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COMMENTARY

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Key Points:

- L-band satellite soil moisture effective depth of representation is often deeper than the commonly referenced 5 cm limit
- Isotopic tracer studies reveal common preferential plant water use of moisture in these upper soil layers either primarily or seasonally
- The optimal soil moisture product changes in time and space, with satellite soil moisture often being optimal for many vegetated surfaces

Supporting Information:

Supporting Information may be found in the online version of this article.

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Remotely Sensed Soil Moisture Can Capture Dynamics Relevant to Plant Water Uptake

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Abstract A frequently expressed viewpoint across the Earth science community is that global soil moisture estimates from satellite L-band (1.4 GHz) measurements represent moisture only in a shallow surface layer (0–5 cm) and consequently are of limited value for studying global terrestrial ecosystems because plants use water from deeper rootzones. Using this argumentation, many observation-based land surface studies avoid satellite-observed soil moisture. Here, based on peer-reviewed literature across several fields, we argue that such a viewpoint is overly limiting for two reasons. First, microwave soil emission depth considerations and statistical considerations of vertically correlated soil moisture information together indicate that L-band measurements carry information about soil moisture extending below the commonly referenced 5 cm in many conditions. However, spatial variations of effective depths of representation remain uncertain. Second, in reviewing isotopic tracer field studies of plant water uptake, we find a prevalence of vegetation that primarily draws moisture from these upper soil layers. This is especially true for grasslands and croplands covering more than a third of global vegetated surfaces. Even some deeper-rooted species (i.e., shrubs and trees) preferentially or seasonally draw water from the upper soil layers. Therefore, L-band satellite soil moisture estimates are more relevant to global vegetation water uptake than commonly appreciated (i.e., relevant beyond only shallow soil processes like soil evaporation). Our commentary encourages the application of satellite soil moisture across a broader range of terrestrial hydrosphere and biosphere studies while urging more rigorous estimates of its effective depth of representation.

1. Introduction

Global soil moisture retrievals from microwave satellites are now widely used across the Earth science community to study various topics related to the global climate system and its water, carbon, and energy cycles. While soil moisture in the unsaturated zone stores only 0.005% of Earth's water by volume (Bras, 1990), its position at the interface of the land and the atmosphere is of high value for understanding these global cycles (Koster & Suarez, 2001; McColl et al., 2017). As such, satellite-based soil moisture estimates are increasingly being used in studies of land-atmosphere interactions, numerical weather prediction, plant function and stress, and land surface response to climate change (Akbar et al., 2020; Dong et al., 2020; Feldman, Akbar, & Entekhabi, 2018; Feldman et al., 2022; Konings et al., 2017; Purdy et al., 2018; Santanello et al., 2019; Short Gianotti et al., 2020; Taylor et al., 2012; Tuttle & Salvucci, 2016).

However, there is now a frequently expressed viewpoint that microwave satellite soil moisture products are of limited use for studying vegetated landscapes because they sense only a superficial fraction of the rootzone.

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Across global studies using satellite-derived soil moisture, there is widespread, explicit mention of this limitation (Bassiouni et al., 2020; Denissen et al., 2020; Ford et al., 2014; Peng et al., 2017, 2021; Qiu et al., 2014; Sehgal et al., 2021). Some studies use this limitation as the basis for using modeled rootzone soil moisture data sets instead of satellite observations for land surface studies (Farahmand et al., 2021; Koster et al., 2019; Liu et al., 2020) or alternatively estimating a rootzone soil moisture (Calvet & Noilhan, 2000; Ford et al., 2014; Li et al., 2010; Scott et al., 2003). Others are less explicit, but may have similar reasoning for avoiding use of satellite soil moisture and favoring precipitation-based wetness indices or rootzone moisture products from model reanalysis (Li et al., 2021; Mueller & Seneviratne, 2012; Zhou et al., 2021).

A major contributor to this viewpoint is the history of the microwave remote sensing community generally offering a simplified view of a single, shallow observing depth of satellite-based retrievals. Modeling and field studies have characterized microwave emission profiles that are a function mainly of soil moisture (Shen et al., 2021; Tsang et al., 1975; Ulaby & Long, 2014), but the emission profiles are commonly simplified to single, conservative support scale values (see, e.g., Wilheit, 1978). Reflecting this, the Soil Moisture Active Passive (SMAP) and Soil Moisture and Ocean Salinity (SMOS) L-band satellite missions are often described as producing estimates of soil moisture within the top 5 cm of soil (Entekhabi et al., 2010; Kerr et al., 2010). Similarly, the Advanced Microwave Scanning Radiometer (AMSR) satellite series and the Advanced Scatterometer (ASCAT) (at higher C-band and X-band frequencies) are thought to observe only the top 1–2 cm of soil (Njoku et al., 2003). Other contributors to this viewpoint include the prevalent use of the top-most in situ sensors for assessing satellite soil moisture products (Chan et al., 2016), and a simplified intuition that the maximum rooting depth defines the relevant water uptake profile (Nippert & Holdo, 2015).

According to this viewpoint, if roots supply plants from soil layers down to maximum rooting depths that are meters below the top 5 cm, then L-band satellite soil moisture estimates have little value for the global study of terrestrial water, carbon, and energy fluxes, given that these fluxes can rely heavily on plant use of soil moisture (Jasechko et al., 2013; Katul et al., 2012). If satellite soil moisture retrievals were to hold more information about the rootzone, they could be considered more desirable than reanalysis products for some observation-based land-atmosphere and ecological applications; they are observations independent of model-prescribed linkages with other land surface variables and provide direct information about plant water use and evapotranspiration (Dong & Crow, 2019).

In fact, current evidence from soil moisture vertical coupling studies as well as microwave emission modeling and field experiments suggests that L-band satellite retrievals often represent soil moisture below the shallow (0–5 cm) surface soil layer. Under drier soil conditions, microwave emission models and field measurements show that microwave emission originates from layers below a depth of 5 cm (Liu et al., 2016; Lv et al., 2018; Moghaddam et al., 2000; Ulaby & Long, 2014). Under wetter soil conditions, studies show surface and rootzone moisture dynamics are often hydraulically connected and correlated despite soil evaporation acting to decouple these layers (Akbar et al., 2018; Ford et al., 2014; Qiu et al., 2014). This is because rootzone moisture is driven by surface forcing and has strong spatiotemporal memory resulting in similar soil moisture dynamics in the upper surface and deeper soil layers (though these conditions are reduced in dry climates with strong seasonal drying and consequent decoupling of upper and deeper soil layers) (Albergel et al., 2008; Crow et al., 2017; McColl et al., 2017). As a result, the effective vertical depth of representation, or support scale, of L-band satellite soil moisture retrievals have been shown to be deeper than 5 cm for wetter, coupled soil conditions (Akbar et al., 2018; Short Gianotti et al., 2019).

Furthermore, part of the argument to reject use of satellite soil moisture is an emphasis on the fact that maximum rooting depths can extend plant water uptake meters into the soil (Nepstad et al., 1994). However, this notion neglects the fact that active water uptake is rarely uniform across the rooting profile (Nippert & Holdo, 2015). Specifically, global observations and optimally modeled rooting profiles indicate that a large proportion of plants preferentially draw water from the upper soil layers to take advantage of these layers' pulse water and nutrient availability (Collins & Bras, 2007; Jackson et al., 1996; Nippert & Holdo, 2015). As such, not only soil evaporation, but also root water uptake can conceivably influence these upper soil layer moisture dynamics. Even for deeper-rooted vegetation, high sensitivity to upper layer soil moisture is also found based on findings of decreasing rooting biomass and root hydraulic conductance with depth (Nippert et al., 2012; Werner et al., 2021). Therefore, to learn about nominal plant water use and evapotranspiration, rootzone soil moisture products may not always need to integrate moisture dynamics down to the maximum rooting depth.

