Opinion

The two water worlds hypothesis: ecohydrological separation of water between streams and trees?

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Recent work in ecohydrology has shown that in some forested watershed systems, streams and trees appear to return different pools of water to the hydrosphere. Thus far, evidence for this has come exclusively from wet Mediterranean climates. This short opinion article outlines the hypothesis and a research agenda for future work. The most pressing issue is the need to gather more data points whereby dual isotope-based studies in forested catchments compare samples of plant water and tightly bound soil water as well as mobile waters (soil, groundwater, and streamflow) in the catchment. New work is needed to test the hypothesis across different climates and vegetation regimes, especially places that contrast with the Mediterranean climates and forest types where two water worlds have been found. These include, but are not restricted to humid areas where plant water use and precipitation input are in phase, wetter zones where seasonality of precipitation is low, and drier zones where water stress is higher. Of equal importance to these basic research issues are the practical issues surrounding the sampling methods of plant and soil waters. Studies are needed to compare extraction techniques for low and high mobility soil waters and to understand the effect of sampling protocol on water isotope composition. Once these issues are resolved, high frequency sampling of soil and xylem waters will be especially instructive in development of mechanistic models of ecohydrological interaction—and an explanation for the hypothesis that is still wanting.

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INTRODUCTION

How water moves in forested, humid watersheds has been the focus of studies for almost a century.[1] Central to this work has been the concept of translatory flow[2] where water entering the soil surface as infiltrating precipitation displaces water held in the soil prior to the precipitation event and pushes it deeper into the soil profile and ultimately into the stream. A main tenant of forest hydrology is that trees transpire water that would otherwise form streamflow within a well-mixed subsurface reservoir. Brooks et al.[3] questioned this existing translatory flow[a] and single ecohydrological reservoir paradigm. They showed, for a humid but seasonally dry watershed in Oregon, USA, that tightly bound water in the soil (retained following the long summer dry season and used by trees) did not participate in the runoff process later on in the wet season. In other words, water was not displaced via translatory flow and did not mix with or displace mobile water and did not enter the stream. For that catchment, there were 'two water worlds': one water world used by trees and

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seemingly not contributing to streamflow and a second, mobile water world related to infiltration, groundwater recharge, hillslope runoff, and streamflow that possessed a character unrelated to the water taken up by trees.

Since Brooks et al.,[3] other studies have seen evidence in support of the two water worlds hypothesis, defined here as 'vegetation and streams returning different pools of water to the hydrosphere'. In forested watersheds in Mediterranean climates in Mexico[5] and in the Coast Range of Oregon[6] there have been similar observations of forests and streams, metaphorically, existing in the same key but playing to a different melody. While the significance of these findings has been commented upon,[7] the evidence is still in its infancy. Indeed, it is still puzzling why plants would 'prefer' water that is not easiest, energetically, to obtain. I argue here that posing the two water worlds hypothesis as a rejectable null hypothesis has value. This short opinion article serves to outline a research agenda for going forward with such testing and the pressing priorities for future research.

TWO WATER WORLDS: ABSENCE OF EVIDENCE OR EVIDENCE OF ABSENCE?

To understand the two water worlds hypothesis is to understand the cycling of the stable isotopes of water through a forest catchment. Figure 1(a) shows a stylized dual isotope plot of data derived from catchments where two water worlds have been observed. As with findings from humid catchments around the world, mobile water sampled from precipitation, suction lysimeter-derived soil water, groundwater, hillslope runoff (as sampled from a trench), and streamflow, all fall on the meteoric water line (Figure 1(a)). Like most data sets from such regions, precipitation spans the widest range of delta values, with a progressive damping of the extremes of heavy and light per mil values in soil water, streamwater, and groundwater. Prior to Brooks et al.,[3] we thought that if we sampled the xylem water of trees growing in humid catchments, the delta values would also fall on the meteoric water line, perhaps constrained within the range of soil water or groundwater values and in keeping with single isotope-derived estimates of plant water sources (see early important work by Dawson and Ehleringer).[8] Figure 2(b) shows what such xylem delta values actually look like in dual isotope space of the Brooks et al.[3] and Goldsmith et al.[5] studies: they plot on a slope considerably less than the local meteoric water line for precipitation in that region. This begs the question: Where are trees getting their water if soil water sampled via suction lysimeters falls on the meteoric water line?! It was not until soil samples were extracted and subjected to cryogenic extraction in[3] using methods of West et al.,[9] where all the water is removed and analyzed (down to -15 MPa) that the answer became obvious: tightly bound soil water. Of course, these data do not indicate how tightly bound the water is that the plants are using—simply that the water is held under greater tension than that sampled with a suction lysimeter and less than the extremes of plant water tension represented by the cryogenic extraction capability[b]. Such type and character of soil water is rarely examined in hydrologically based studies of soil water where mobility, as linked to flow and transport, is often the focus. In the case of Brooks et al.,[3] such cryogenically extracted water was always more depleted than the water sampled from suction lysimeters. Hence, the water that the trees were using was not the water found in the stream and the water in the stream is not the water that the trees were using. While now obvious in hindsight, such a distinction was not anticipated against the historical backdrop of displacement and mixing described by Hewlett and Hibbert,[2] and the many forest hydrology studies that followed.

