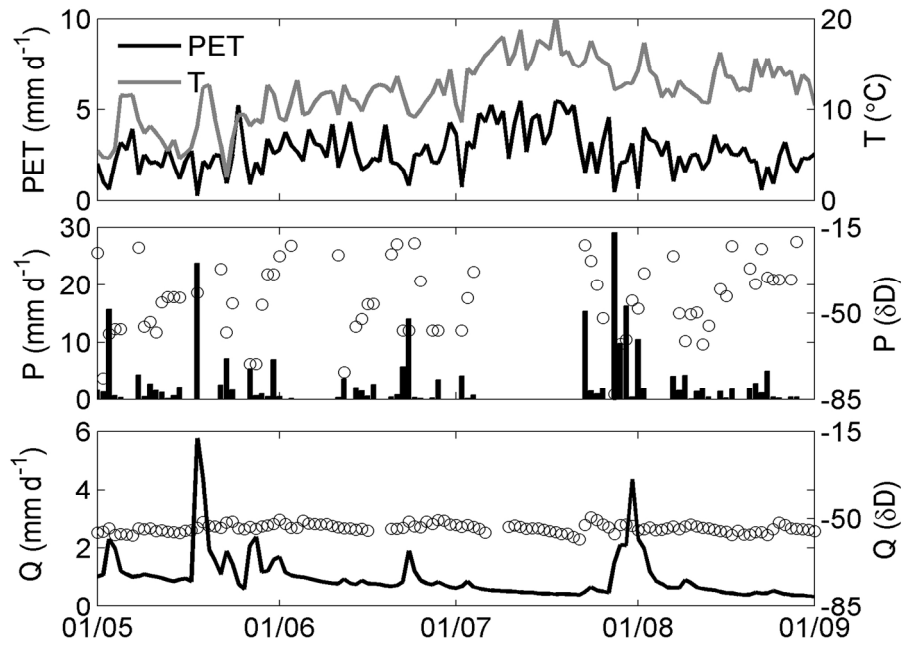


Figure 2 Hydroclimatic data (potential evapotranspiration, temperature, precipitation, and discharge) plots for May-August 2013, and deuterium data for catchment precipitation inputs and discharge outputs.
190x142mm (300 x 300 DPI)

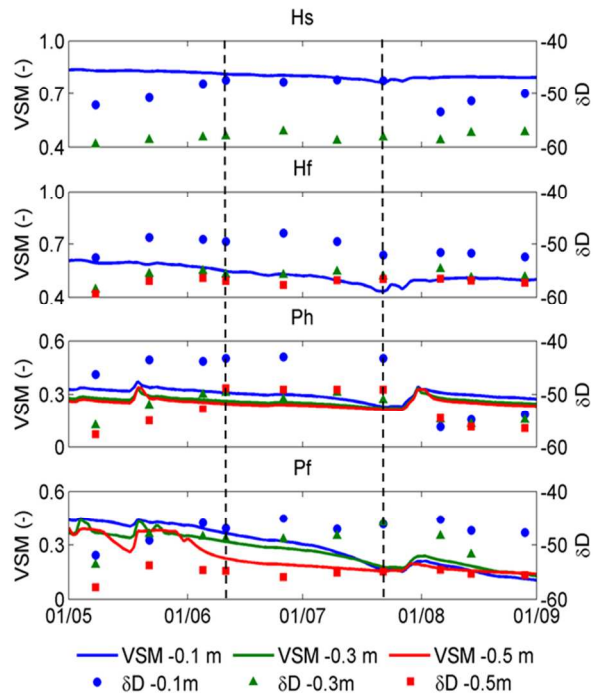


Figure 3. Temporal dynamics in volumetric soil moisture (VSM) and deuterium timeseries for the May - August 2013 period. Data for three sampling soil depths are shown (-0.1 m in blue, -0.3 m in green, and -0.5 m in red) for the four sampling sites: Histosols with Sphagnum (Hs) and Forest (Hf) cover, and Podzols with Heather (Ph) and Forest (Pf) cover. The dotted lines indicate times of sampling for other soil water extraction methods.

190x142mm (300 x 300 DPI)