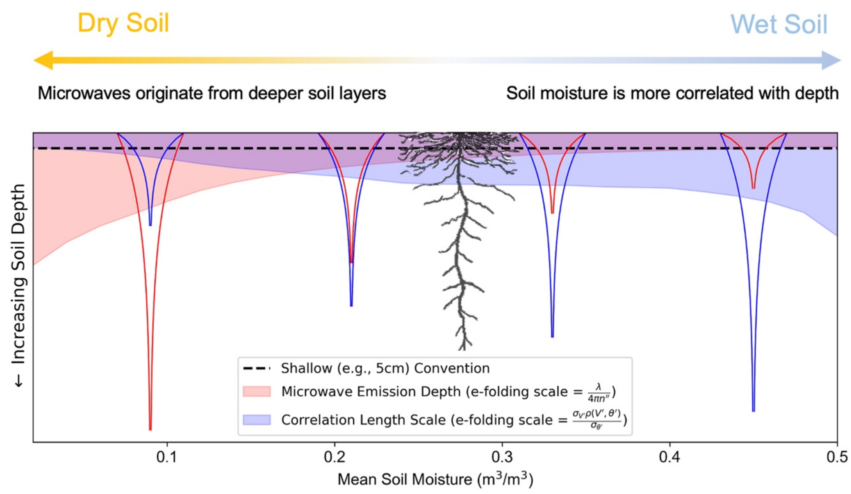

Figure 1. Effective depth of representation of microwave satellite soil moisture retrievals based on consideration of both microwave soil emission physics and vertical hydraulic connectivity of soil moisture. Satellite effective depths of representation of soil moisture likely extend deeper than 5 cm across many conditions at L-band. However, effective depths across space remain uncertain with current evidence discussed in Sections 2.1 and 2.2. Note that single value depths refer to a profile of soil moisture representation; as examples shown in this diagram, effective depths of representation (red/blue shading) are e-folding scales determined from modeled microwave soil emission vertical distributions (red lines) and estimated soil moisture vertical correlation distributions (blue lines). Under drier conditions, microwave emission theoretically originates directly from deeper layers, while for wetter conditions, correlation length scale arguments only provide an effective representation of deeper soil layers. The diagram can scale depending on the frequency across low frequency microwaves. For equation details, see Appendix A. The displayed root profile image was adapted with permission from Nippert and Holdo (2015). It has a commonly observed vertical structure of decreasing root biomass with depth. However, note that the length scale of this root density decay will vary globally.

Here, we ask: do L-band microwave remote sensing products only represent soil moisture in the top 0–5 cm? Can L-band satellite soil moisture retrievals be useful for studying plant water use and, if so, under what conditions? In this commentary, we provide a novel synthesis of results from microwave remote sensing, soil hydrology, and plant water isotopic tracer studies to illustrate that satellite soil moisture observations are more useful than commonly believed for studying global vegetated surfaces.

2. Satellite Soil Moisture's Effective Depth of Representation

The true vertical support, or effective depth of representation, of remote sensing-based soil moisture retrievals is dependent on both (a) the microwave emission properties of the soil column and (b) the vertical autocorrelation of typical soil moisture profiles and their dynamics (Njoku & Entekhabi, 1996; Short Gianotti et al., 2019). Both principles typically result in the remote sensing signal being representative of a soil moisture profile that decays with depth (e.g., exponential distribution). Therefore, reported single depth values are length scales, or the depth at which the satellite signal holds a portion (e.g., 63% for e-folding scales) of soil moisture information from the sensed profile with some information coming from deeper layers. Furthermore, these principles trade off in dominance from dry to wet conditions (Figure 1). Ultimately, we argue here that evidence for both principles result in effective L-band depths of representation deeper than 5 cm across many conditions. Additionally, reported depths at a single value (e.g., 5 cm) are not a limit, but rather length scales describing a profile of soil moisture representation that continues below the reported value. A more quantitative discussion of satellite soil moisture depths of representation is provided in Sections 2.1 and 2.2.

For drier soils, L-band satellites typically directly detect soil moisture in a deeper soil column because microwave emission originates from deeper soil layers than for wetter soils (Figure 1). Specifically, modeling microwave emission from a soil layer that is assumed to be a homogenous, dielectric medium with uniform moisture and temperature profiles reveals that soil emission depth increases with aridity and vertically decays approximately exponentially (Njoku & Entekhabi, 1996; Njoku & Kong, 1977). Therefore, despite drier periods resulting in less coupling between surface and deeper layer soil moisture (Figure 2), satellites should directly sample deeper into the soil column for drier soils, where the emission likely originates partly below a depth of 5 cm but can be hindered by fine soil texture and large soil scatterers. Microwave emission depth e-folding scales in Figure 1

