Ecohydrologic separation of water between trees and streams in a Mediterranean climate

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Water movement in upland humid watersheds from the soil surface to the stream is often described using the concept of translatory flow1,2, which assumes that water entering the soil as precipitation displaces the water that was present previously, pushing it deeper into the soil and eventually into the stream3. Within this framework, water at any soil depth is well mixed and plants extract the same water that eventually enters the stream. Here we present water-isotope data from various pools throughout a small watershed in the Cascade Mountains, Oregon, USA. Our data imply that a pool of tightly bound water that is retained in the soil and used by trees does not participate in translatory flow, mix with mobile water or enter the stream. Instead, water from initial rainfall events after rainless summers is locked into small pores with low matric potential until transpiration empties these pores during following dry summers. Winter rainfall does not displace this tightly bound water. As transpiration and stormflow are out of phase in the Mediterranean climate of our study site, two separate sets of water bodies with different isotopic characteristics exist in trees and streams. We conclude that complete mixing of water within the soil cannot be assumed for similar hydroclimatic regimes as has been done in the past3,4.

Links between plant water-use (transpiration) and hydrology have been examined quantitatively since the paired-watershed studies in 1921 (ref. 5). These watershed-scale experiments clearly demonstrated links between vegetation and streamflow. However, the paired-watershed approach can only infer the mechanisms behind these vegetation–streamflow interactions6–8. Central to these inferred mechanisms is translatory flow downslope to the stream, and mixing of water within the soil profile1,2. Complete mixing of water in the subsurface is the central tenant of most watershed hydrology models today9,10. These concepts influenced ecology, leading to the idea that roots take up water from the same pool that is moving to the stream. However, is this really so? Using stable isotopes, Dawson and Ehleringer11 demonstrated complex interactions between plant water and hydrological pools, showing that some streamside trees used deeper groundwater instead of streamwater. Nevertheless, diel fluctuations in baseflow at watersheds around the world demonstrate clear interactions between transpiration and streamflow12.

Here, we directly explore links between hydrology and transpiration at the small watershed scale in a seasonally dry climate. Our central questions were: to what extent do trees and streams return the same water pool to the hydrosphere and how does this vary spatially within a watershed? These questions are fundamental to testing watershed hydrology models3,13 and coupled ecology–biogeochemical–hydrology models, which assume complete mixing of water moving through the soil towards the stream. Little if any empirical evidence exists to support or refute this assumption in humid regions. We examined δ18O and δ2H of rainfall, streamflow and in soil and tree water collected from 32 plots throughout a 10 ha

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Figure 1 | Water isotopes (δ18O and δ2H) of bulk soil water, xylem water, stream and estimated annual average precipitation. Isotopes were collected on three different dates at 32 plots randomly distributed across Watershed 10. LMWL represents the local meteoric water line (dashed line, based on autumn 2006 precipitation data, δ2H = 10.3 + 7.8 δ18O) and GMWL is the global meteoric water line (solid line, δ2H = 10 + 8 δ18O).
hydrologic dynamics during autumn 2006. a–d, Seasonal course of precipitation (a), soil moisture at six soil depths (b), precipitation δ18O (c) and stream flow (d). The grey bar in c represents the range of isotope values measured in the stream during this timeframe. Precipitation isotopes were collected at both the top and bottom of the watershed in 5 mm increments, except in December when the bottom collector malfunctioned and collected samples integrated over a week. Precipitation and streamflow δ2H values are not shown, but all samples fell on or very near the LMWL (Supplementary Fig. S4).