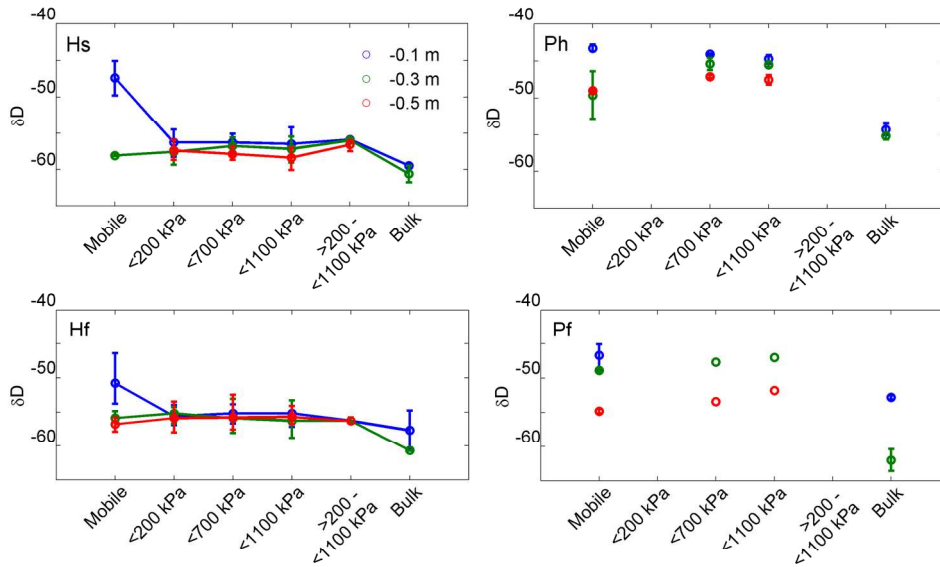


Figure 4. Soil water deuterium signatures for water extracted at different tensions. Data for three sampling soil depths are shown (-0.1 m in blue, -0.3 m in green, and -0.5 m in red) for the four sampling sites: Histosols with Sphagnum (Hs) and Forest (Hf) cover, and Podzols with Heather (Ph) and Forest (Pf) cover. June and July samples are bulked.
190x142mm (300 x 300 DPI)

view

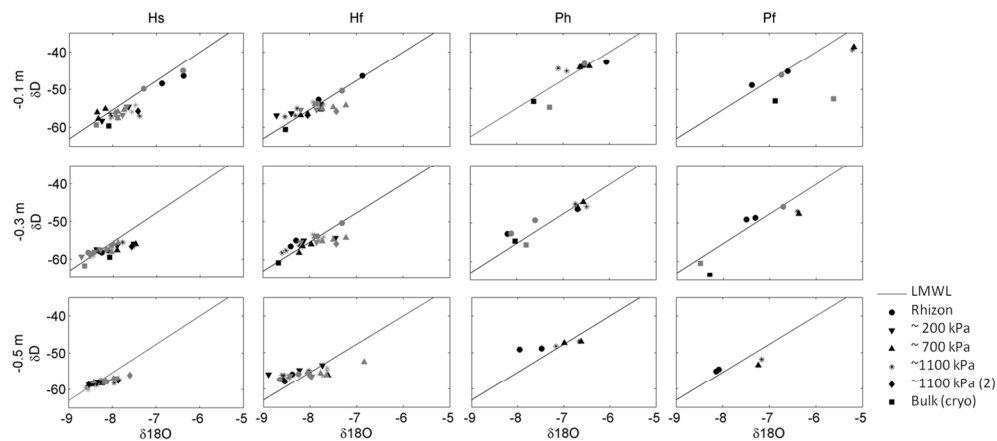


Figure 5. Soil water data for the four monitoring sites and three soil depths using different water extraction techniques representing water held at different soil water tensions. The black data are for the June collection; the grey for the July collection.
190x142mm (300 x 300 DPI)

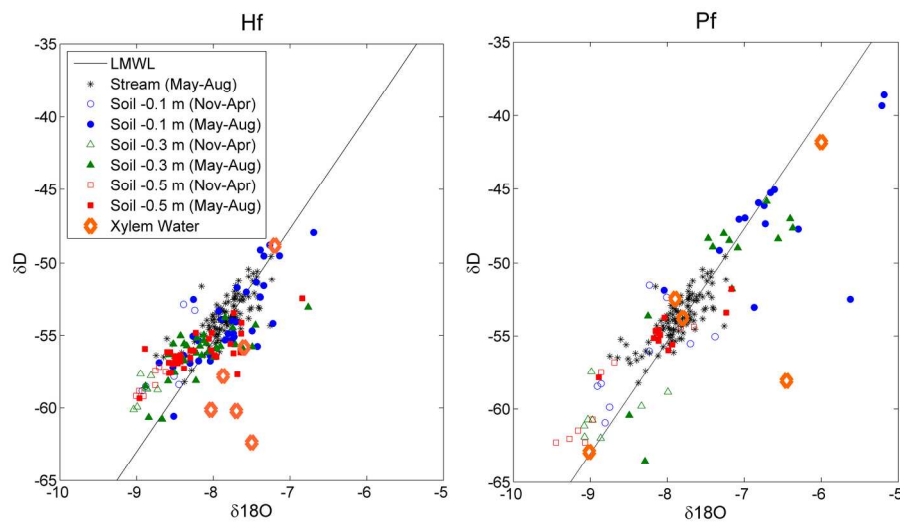


Figure 6. Isotope composition for stream water, soil water at the three sampling depths, and xylem water for tree covered sites with Histosol (Hf) and Podzol (Pf) soil types. The filled soil water symbols include mobile Rhizon, centrifuged and cryogenically extracted samples collected during the 2013 growing season. Open symbols indicate mobile soil water collected during the winter prior to the main monitoring period.

179x100mm (300 x 300 DPI)