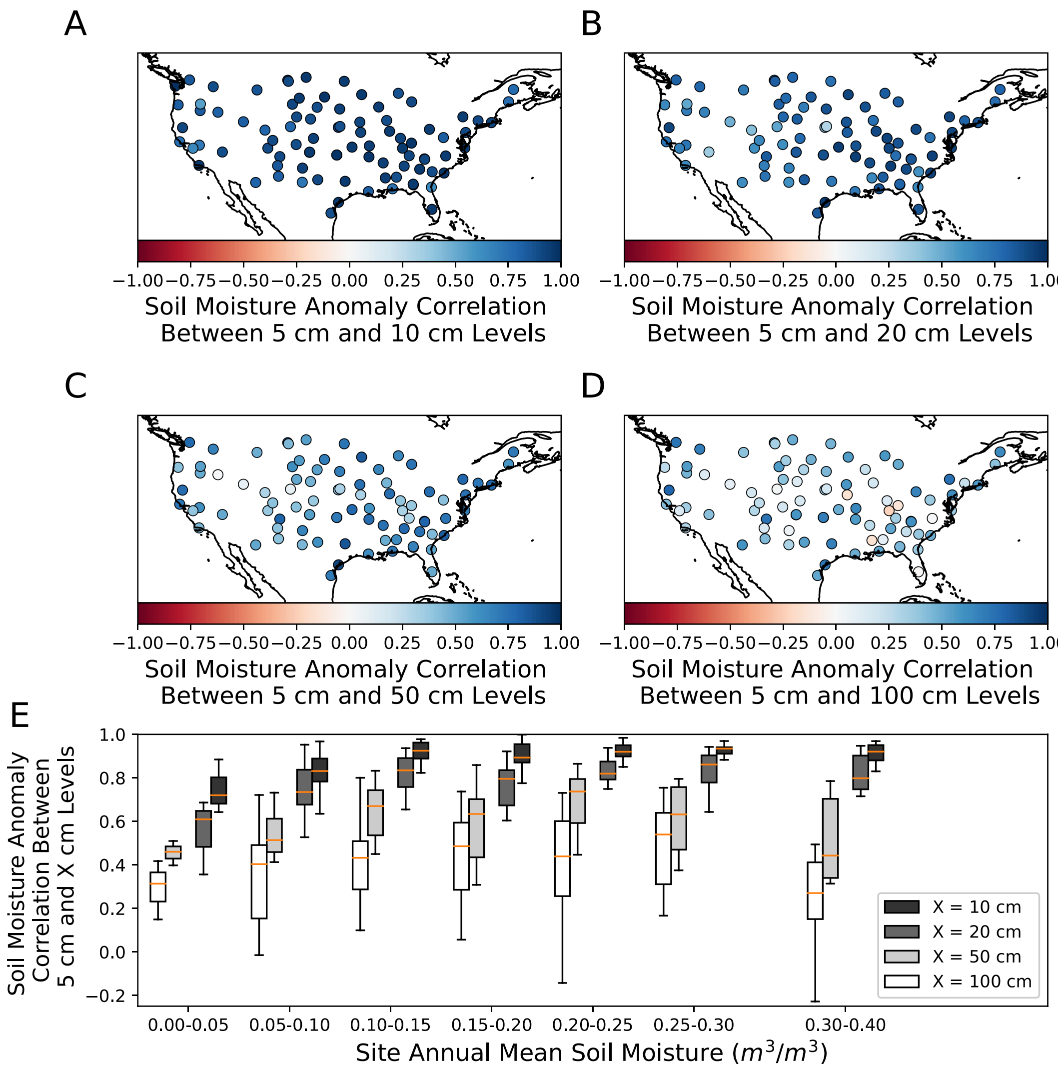

Figure 2. Vertical correlations from in situ U.S. Climate Reference Network (USCRN) measurements support that soil moisture in the upper 5 cm layers holds information about variations in rootzone soil layers under wetter soil moisture conditions. Soil moisture daily anomaly correlations between 5 cm sensor measurement depth and soil depths of (a) 10 cm, (b) 20 cm, (c) 50 cm, and (d) 100 cm using USCRN soil moisture (Bell et al., 2013). (e) Spatial distributions of anomaly correlations from (a) to (d) panels with USCRN sites binned as a function of the sites' mean annual soil moisture.

are computed based on a soil emission model (Equation A1, which is from Njoku and Entekhabi (1996)). See Section 2.1 for a more quantitative discussion.

For wetter soils, despite shallower soil emission depths from an electromagnetic perspective, surface soil moisture has a greater hydraulic connectivity with deeper soil layers (Figures 1 and 2). This is because soil moisture is a storage variable with strong spatiotemporal memory (McColl et al., 2017). This memory results in daily soil moisture variations at a 5 cm depth (the emission depth under wetter conditions) correlating with deeper soil moisture variations. Such vertical autocorrelation information decays approximately exponentially with depth (Figure 1). E-folding vertical correlation length scales reported in Figure 1 are global remote sensing-based vertical length scales estimated using Equation A2 in Short Gianotti et al. (2019). See Section 2.2 for a more quantitative discussion.

Combining these electromagnetic and statistical considerations suggests that, across soil moisture conditions, L-band satellite soil moisture retrievals effectively carry information about soil moisture dynamics deeper than 5 cm depending on the subsurface conditions (Figure 1). This deeper effective depth of representation results from electromagnetic and statistical considerations of satellite-based soil moisture trading off in their dominance of vertical soil representation from dry to wet conditions. In principle, the combined support scale of the satellite-based soil moisture dynamics is at least the deeper of the two considerations, and we urge future work to estimate holistic effective depths of representation across the globe. Deeper layers well below 5 cm are often still integrated but contribute progressively (i.e., exponentially) less to the effective satellite soil moisture signal with depth (Figures 1 and 2). By contrast, reanalysis rootzone moisture products often assess the uniform, column-averaged soil moisture typically between 0 and 100 cm and/or discretized portions of this range.

The modifier "effective" is used to describe the depth of representation here because both direct and indirect sensing contributes to the estimated depth of representation. In the case of drier soils, the microwave emission typically originates from layers deeper than 5 cm (see Section 2.1), which would provide direct observation of the magnitude and time variations of deeper layer soil moisture. However, in wetter conditions, only the soil moisture magnitude and variations in the upper soil layers, likely shallower than 5 cm, are directly observed by L-band satellite sensors. Nevertheless, the typically high hydraulic connectivity between shallow and deeper layers in these wetter conditions at daily to weekly timescales allows indirect observation of the soil moisture magnitude and variations in the deeper layers. As such, the vertical depth of representation is indirect and more "effective" when using statistical arguments in wetter conditions.

2.1. Depths of Representation Under Drier Conditions

Microwave emission depth scales theoretically increase with drying soil (Burke et al., 1979; Ulaby & Long, 2014). However, estimates of emission depths under dry conditions as a function of soil texture remain uncertain with differences between model and experimental evidence. Ultimately, based on current evidence, we expect that the mean emission depth scales under dry soils are deeper than 5 cm under many conditions, and likely between the shallower experimentally determined values and deeper model-based values. Furthermore, given that microwave emission is based on an emission profile (not a uniform profile with a cutoff), some emission will originate from below the reported length scale values here (see profiles in Figure 1).

Under dry soils, microwave emission models produce e-folding depth of representation scales deeper than 5 cm, with estimates below 30 cm for the driest soils. This result holds for a wide range of clay fraction values (Figure 1 shows case of 20% clay fraction), with soil texture only minimally impacting emission depth (Shen et al., 2021). Furthermore, emission depth magnitudes from several different emission and dielectric models tend to agree with that of Equation A1 (Fluhrer et al., 2022; Lv et al., 2018; Njoku & Entekhabi, 1996).

However, these model-based emission depth estimates are likely upper bounds. In assuming homogenous media without an air-soil boundary, these emission models will underestimate scattering effects (Zwieback et al., 2015). Specifically, scattering due to the air-soil boundary and scattering from subsurface features at the scale of the microwave wavelength within the medium will reduce the emission depth (Newton et al., 1982). Formation of biocrusts, prevalent in global drylands (Phillips et al., 2022), and near-surface debris may also create scattering effects that will limit emission depths. These models also assume uniform soil moisture and temperature with depth. However, since soil commonly dries at the surface first, emission will only originate from the dry upper layers and little from below the transition to wet layers (Shen et al., 2021).

Experimental studies suggest emission from deeper than 5 cm in dry conditions, but results are variable without well-known dependencies. Some studies find emission depths of 5–10 cm under drier soils, and potentially closer to 5 cm for soil with high clay content (Lv et al., 2018; Owe & Van De Griend, 1998; Rao et al., 1988). Another finds deeper soil moisture representation of near 100 cm (Moghaddam et al., 2000), though this may be due to reduced scattering in more uniform sand (Mätzler, 1998). Others suggest these emission depths may still be within the top 5 cm for dry soils similarly to wetter soils (Escorihuela et al., 2010; Newton et al., 1982).

However, there are confounding factors in these experimental studies that likely cause underestimations of dry soil sensing depths. Many field studies that suggest emission is from shallower than 5 cm across conditions draw conclusions using a wide range of soil moisture values (Escorihuela et al., 2010; Owe & Van De Griend, 1998; Shen et al., 2021). These procedures will likely underestimate the dry soil emission depth by including wet soils conditions. Additionally, some studies draw conclusions about shallow emission depths without measuring soil moisture values below their depth estimate and/or without explicitly showing that the soil moisture values below their depth estimate contribute less to the signal (Escorihuela et al., 2010; Owe & Van De Griend, 1998). We argue that more targeted microwave experiments are needed to better estimate the dry soil emission depths globally and their dependencies (see recommendations in Section 5).