watershed at the H. J. Andrews Experimental Forest in Oregon. Our working hypothesis was that the δ18O and δ2H of soil and tree water from plots near the stream would be more isotopically similar to streamwater than plots located further away. However, we did not find any plots where soil or tree water was isotopically similar to the stream (Fig. 1). Isotope ratios from streamwater and the average annual precipitation weighted by volume were similar (−73.0‰ and −72.5‰ for δ2H and −10.7 and −10.8‰ for δ18O, respectively) and plotted on the local meteoric water line (LMWL), indicating that neither streamwater nor precipitation was measurably altered by evaporation. In contrast, all soil and tree water samples fell below the LMWL, indicating some evaporation. Surprisingly, vertical variation in soil–water isotopes at a single plot was much greater than spatial variation at any depth across the watershed (analysis of variance, F = 106.6 for depth, F = 2.9 for plots). Soil–water isotope ratios decreased with depth at all plots, from an average of −8.3 and −71.5‰ at 10 cm to −12.3 and −94.6‰ at 100 cm for δ18O and δ2H, respectively. This pattern was consistent for three different sampling times during two summers. Isotope ratios of tree water were similar to integrated values of the soil–water isotope ratios (−10.1 and −10.3‰ for δ18O and −85.7 and −81.0‰ δ2H for trees and soils, respectively). These findings suggest, paradoxically, that even in this steep, humid watershed, trees take up water from soil-water pools that do not contribute measurably to streamflow—and that streamwater shows no evidence of evaporative enrichment that is evident within the soil water during the dry summer. These two water worlds (mobile water expressed in the stream and tightly bound water represented by the plant water) are surprisingly distinct.

Although evaporation can account for the isotopic ratios falling to the right of the LMWL (Fig. 1), evaporation cannot account for variation along the line, particularly low isotope ratios found in soil water at depth: values that are lower than base-flow streamwater and the annual average precipitation isotope ratio. Furthermore, soil–water isotopic ratios collected in September 2004 were not correlated with isotopic ratios collected in August 2005 at the same depth and the same plot (P = 0.93, 0.73 and 0.50 for 100, 50 and 30 cm depths respectively), indicating that this tightly bound water is not the same year to year. Rainfall that occurred before sampling did not have isotopic ratios that could account for this pattern with
depth (Supplementary Fig. S1), leaving another paradox as to how these isotopic patterns were created.

We suggest that the observed depletion in heavy isotopes of water with depth is caused by soil–water recharge during the first large autumn rain event, whereby increasingly isotopically depleted precipitation through the event recharges deeper and deeper soil. We observed that precipitation isotope values (in 5 mm increments) ranged from $-3.7$ to $-23.2\%$ for $\delta^{18}O$ and from $-26.8$ to $-174.1\%$ for $\delta^2H$ during 2006 early autumn rain events, spanning the range of isotopic values found in the soil. Rainfall isotope ratios became more depleted through rain events, spanning the range of isotopic values found in the soil. Rainfall isotope ratios became more depleted through rain events resulting from Rayleigh distillation of heavy isotopes14,15 (Fig. 2c), such that $\delta^{18}O$ values similar to deep soil values during summer ($-14$ to $-12\%$) were frequently observed at the end of intense rainfall. During the first storm where large rainout effects were noted, we observed the largest annual increase in soil moisture (Fig. 2b, Supplementary Fig. S2), but this event had minimal impact on stream discharge (Fig. 2d). Once soil moisture had reached a maximum, stream discharge became responsive to precipitation (Fig. 2a,d). For example, the increase in stream discharge after the first big storm on 15 October accounted for only 4% of rainfall input, whereas after soil moisture was fully recharged on 2 November, discharge accounted for 55% of rainfall input, whereas after soil moisture was fully recharged on 2 November, discharge accounted for 55% of rainfall input, whereas after soil moisture was fully recharged on 2 November, discharge accounted for 55% of rainfall input.

Examine the interaction between soil–water recharge and the isotopic rainout effect during precipitation events reveals that precipitation isotopes were relatively enriched when the shallower soil–water content increased (Fig. 3). Later, when water content increased in deeper soil, the precipitation $\delta^{18}O$ values were markedly lower (approximately $-12\%$): the range observed at 1 m depth during the summer. We hypothesize that this interaction explains the pattern of soil-water isotopes observed during the dry summers.