PRESSING PRIORITIES FOR FUTURE RESEARCH

Clear, testable, well-posed null hypotheses are rare in hydrology and ecohydrology. I argue here that the two water worlds hypothesis is one such example. There are many pressing priorities for research going forward in this area. Chief among these, and beyond the scope of this commentary, are the plant physiological and soil physics underpinnings of this water use behavior. Evidence from the dual isotope approach in the context of the water worlds hypothesis indicates that plants are using more tightly bound soil water. Given that water moves through plants via gradients of water potential, the use of more tightly bound water remains counterintuitive. In short, we do not understand why plants would use more tightly bound water over less tightly bound water. How mycorrhizal fungi may facilitate extraction of the tightly bound water is also an important research question. These and other plant water use strategy questions remain open to scientific inquiry. Neither Ref 3 nor Ref 5 has yet provided a mechanism for the observed findings. But in the spirit of 'the isotopes don't lie', such mechanistic explanation must indeed follow. But before that, several pressing priorities for research remain to help facilitate such discovery. Regardless of whether or not the reader 'believes' in the hypothesis and the veracity

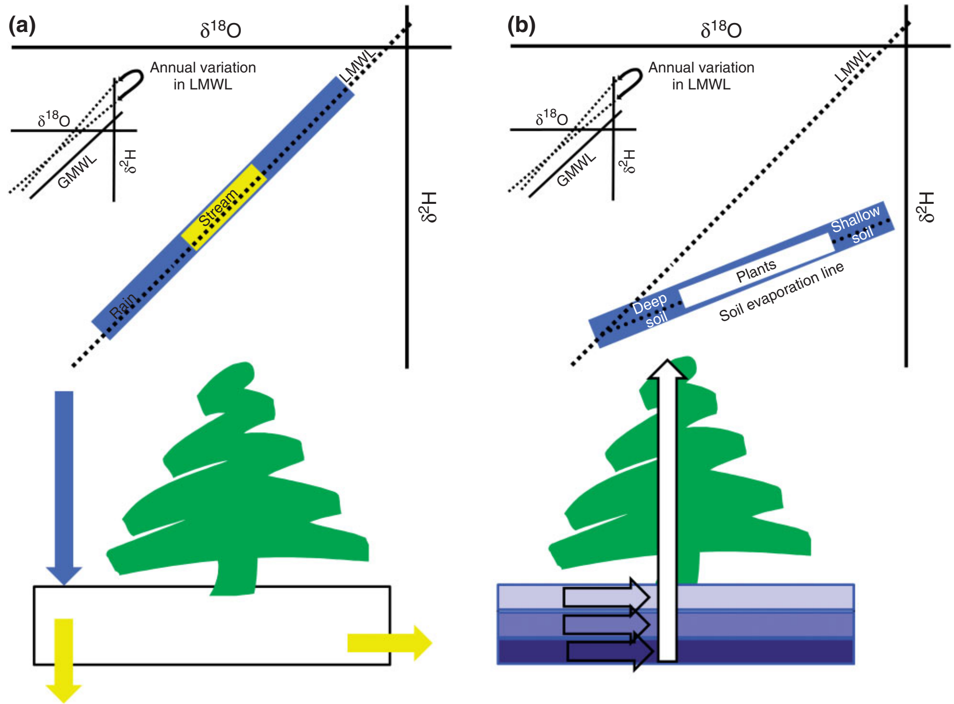

FIGURE 1 | The two water worlds hypothesis in diagrammatic form, showing (a) the mobile water mixing space and schematic representation of mixing and (b) the low mobility water mixing space and schematic representation of mixing. Streamwater is lagged and damped relative to the rainfall input signal and therefore represents a narrower distribution of isotope values. Similarly, the plant water values represent a narrower range than the tightly bound soil water, representative of the depth where water is extracted through the soil profile. Shallower soil waters plot farthest away from the meteoric water line (due to evaporation); deepest soil waters plot on the meteoric water line.

of the data in the papers that have yet shown it, these priorities have potential to advance more generally our understanding of hydrological–ecological linkages.