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2.2. Effective Depths of Representation Under Wetter Conditions

Under conditions ranging from moderately wet to very wet conditions, microwave field experiments tend to find a 5 cm emission depth as measured by L-band radiometers, suggesting that L-band satellites like SMAP and SMOS directly sense the first 5 cm of soil with a weaker contribution of emission from deeper than 5 cm (Jackson et al., 1984; Njoku & O'Neill, 1982; Wang, 1987). Some studies argue that L-band microwave emission may only observe soil moisture in the first 2 cm of the soil (Escorihuela et al., 2010; Schmugge, 1983; Wilheit, 1978). However, these findings of shallower emission may be under scenarios of high air-soil interface roughness (Newton et al., 1982). These results may also be uncertain due to interpretation of small correlation differences between soil moisture and brightness temperature in different soil layers.

Nevertheless, soil moisture in the top few centimeters is typically well-correlated with deeper layer soil moisture. Across wetter environments, in situ soil moisture sensors show high soil moisture anomaly correlations (>0.8) between 5 cm and depths of 10 and 20 cm (Figure 2). The correlation increases with higher mean soil moisture (Figure 2e) are consistent with the interpretation that the partially saturated soil hydraulic conductivity increases with moisture content and allows redistribution of soil moisture across the profile under matric and elevation head gradients. Consideration of lagged correlations does not change the correlations appreciably, meaning much of the subsurface coupling can be accounted for within daily dynamics. Using this concept, L-band satellite soil moisture retrievals have been previously used to globally estimate effective depths of representation, which tend to be deeper than 5 cm across wetter conditions, but only rarely more than 30 cm (Akbar et al., 2018; Short Gianotti et al., 2019). For deeper layers, these correlations can greatly decrease and even show anticorrelations between anomalies in shallower and deeper soil layers (Figure 2). More detailed study is needed to quantify effective length scales and how they vary with soil hydraulic conditions.

The vertically correlated nature of soil moisture under wetter conditions has emerged in previous work. Surface soil moisture has been shown to have similar information content as deeper layer soil moisture in explaining evapotranspiration fluxes and moisture thresholds between evaporative regimes (Dong et al., 2022; Qiu et al., 2016). Experimental microwave L-band field studies have found emission depths deeper than 5 cm under wetter conditions, but this may have been due to soil moisture being correlated with depth (Macelloni et al., 2003; Pampaloni et al., 1990). Finally, L-band satellite soil moisture was useful as a direct representation of rootzone conditions deeper than 5 cm when modeling ecosystem carbon fluxes (Zhang et al., 2022).

C-band and X-band (6.9 and 10.7 GHz) depths of representation are shallower and potentially have less utility for our arguments (Owe & Van De Griend, 1998; Wilheit, 1978). Namely, these wavelengths are about 5 and 8 times smaller than L-band, respectively, which in principle result in 5 and 8 times shallower soil emission depths (Equation A1) across moisture and texture conditions. However, similar vertical soil moisture correlation arguments can be applied to these higher C-band and X-band frequencies under wetter conditions. We encourage the analysis with Equation A2 in the Short Gianotti et al. (2019) study to be repeated with C-band and X-band radiometer observations to estimate their correlation length scales.

3. Relevance of Satellite Soil Moisture Retrievals to Plant Water Uptake

A frequently expressed argument when discouraging the use of satellite soil moisture is that rootzones are (qualitatively) "deep," which argues against using an upper rootzone soil moisture data set to study vegetated landscapes. Indeed, maximum rooting depths often extend to 1–2 m and, at times, tens of meters below the surface depending on climate, edaphic conditions, and topography (Fan et al., 2017; Nepstad et al., 1994; Schenk & Jackson, 2002a; Tumber-Dávila et al., 2022). Existence of deep roots indicates adaptation to plant water stress, where access to deeper, less variable water sources allows plants to continue transpiring to survive under seasonal or severe water limitation (Jiang et al., 2020; Stocker et al., 2021; Tumber-Dávila & Malhotra, 2020). However, in the context of nominal plant water uptake, such a perspective can result in over-emphasis of the maximum rooting depth and neglect of the nature of typical rooting profiles when discouraging the use of satellite soil moisture. Specifically, while there are indeed many cases of deep root water use, global rooting profiles are often concentrated in the upper soil layers and decrease in root density with depth (Jackson et al., 1996). Some estimates indicate that most species (potentially as high as 90%), and especially herbaceous plants, concentrate the majority of their roots in depths shallower than 30 cm (Schenk & Jackson, 2002b).

Due to root suberization and woody root development that prevents root water uptake, the rooting distribution does not necessarily match the actual vertical profile of root water uptake (Kramer & Boyer, 1995). Instead,

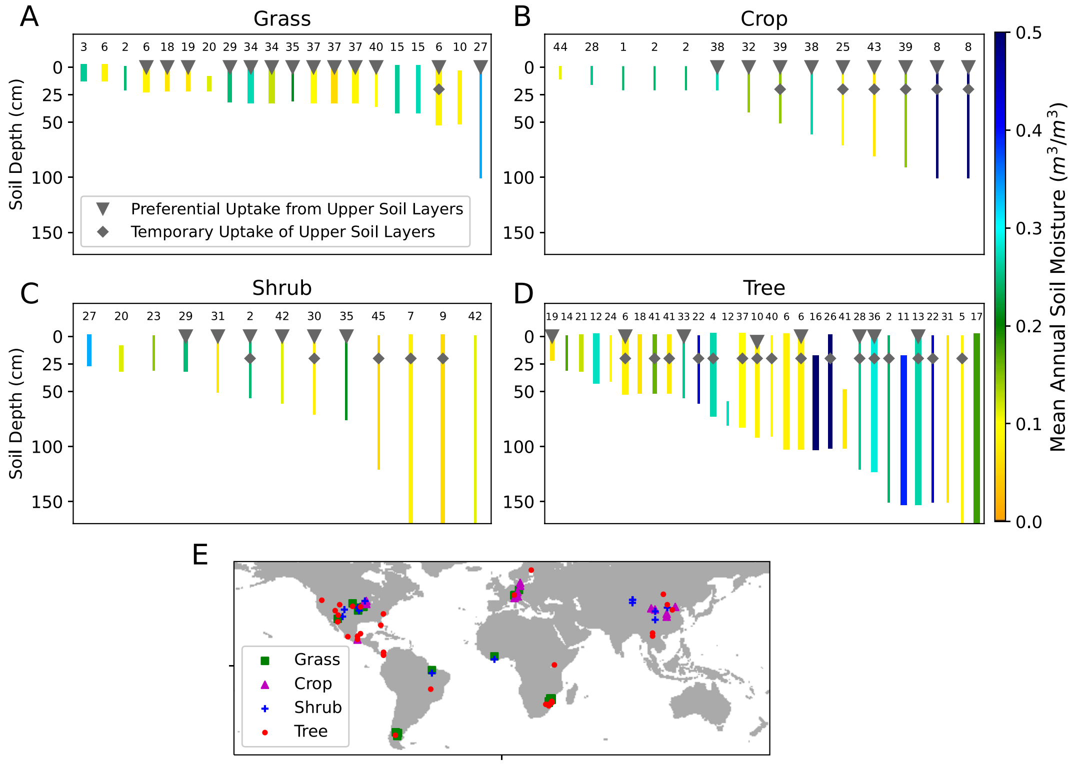

Figure 3. Primary root water uptake profiles (or functional rooting profile) based on field stable isotope tracer studies for species binned in (a) grass, (b) crop, (c) shrub, and (d) tree categories based on Table S1 and data set in Feldman et al. (2023). The triangle symbol means the study found preferential water uptake nearer to the surface and decreasing uptake with depth. The diamond symbol means that while the study found uptake to 50 cm soil depths or below, root water uptake switched primarily to the upper soil layers (<~30 cm) temporarily during the year. Placement of the diamond symbol at 20 cm is arbitrary. Thickness of the line indicates number of species studied in the given reference. The number above the plotlines is the reference index (see Table S1 in Supporting Information S1). The line colors refer to the mean annual Soil Moisture Active Passive (SMAP) soil moisture shown in the colorbar for each field site using the nearest 36 km pixel. (e) Locations of the isotopic field measurements.

isotopic tracers can be used to estimate the true range of primary water uptake, commonly called the functional rooting profile (Dawson & Pate, 1996; Ehleringer & Dawson, 1992). Within the limits imposed by isotopic mixing model uncertainties (Case et al., 2020; Ogle et al., 2004), isotopic tracer methods can determine water uptake profiles and/or ranges more relevant to the water cycle than knowledge of the rooting profile alone.