It is striking that these first waters that wet-up the soil are able to persist in the profile through an entire rainy season. If the observed isotopic pattern of soil water during the summer (Fig. 1) came from initial autumn rainout events, then precipitation over the remainder of the year did not mix fully with water in those small pores. We tested this by comparing the isotopic content of tightly bound soil water with mobile soil water. We measured soil water collected in low-tension lysimeters, which represents mobile water, and bulk soil water extracted cryogenically16, which contains both mobile and matrix-bound water. For each collection when lysimeter water was present, bulk soil water was always more depleted in heavy isotopes than lysimeter water collected at the same depth and location (Supplementary Fig. S3). Isotopic fractionation is not likely because all water samples fall on the LMWL, are within the range of precipitation inputs (Supplementary Fig. S4) and advection processes do not fractionate water isotopically14. This difference between pools could occur only if tightly bound water did not fully mix with water moving through the profile.

Soil in this watershed has a bimodal distribution of pore sizes, with approximately 40% of pores greater than 0.3 mm and 45% smaller than 0.03 mm in the upper soil. Below 1 m depth, this ratio shifts to 70% of pores smaller than 0.03 mm (ref. 17). As the clay content is over 30%, many of these small pores would be similar in size to clay particles, which are less than 2 μm. As a result of interactions between matric and gravitational potential, pores with the smallest body size (the largest diameter of the pore) are the first to fill, and pores with the smallest neck size (the smallest diameter of the pore) are the last to drain. Therefore, pores with small diameters for both the body and neck fill first and drain last, thus containing water that would be relatively immobile compared with water in larger pores. As in saturated soils, hydraulic conductivity increases to the fourth power with increasing pore diameter, large pores would be the dominant pathway of water moving through the profile during the rainy season. However, during the summer once soils are below field capacity, the large pores that make the least tension to drain would be empty, and remaining soil water would be in small pores having matric potentials less than what gravity can drain. These pores have the longest water-residence time19,20 and probably have retained the same water that initially filled them during the autumn wet-up.

Primary forces in soils sufficient to drain smaller pores are tensions exerted by plant roots or direct soil evaporation. As evaporation from soil decreases rapidly with depth21, plant roots are primarily responsible for soil drying significantly below field capacity. As summer proceeds, progressively smaller pores would contain water held by lower matric potentials. We have observed...
soil matric potentials in Douglas-fir stands at −300 kPa at 1 m depth to −1,200 kPa at 20 cm depth22,23 and Douglas-fir roots can continue to take up water at water potentials below −1,500 kPa (ref. 24). Thus, plants are able to take up tightly bound soil water when mobile water is not available during the dry summer.

Our results indicate that for this seasonally dry watershed within the Cascade Mountains of Oregon, soil water is separated into two water worlds: mobile water, which eventually enters the stream, and tightly bound water used by plants. We conceptualize that during water worlds: mobile water, which eventually enters the stream, and the Cascade Mountains of Oregon, soil water is separated into two when mobile water is not available during the dry summer. Thus, plants are able to take up tightly bound soil water – continue to take up water at water potentials below water was collected hourly during storms and every 4–8 h between storms. Soil 29 and lower parts of the watershed using passive sequential samplers was present. Precipitation was collected in 5 mm increments at both the upper location. Xylem samples and soil samples were collected as outlined above, except another for gravimetric soil moisture measurement. In addition, several stream samples were collected at 32 locations next to permanent vegetation plots randomly distributed throughout the watershed covering the range of elevation and aspect. Samples were collected at 32 locations next to permanent vegetation plots randomly distributed across the sample and VSMOW. Measurement precision for the high-temperature conversion/elemental analyser was 1.5 and 0.2% for δ18O and δD, respectively, and for the laser spectrometer, precision was 0.5 and 0.2% for δ18O and δD, respectively.

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**Author contributions**

J.R.B. designed the research plan, obtained financial support, analysed and interpreted the data and wrote the paper. H.B. participated in data collection, analysis and interpretation, and contributed to the writing of the paper. R.C. coordinated sample collection efforts, led field crews and ensured the data quality of all field collections. J.M. advised throughout, assisted with interpretation of the results and contributed to the writing of the paper.

**Additional information**

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to J.R.B.