Going Beyond the Single Isotope Approach

While obvious, it is important to distinguish between the single (i.e., using ^{2}H or ^{18}O) versus dual isotope (i.e., both together on a meteoric water line plot) approach to determining plant water sources. Dual isotopes are needed for a two water worlds hypothesis test as the meteoric water line is the key reference point for evaporative enrichment and water pool differentiation. The early Dawson and Ehleringer[8] paper used a single isotope approach. Since then, many studies have appeared that have related xylem water to source waters using ^{18}O or ^{2}H. Single isotope studies continue to build on this work in quantifying the depth of water uptake by plants. Li et al.[10] quantified tree water sources in cold, semi-arid regions of Mongolia; Bertrand et al.[11] have explored the spatiotemporal variability of tree water uptake in Switzerland. Many studies in the tropics have used the single isotope approach to quantify tree water sources[12–16] and seasonally dry environments.[17,18] While these and many other studies have used either ^{18}O or ^{2}H to determine tree water sources in space and time, few beyond Brooks et al.[3] and Goldsmith et al.[5] have explicitly addressed the on–off the meteoric water line issue via the needed dual isotope approach. Where studies have used a dual isotope approach, the focus on plants has usually resulted in the absence of data on mobile waters and streamwater isotopes.[19–21] Where studies have used a dual isotope approach in hydrological studies, the focus on streamflow has usually resulted in the absence of data on plants.[22]

The Need for Dual Isotope Approaches from a Variety of Systems

Thus far, the two water worlds finding has really only been seen in Mediterranean climate regimes where precipitation input and the main transpiration output are out of phase. Systematic examination and testing of the two water worlds hypothesis across different climate and vegetation assemblages is most needed in areas where precipitation inputs and transpiration outputs are in phase. In very recent preliminary work, Penna et al.[23] suggested that xylem water in a small pre-alpine catchment in Italy was similar to soil and rain waters, but statistically different from streamflow and groundwater. They found no marked difference between the isotopic composition of the xylem water of trees located in the riparian zone versus those located on hillslopes. Other recent preliminary work from Scotland by Geris et al.[24] hints that the two water worlds hypothesis may not apply in the wet Scottish highlands with little precipitation seasonality. While no vegetation water was presented, they showed via centrifuge analysis that tightly bound soil water was similar to mobile water in the soil. Work elsewhere is urgently needed; across climate, vegetation, and soil types. Such systematic examination will be very helpful for hydrologists to understand where trees actively alter subsurface mixing and helpful to ecologists for (partially) informing plant-soil-climate coevolution.

The Need to Compare Soil Water Extraction Approaches

Soil water extraction approaches for mobile and immobile waters need urgent comparison. For mobile waters, Landon et al.[25] showed that isotope values for soil water collected from suction lysimeters and wick samplers differed because each sampling method collected different fractions of the total soil water reservoir. This discrepancy reflected the presence of relatively more and less mobile components of soil water. Unlike the collection of mobile waters via suction lysimetry and wick samplers, sampling of tightly bound soil water (and plant water) for isotopic analysis is difficult and extremely time-consuming. This is because it requires separation of the water from the plant or soil media via a lab-based extraction technique (azeotropic distillation, centrifugation, cryogenic extraction, etc.). Scrimgeour[26] provided an early review of the measurement of plant and soil waters isotope composition. While cryogenic extraction (where water is evaporated from the sample and condensed in a collection tube) represented a major advance over azeotropic distillation, many have commented on the extreme laboriousness of the approach.[27] Recent work has suggested procedures to reduce time for the cryogenic method[28] but still little, if any intercomparison (beyond important work in Ref 8) between each of the various techniques has been done.

The two soil water (or pore water) extraction intercomparison studies that have been done suggest differences between approaches. Kelln et al.[29] compared direct CO_2 core equilibration against mechanical squeezing, centrifugation and azeotropic distillation, and found differences in the completeness of the extractions between all techniques—in their case, different fractions of the clay water reservoir. More recently, Figueroa-Johnson et al.[30] compared water collected by centrifugation and azeotropic distillation to water collected by suction lysimetry. They found that the δ^{18}O of water from a sandy soil was about 0.25 per mil more negative when collected by centrifugation and azeotropic distillation than when collected by suction lysimetry. Additionally, for a well-structured soil, they found a greater difference, on the order of 2.0–7.0 per mil. However, their results were very preliminary.