Therefore, instead of rooting profile information, we have collated isotopic tracer studies that determine the vertical range of roots contributing the most to xylem water within plants (Figure 3). Our main goal was to assess whether there are widespread cases of plants using soil moisture that may be relevant to L-band satellite representation of upper layer soil moisture. Values displayed in Figure 3 reflect the primary zones of water uptake over most of the year indicated by each reviewed study. In our web search of peer-reviewed literature, our keywords included "stable", "isotope," "tracer," "plant," "root," "water uptake," and "soil." We only sampled studies that (a) explicitly stated or displayed the primary depths of water uptake (avoiding subjective judgment of results), (b) assessed naturally occurring plants under nominal conditions (avoiding experimental manipulation, extreme stress, and laboratory experiments), and (c) evaluated plant species with an unobstructed rootzone (avoiding riparian, coastal, and shallow bedrock environments). Our search resulted in 45 references that met our criteria (Figure 3 and Table S1 in Supporting Information S1).

We find that grass and crop species (primarily herbaceous) across global climates typically extract water from the upper soil layers (shallower than 25 or 30 cm) over most of the year, with preferential uptake of water nearer to the surface (Figures 3a and 3b). Seventy percent of studied grass species typically use water in the upper 30 cm of soil. Sixty five percent of grass studies find increased proportional uptake in the top-most soil layers, with many explicitly reporting use of water at 0–5 cm depths (Figure 3a). While 43% of studied crop species use water mainly shallower than 25 cm, all sampled crop species preferentially draw water from the upper soil layers with decreasing water use with depth (Figure 3b). All crop studies that found water use extending deeper than 50 cm also found proportionally higher water use in the upper soil layers. Eighty-eight percent of these same studies also found the primary plant water uptake zone transitioned at least temporarily to the upper soil layers (see diamond symbols in Figure 3b).

Shrub and tree species show a larger vertical range of water uptake, with water uptake commonly extending to well below 50 cm (Figures 3c and 3d) often related to root-niche separation under competition with grasses (Case et al., 2020). However, even in these deeper water uptake cases, 89% of shrub and 67% of tree isotopic studies found either proportionally higher water uptake from the upper soil layers or the primary water use zone transitioned temporarily to the upper soil layers. Absence of triangle and diamond symbols indicate that the study did not mention either phenomenon, not that the phenomenon does not exist. Therefore, these percentages that indicate preferential or temporary uptake of upper soil layer moisture are lower bounds.

We acknowledge potential biases in our search. For example, a greater proportion of studies in the midlatitudes arises due to abundant field research facilities in Asia, Europe, and North America as well as due to a lack of field measurements in the tropics (Schimel et al., 2015). More studies also take place in semiarid and sub-humid environments because of their higher proportion of global land cover. While our search yielded few tropical forest studies, we expect these regions may have deeper functional rooting profiles similarly to those found in Figure 3d (Ichii et al., 2007). However, we argue that this search provided a representative distribution of species across grass, crop, shrub, and tree categories and across global moisture availability gradients.

Though roots and consequent root water uptake profiles can extend below 30 cm, likely beyond the profiles of L-band satellite soil moisture representation (especially for shrubs and trees), our analysis shows that shallow root water uptake is widespread (Figure 3). Furthermore, even in the presence of deep roots, this analysis shows that shallow preferential soil water uptake and deeper roots can exist concurrently—the existence of a deep maximum rooting depth does not always imply low plant utilization of shallow soil moisture. This claim is supported by previous estimates that root water use from deeper layers may be smaller, or less than 10% of annual plant water uptake (McCormick et al., 2021; Miguez-Macho & Fan, 2021). This lower contribution of water uptake from the deeper layers may be, in part, because there are hydraulic limitations in transporting water over long vertical distances from deeper roots, with high radial and axial resistances in roots that can increase with depth (Jones, 2014; Landsberg & Fowkes, 1978; Nippert et al., 2012). As such, deeper roots may be more important for survival under seasonal or severe water limitation rather than nominal uptake (Stocker et al., 2021; Wang-Erlandsson et al., 2016). Use of deeper roots is limited in many water-limited ecosystems (Nippert & Holdo, 2015), where rainfall infiltration is often shallow (<30 cm) and plants must rely on this more frequently wetted shallow zone for survival (Scott & Biederman, 2019). Additionally, essential limiting nutrients are typically highly concentrated in the upper soil layers due to decaying organic matter, which may prevent sole plant reliance on deeper moisture sources (Jobbágy & Jackson, 2001). This motivates strategies like hydraulic redistribution where plants actively move water via the roots to upper soil layers for easier uptake of nutrients under dry conditions (Cardon et al., 2013). As such, knowledge of maximum rooting depths should be used with caution when evaluating nominal plant water uptake throughout the year in the context of global soil moisture estimates (Nippert & Holdo, 2015).

This evidence together with Section 2 ultimately indicates that plant water use of upper soil layers is likely prevalent within a satellite pixel in some biomes, especially those with herbaceous vegetation, and highlights the utility of L-band satellite soil moisture for studying water control of many vegetated surfaces. We stress that we are not making wider claims about global dominance of shallow plant uptake strategies, but rather that deep root water use may be overemphasized when discussing limitations of using satellite soil moisture to study the terrestrial biosphere.

4. Effective Depth of Representation Limitations

Several soil and vegetation processes can limit L-band retrievals effectively capturing soil moisture dynamics from deeper than 5 cm. We discuss several limitations here and comment on whether our arguments are confounded by or robust to these processes.

Regarding microwave soil emission depth arguments in dry conditions, large subsurface scatterers, like woody roots and rock inclusions that are larger than the wavelength of L-band microwaves (~20 cm) can reduce the depth of soil microwave emission (Roth & Elachi, 1975; Xiong et al., 2017). This is especially the case if belowground rooting density and rock inclusions are present across the satellite footprint. Deeper soil emission may occur in many drier regions (Section 2.1), which climatically tend to have lower woody vegetation density and thus may be less consistently influenced by larger roots (Good & Caylor, 2011). However, the existence of large abiotic soil scatterers across a satellite footprint can reduce the depth of microwave soil emission, in which case modeled dry soil emission depth values are an overestimate. The global distribution of soil scatterer density is uncertain and it is ultimately unclear how soil texture heterogeneity at small spatial scales translates to uncertainties for our larger scale arguments (Baroni et al., 2017; Or, 2020).

Regarding vertical correlation arguments in wet conditions, soil conditions that promote heterogeneous vertical moisture movement rates in the subsurface can decouple surface and deeper soil layers. This includes bare soil evaporation (i.e., the formation of an evaporation front). A soil evaporation front forms with differential bare soil drying of upper soil layers, which can act to decouple the near-surface soil moisture dynamics from the rootzone especially over long seasonal drydowns in seasonally dry environments (Scott & Biederman, 2019). Nevertheless, macropores (Vereecken et al., 2022) and processes like hydraulic redistribution of moisture from wet to dry soils by roots of some plant species (Katul & Siqueira, 2010; Nadezhdina et al., 2010) could act to further couple the surface and deeper soil layers. Macropores are large soil pore spaces that make up less than 1% of soil volume, but can dominate gravity drainage rates in the soil under wet conditions (Fatichi et al., 2020; Hirmas et al., 2018; Kramer & Boyer, 1995). Ultimately, our arguments that shallow soil moisture under wet conditions captures moisture dynamics of deeper than 5 cm due to vertical correlation are based on satellite and in situ observations, and thus they already integrate these soil and vegetation processes and their limitations (Figures 1 and 2).

Soil evaporation influences soil moisture at depths between 0 and 80 cm depending on soil texture (Aminzadeh & Or, 2014; Lehmann et al., 2008; Or & Lehmann, 2019). As such, near-surface soil moisture dynamics will have a signature of soil evaporation physics (Haghighi et al., 2013; Salvucci, 1997). However, the existence of soil evaporation in the upper soil layers does not preclude root water uptake from being sensitive to upper rootzone soil moisture, including 0–5 cm. Our analysis indicates that many plant species prefer moisture in upper soil layers (Figure 3), with many isotopic studies finding dominant uptake from 0 to 5 cm (Asbjornsen et al., 2008; Case et al., 2020; Kulmatiski & Beard, 2013; Kulmatiski et al., 2010; Le Roux et al., 1995; Ogle et al., 2004; Prechsl et al., 2015). As such, soil moisture in these upper layers is indeed influenced by root water uptake along with bare soil evaporation in many cases. It is also not likely that either bare soil or root water uptake entirely dominate globally based on estimates of transpiration and evaporation partitioning (Fatichi & Pappas, 2017; Good et al., 2015; Jasechko et al., 2013). Remotely sensed soil moisture dynamics are thus a function of both root water uptake and bare soil evaporation processes, but future work should determine how much soil moisture dynamics in these layers is explained by plant water uptake.

Aboveground vegetation biomass, from a passive microwave emission perspective, does not necessarily impact the soil microwave emission profile and depth. Dense, wooded vegetation canopies depolarize the strongly horizontally and vertically polarized soil microwave emission signal, where multiple-scattering of microwave emission through the canopy reduces sensitivity to soil reflectivity and thus to soil moisture (Feldman, Akbar, & Entekhabi, 2018; Kurum et al., 2011). Therefore, dense vegetation results in a higher soil moisture retrieval error variance (Feldman et al., 2021; Zwieback et al., 2019), but does not directly change the physics of electromagnetic attenuation in the soil, and thus does not change the depth of microwave emission. Nevertheless, our deeper direct microwave emission depth arguments pertain to dry soil conditions (Section 2.1), where vegetation density tends to be lower and would thus be less influenced by vegetation presence.

5. Conclusions and Recommendations

Our findings convey that satellite L-band retrievals effectively capture global soil moisture dynamics deeper than 5 cm in many conditions (Section 2) and are more relevant for evaluating plant function than commonly appreciated (Section 3). We find that L-band satellite soil moisture retrievals will likely have their highest utility for studying most grasslands and croplands, which cover more than a third of global vegetated surfaces. This land cover proportion is higher when including nonvegetated surfaces, given that these L-band measurements also have utility for evaluating bare surfaces where soil evaporation dominates. Grass and crop water use also decreases with depth, much like the decreasing L-band satellite soil moisture representation with depth (Figure 1). Therefore, reanalysis soil moisture data sets that integrate rootzone dynamics between 0 and 100 cm and deeper may in fact be less useful than L-band soil moisture for representing plant-relevant soil moisture dynamics in grass and croplands (Figure 3). This is because soil moisture products representing the 0–100 cm layer will integrate subdued moisture dynamics in deeper layers not relevant to the functional rooting profile concentrated in the upper soil layers. Additionally, even woody plant species that exhibit deeper root water uptake (shrubs and trees; see Figure 3) frequently draw water nearer to the surface preferentially or temporarily within a given season. L-band soil moisture observations are still useful for these scenarios at least during certain times of the year.

We stress that deeper layer (0–100 cm and beyond) soil moisture products based on the assimilation of L-band observations (i.e., SMAP L4 rootzone soil moisture; Reichle et al., 2019) are likely more optimal for the study of soil moisture memory in the context of land-atmosphere interactions, the study of deeper-rooted vegetation function under water stress conditions, the study of infiltration and drainage fluxes, and the initialization of dynamical seasonal forecasts. Our findings here also indicate that reanalysis rootzone soil moisture products are needed for the study of many forested and mixed (i.e., savanna) landscapes that have deeper plant water uptake and often higher errors in remote sensing soil moisture retrievals.

Additionally, we argue that there is no single global soil moisture product that will integrate the soil moisture layers relevant to plant water uptake and thus terrestrial water, carbon, and energy exchanges. Instead, the optimal soil moisture product changes in time and space. For studies of water, carbon, and energy exchanges at landscape scales, we encourage first understanding the typical root water uptake patterns for plant species in the study region and then carefully selecting a soil moisture data set. Potentially, multiple products and their synergistic use are needed depending on the complexity of root water uptake scenarios.

For example, for landscapes with primarily herbaceous vegetation including many croplands, grasslands, and savannas with sparse tree cover, the L-band soil moisture products are more optimal for integrating the relevant rootzone moisture information because they are typically sensitive to the shallow rootzone layers and often progressively decrease in sensitivity to deeper soil moisture, much like these ecosystem's functional rooting profiles. These observations will additionally be optimal for the study of mostly bare surface supplied mainly by soil evaporation. Alternatively, in scenarios where prevalent deeper-rooted shrubs and trees are mixed with a shallow-rooted understory, data sets representing a uniform distribution of integrated soil moisture across the top 1–2 m of soil (i.e., model reanalysis rootzone soil moisture products) would be optimal (Reichle et al., 2019). P-band (0.4 GHz) soil moisture remote sensing applications may be useful for these scenarios as well—with potentially twice as deep of effective depths of representation than at L-band and less sensitivity to the overlying vegetation (Chapin et al., 2012; Konings et al., 2014; Shen et al., 2021). These data sets may be similarly useful for plant water stress scenarios if the given vegetation shifts its water use to deeper layers. Finally, in scenarios where root water uptake extends well below 1 m for consistent or transient use of deep moisture or groundwater (McCormick et al., 2021; Miguez-Macho & Fan, 2021), care must be taken in determining when this uptake occurs. Such scenarios may occur in tropical rainforests where L-band satellite soil moisture retrievals are suboptimal due to vegetation multiple-scattering of microwaves (Feldman, Akbar, & Entekhabi, 2018; Kurum et al., 2011). Satellite-based terrestrial water storage variations (i.e., GRACE and GRACE-FO) may be useful to study these cases and can be used in tandem with reanalysis rootzone products (Rodell & Famiglietti, 2001).