More recently, a vapor-based pore water sampling approach has been introduced by Wassenaar et al.[31] that capitalizes on the new vapor laser spec machines. This method takes advantage of isotope ratio infrared spectroscopy where no extraction or distillation is necessary, thus significantly reducing the time necessary to prepare samples for analysis. The analysis speed of laser-based instruments is now leading to efforts designed to monitor changes in soil water isotope composition in the field in real-time.[32–34] This is in contrast to previous approaches that were limited to discrete time points. Of course, this holds much promise for easing the sampling and analysis of tightly bound soil and plant waters, as well as improving temporal resolution of the sampling. Despite these developments, work is urgently needed to compare values obtained via the vapor technique against cryogenic extraction. We still do not know if they allow interrogation of the same water.

Soderbery et al.[35] have recently reviewed measurement and modeling techniques for stable isotopes of water vapor in the vadose zone, however, intercomparisons of techniques remain limited. For instance, Garvelmann et al.[33] showed using their vapor approach for two hillslopes in the Black Forest, Germany, that sampled soil water was well linked to streamwater; but again, we still do not know how this compares to cryogenically extracted soil water. Lastly, more work is needed to quantify and resolve the discrepancies observed in the stable isotope values of plant and soil waters analyzed by isotope ratio infrared spectroscopy versus isotope ratio mass spectrometry as shown by West et al.[8,25]

Towards High Frequency Sampling of Soil and Vegetation Waters

High frequency sampling of rainfall and streamwaters with field deployed laser specs has commenced.[22] The same is needed in the context of two water worlds with an explicit focus on temporal resolution. A key to better coupled ecohydrological understanding will be elucidating the temporal dynamics of draining and refilling of soil water by plants. Most of the evidence for the two water worlds to date derives from very few data points, given the laborious cryogenic approach. We need studies in higher frequency that effectively ‘fill in the gap’ between plant and soil, and test explicitly the types of models shown in Figure 1(b). We need higher resolution sampling during times when refilling is occurring and we need to do that sampling with an eye to the time lags that are occurring between soil and tree water uptake. This goes beyond the useful work on the uptake of water from soil by tree roots (e.g., Refs 36 and 37) and focuses on tracing transport in the subsurface.[20] In the future, such work should be done with field-based vapor approaches once tested against the other standard methods as discussed above.

CONCLUSIONS

While all soil and plant waters are ultimately precipitation-derived (perhaps except for foliar uptake), the two water worlds hypothesis suggests a much more compartmentalized ecohydrological system. Phillips[6] termed this ‘wetness-dependent interconnectivity’. Such effects have important implications for how transpiration is linked to streamflow, how labile nutrients are flushed on forest hillslopes, and the nature of streamwater transit time distributions in forested catchments. This short opinion article has attempted to show the two water worlds hypothesis as a useful, rejectable null hypothesis that needs testing. There are many pressing research priorities for future work. Most pressing perhaps is the need for isotope-based studies in forested catchments to use a dual isotope approach and include samples of plant water and tightly bound soil water as well as mobile waters (soil, groundwater, and streamflow) in the catchment. Work is needed in contrasting climates and vegetation regimes, especially places that contrast with the Mediterranean climates and forest types where two water worlds have been found: humid areas where plant water use and precipitation input are in phase, wetter zones where seasonality of precipitation is low, and drier zones where water stress is higher. Of equal importance to these basic research issues are the practical issues surrounding the sampling of plant and soil waters. Studies are needed to compare extraction techniques for low and high mobility soil waters and to understand the effect of sampling protocol on water isotope composition. While promising, the new vapor laser spectrometer methods that facilitate simpler and quicker sampling need comparison against cryogenic extraction. Once these issues are resolved and understood, high frequency sampling of soil and xylem waters during times when refilling is occurring within the soil and within the plant will be especially instructive in the development of robust mechanistic models of how plant water use and streamflow generation combine within different ecohydrological regimes. Such work is a grand challenge in forest hydrology as the implications go well beyond academic exercise and water balance nuances (although the work suggested here should of course be complemented by traditional hydrometric measurements of key fluxes in small watersheds). It is hoped that this opinion is a useful starting point for organizing such research efforts.

NOTES

[a] Although much non-isotope-based literature has questioned the translatory flow concept in the past two decades based on evidence of preferential flow at plot and hillslope scales (e.g., Ref 4).

[b] Of course one would not expect plants to be using water held at −15 MPa—however, with present techniques, we lack the fidelity to sample water at tensions intermediate between ‘free water’ in a suction lysimeter and the −15 MPa water represented by cryogenic extraction.

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