Our commentary ultimately encourages broader use of L-band satellite soil moisture for the study of soil moisture's impact on the terrestrial net carbon balance, water movement in the soil-plant-atmosphere continuum, land-atmosphere coupling, and crop yield forecasting. This is the case for grasslands and some croplands but may only extend to woody biomes in some contexts. Based on the evidence presented here, we argue that L-band satellite soil moisture is more useful than suggested by the frequently assumed skin depth support scale. Furthermore, satellite soil moisture retrievals can often serve as a more direct observation of relevant upper rootzone soil moisture than less direct precipitation wetness indices or modeled rootzone products which may include process assumptions that confound interpretations of emergent terrestrial behavior.

With the availability of X-band, C-band, and L-band soil moisture observations, we urge more study into quantifying effective depths of representation at each frequency and how they change with soil structure and moisture across the globe. These estimates should consider both microwave soil emission depths and statistical vertical correlation arguments because previous studies evaluate these considerations in isolation (Lv et al., 2018; Njoku & Kong, 1977; Short Gianotti et al., 2019). Correlative evidence between brightness temperature and soil moisture across many depths can simultaneously capture both the direct emission depths within the radiometric brightness temperature measurements and the effective, vertical connections within the soil moisture measurements. Furthermore, to draw more conclusive evidence about L-band sensing depths under drier soils,

10.1029/2022WR033814

we recommend that (a) microwave emission models used to estimate sensing depths should be adapted to account for air-soil boundary and within-layer scattering due to soil heterogeneity. (b) Field experiments should explicitly test dry soil conditions without using methods that include wet soil conditions. Drydown experiments as shown in a previous experiment may be useful in this endeavor (Newton et al., 1982). (c) Field experiments should also establish that soil moisture from deeper layers contributes much less to the signal in order to define a depth of representation.

Finally, the potential value of satellite-based soil moisture deeper than a 5 cm skin depth highlights the need to maintain continuity of L-band satellite remote sensing missions. Additionally, we have discussed several factors that limit the effective L-band depth of soil representation, which motivate the need to directly observe deeper soil moisture layers with upcoming satellite missions. We namely advocate for P-band satellite soil moisture missions that can directly detect several times the effective L-band depth of representation. Planned P-band missions include the European Space Agency's BIOMASS mission and NASA's Signals of Opportunity P-band Investigation (SNOOPI) (Garrison et al., 2019; Quegan et al., 2019).

Appendix A

The e-folding length scale of microwave emission used to estimate surface soil moisture can be modeled by:

$$L_{\text{Emission}} = \frac{\lambda}{4\pi n''} \tag{A1}$$

where λ is the emission wavelength (Njoku & Entekhabi, 1996). n'' is the imaginary part of the refractive index, which is the square root of the dielectric constant. The dielectric constant is a function largely of soil moisture and soil texture (i.e., clay fraction), though soil texture has smaller influences (Shen et al., 2021). Incidence angles are not explicitly considered in these models, the consequences of which are not well known (Shen et al., 2021). L_{Emission} is the e-folding scale that represents the emission depth of microwaves. Measurements of these microwaves are used to estimate satellite soil moisture. Nearly identical emission length scales are found when using other common emission and dielectric models (Fluhrer et al., 2022; Lv et al., 2018).

The e-folding vertical correlation length scale of soil moisture dynamics can be computed by:

$$L_{\text{Correlation}} = \frac{\sigma_{V'}\rho\left(V', \theta_s{}'\right)}{\sigma_{\theta_s{}'}} \tag{A2}$$

where V is the total volume soil moisture in the column, θ_s is the surface soil moisture, ρ is correlation, and σ is standard deviation (Short Gianotti et al., 2019). Prime superscripts indicate the time derivative. $L_{\text{Correlation}}$ is a correlation length scale, or the e-folding scale, that captures the decay of surface soil moisture's correlation with the total column soil moisture. $L_{\text{Correlation}}$ is thus the effective depth to which the surface soil moisture (here, being measured at least at a 5 cm depth) holds information about the total soil column moisture. Similar theoretical arguments allow interpretation of $L_{\text{Correlation}}$ to be a support scale of the soil moisture magnitude and time dynamics (Akbar et al., 2018).

While Equation A2 is an exact solution, total column volumetric moisture is not widely available to estimate $L_{\text{Correlation}}$ globally. Thus, Short Gianotti et al. (2019) estimate $L_{\text{Correlation}}$ using information about the variance of surface hydrologic fluxes (rainfall minus surface hydrologic losses) as well as surface soil moisture variance and autocorrelation (their Equation 28). GPM rainfall retrievals (Huffman, 2015) and SMAP soil moisture retrievals are used together to globally estimate $L_{\text{Correlation}}$, which are used in Figure 1.

Data Availability Statement

All data used in this study are freely and publicly available. In situ USCRN soil moisture observations were obtained from NOAA (https://www.ncei.noaa.gov/access/crn/). All isotopic uptake profiles were determined from previous work with the data table stored in https://doi.org/10.5281/zenodo.7527459 and shown in Table S1 in Supporting Information S1. $L_{\text{Correlation}}$ length scale estimates were obtained from Short Gianotti et al. (2019) and are included in https://doi.org/10.5281/zenodo.7527459. No software was used or generated in this commentary.

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Water Resources Research

Supporting Information for

Remotely sensed soil moisture can capture dynamics relevant to plant water uptake

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Contents of this file

Table S1

Introduction

This file includes Table S1 and its references that are used to create Figure 3.

Table S1. Field isotropic tracer studies across the globe as displayed in Fig. 3. Crop species are specified and partitioned in the table due to wide variability of cultivated vegetation types (includes both herbaceous and woody species). This dataset is stored in https://doi.org/10.5281/zenodo.7527459.

Reference	Reference Index	Plant Category	Latitude	Longitude	Mean Annual Precipitation (mm)	Uptake Range Top (cm)	Uptake Range Bottom (cm)	Isotope Sampling Months	Decay of Water Uptake With Depth	Temporary Uptake of Upper Layers
Asbjornsen et al. 2007	1	Crop (Corn)	41.5	-93.25	882	0	20	Jul.	No	No
Asbjornsen et al. 2008	2	Grass	41.5	-93	882	0	20	May to Sep.	No	No
Asbjornsen et al. 2008	2	Crop (Soybean)	41.5	-93	882	0	20	May to Sep.	No	No
Asbjornsen et al. 2008	2	Crop (Corn)	41.5	-93	882	0	20	May to Sep.	No	No
Asbjornsen et al. 2008	2	Shrub	41.5	-93	882	0	55	May to Sep.	Yes	Yes
Asbjornsen et al. 2008	2	Tree	41.5	-93	882	0	150	May to Sep.	No	Yes
Bachmann et al. 2015	3	Grass	50.9	11.5	587	0	10	Apr., Jun., Sep.	No	No
Brinkmann et al. 2019	4	Tree	47.5	8.3	1110	0	70	Apr. to Nov.	No	Yes
Brooks et al. 2002	5	Tree	44	-121	550	0	200	Jul. to Sep.	No	Yes
Case et al. 2020	6	Grass	-24	31.5	479	0	10	May, Jun.	No	No
Case et al. 2020	6	Tree	-24	31.5	479	0	50	May, Jun.	Yes	Yes
Case et al. 2020	6	Grass	-24	31.5	510	0	20	May, Jun.	Yes	No
Case et al. 2020	6	Tree	-24	31.5	510	0	100	May, Jun.	No	No
Case et al. 2020	6	Grass	-24	31.5	600	0	50	May, Jun.	Yes	Yes
Case et al. 2020	6	Tree	-24	31.5	600	0	100	May, Jun.	Yes	Yes
Chimner et al. 2004	7	Shrub	37.7	-105.8	121	0	200	Jun., Aug.	No	Yes
Clement et al. 2022	8	Crop (Alfalfa)	55.7	12.3	523	0	100	Jun. to Aug.	Yes	Yes
Clement et al. 2022	8	Crop (Wheatgra ss)	55.7	12.3	523	0	100	Jun. to Aug.	Yes	Yes
Dai et al. 2015	9	Shrub	44.33	87.9	125	0	300	Apr. to Sep.	No	Yes
Eggemeyer et al. 2009	10	Grass	41.9	-100.3	573	5	50	Jan. to Nov.	No	No
Eggemeyer et al. 2009	10	Tree	41.9	-100.3	573	5	90	Jan. to Nov.	Yes	Yes
Ellsworth et al. 2015	11	Tree	27.2	-81.33	1346	20	150	Jan. to Dec.	No	No
Goldsmith et al. 2012	12	Tree	19.75	-97	3186	0	40	Mar., May	No	No
Goldsmith et al. 2012	12	Tree	19.75	-97	3186	60	80	Mar., May	No	No
Hahn et al. 2021	13	Tree	0.5	35.3	1988	0	150	Sep. to Dec.	Yes	Yes
Hartsough et al. 2008	14	Tree	19.5	-103.5	1100	0	30	Mar., Nov.	No	No
Hoekstra et al. 2014	15	Grass	47.47	8.9	927	0	40	Jun. to Aug.	No	No
Hoekstra et al. 2014	15	Grass	47.4	8.5	1176	0	40	Jun. to Aug.	No	No
Jackson et al. 1995	16	Tree	9	-79.5	2600	20	100	Dec. to May	No	No

Jackson et al. 1999	17	Tree	-15.8	-47.8	1550	0	300	Aug., Sep.	No	No
Kulmatiski et al. 2010	18	Grass	-25	31.5	746	0	20	Oct., Nov., Feb., Apr.	Yes	No
Kulmatiski et al. 2010	18	Tree	-25	31.5	746	0	50	Oct., Nov., Feb., Apr.	No	No
Kulmatiski et al. 2013	19	Grass	-25	31.5	746	0	20	Nov., Feb., May	Yes	No
Kulmatiski et al. 2013	19	Tree	-25	31.5	746	0	20	Nov., Feb., May	Yes	No
Le Roux et al. 1995	20	Grass	6.25	-5	1210	10	20	May, Nov., Jan.	No	No
Le Roux et al. 1995	20	Shrub	6.25	-5	1210	10	30	May, Nov., Jan.	No	No
Li et al. 2006	21	Tree	48	108.5	296	0	30	Jun. to Oct.	No	No
Liu et al. 2010	22	Tree	21.9	101.25	1487	0	60	Mar., Dec.	No	Yes
Liu et al. 2010	22	Tree	21.9	101.25	1487	0	150	Mar., Dec.	No	Yes
Liu et al. 2011	23	Shrub	30.85	103	711	0	30	Aug.	No	No
Liu et al. 2019	24	Tree	37.5	114.5	521	0	40	Mar. to Sep.	No	No
Ma et al. 2018	25	Crop (Wheat)	39.5	116.5	540	0	70	Jul., Aug.	Yes	Yes
Meinzer et al. 1999	26	Tree	9	-79.5	2600	0	100	Jan. to May	No	Yes
Moreira et al. 2000	27	Grass	-3	-47	1800	0	100	Apr. Jun., Jul., Dec.	Yes	No
Moreira et al. 2000	27	Shrub	-3	-47	1800	0	25	Apr. Jun., Jul., Dec.	No	No
Munoz-Villers et al. 2020	28	Crop (Coffee)	19.5	-97	1765	0	15	Jan. to May, Aug.	No	No
Munoz-Villers et al. 2020	28	Tree	19.5	-97	1765	0	120	Jan. to May, Aug.	Yes	Yes
Nippert and Knapp 2007	29	Grass	39	-96	850	0	30	Jun. to Aug.	Yes	No
Nippert and Knapp 2007	29	Shrub	39	-96	850	0	30	Jun. to Aug.	Yes	No
Ogle et al. 2004	30	Shrub	33	-107	230	0	70	Jul. to Aug.	Yes	Yes
Ohte et al. 2003	31	Tree	39	109.15	362	0	150	Sep.	No	No
Ohte et al. 2003	31	Shrub	39	109.15	362	0	50	Sep.	Yes	No
Penna et al. 2021	32	Crop (Apple Tree)	46.6	10.7	480	0	40	Jun. to Sep.	Yes	No
Plamboeck et al. 1999	33	Tree	64.25	19.75	614	0	55	Jul., Aug.	Yes	No
Prechsl et al. 2015	34	Grass	47.2	8.3	1110	0	30	Apr. to Oct.	Yes	No
Prechsl et al. 2015	34	Grass	46.5	9.75	950	0	30	Apr. to Oct.	Yes	No
Ratajczak et al. 2011	35	Shrub	39.1	-96.6	835	0	75	Jun. to Sep.	Yes	No
Ratajczak et al. 2011	35	Grass	39.1	-96.6	835	0	30	Jun. to Sep.	Yes	No
Retzlaff et al. 2001	36	Tree	34.8	-79.6	1200	0	120	Mar. to Nov.	Yes	Yes

Schulze et al. 1996	37	Grass	-45.3	-69.8	125	0	30	Mar.	Yes	No
Schulze et al. 1996	37	Grass	-45.3	-70.3	160	0	30	Mar.	Yes	No
Schulze et al. 1996	37	Grass	-44.8	-71.3	290	0	30	Mar.	Yes	No
Schulze et al. 1996	37	Tree	-44.8	-71.6	770	0	80	Mar.	No	Yes
Sun et al. 2021	38	Crop (Pea)	47.5	8.5	994	0	20	May to Jul.	Yes	No
Sun et al. 2021	38	Crop (Barley)	47.5	8.5	994	0	60	May to Jul.	Yes	No
Wang et al. 2010	39	Crop (Corn)	34.9	110.75	590	0	50	May to Oct.	Yes	Yes
Wang et al. 2010	39	Crop (Cotton)	34.9	110.75	590	0	90	May to Oct.	Yes	Yes
Weltzin et al. 1997	40	Grass	31.5	-110.3	602	0	35	Apr., Sep.	Yes	No
Weltzin et al. 1997	40	Tree	31.5	-110.3	602	0	90	Apr., Sep.	No	Yes
Williams et al. 2000	41	Tree	34	-110	430	0	50	May to Sep.	No	Yes
Williams et al. 2000	41	Tree	39	-110	390	0	50	May to Sep.	No	Yes
Williams et al. 2000	41	Tree	39	-110	390	50	100	May to Sep.	No	No
Wu et al. 2014	42	Shrub	44.25	87.75	160	0	300	Mar. to Oct.	No	No
Wu et al. 2014	42	Shrub	44.25	87.75	160	0	60	Mar. to Oct.	Yes	No
Wu et al. 2016	43	Crop (Corn)	37.8	102.9	164	0	80	Jun. to Aug.	Yes	Yes
Yang et al. 2015	44	Crop (Corn)	38.5	100.33	129	0	10	Apr. to Sep.	No	No
Zhu et al. 2011	45	Shrub	38.5	103	111	0	120	May, Jul., Sep.	No	Yes

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