Satellites capture soil moisture dynamics deeper than a few centimeters and are relevant to plant water uptake

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Abstract

A common viewpoint across the Earth science community is that global soil moisture estimates from satellite L-band (1.4 GHz) measurements represent moisture only in the shallow soil layers (0-5 cm) and are of limited value for studying global terrestrial ecosystems because plants use water from deeper rootzones. Here, we argue that such a viewpoint is flawed for two reasons. First, microwave soil emission theory and statistical considerations of vertically correlated soil moisture information together indicate that L-band measurements are typically representative of soil moisture within at least the top 15-25 cm, or 3-5 times deeper than commonly thought. Second, in reviewing isotopic tracer field studies of plant water uptake, we find a global 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. While shrub and tree species tend to draw deeper soil moisture, these plants often still 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, and we encourage their application across terrestrial hydrosphere and biosphere studies.

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Abstract

A common viewpoint across the Earth science community is that global soil moisture estimates from satellite L-band (1.4 GHz) measurements represent moisture only in the shallow soil layers (0-5 cm) and are of limited value for studying global terrestrial ecosystems because plants use water from deeper rootzones. Here, we argue that such a viewpoint is flawed for two reasons. First, microwave soil emission theory and statistical considerations of vertically correlated soil moisture information together indicate that L-band measurements are typically representative of soil moisture within at least the top 15-25 cm, or 3-5 times deeper than commonly thought. Second, in reviewing isotopic tracer field studies of plant water uptake, we find a global 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. While shrub and tree species tend to draw deeper soil moisture, these plants often still 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, and we encourage their application across terrestrial hydrosphere and biosphere studies.

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 and 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 et al., 2018b, 2022; Konings et al., 2017; Purdy et al., 2018; Santanello et al., 2019; Short Gianotti et al., 2020; Taylor et al., 2012; Tuttle and Salvucci, 2016).

However, a viewpoint has spread that microwave satellite soil moisture is of limited use for studying vegetated landscapes because it only perceives the surface layer of deep rootzones. A major contributor to this viewpoint is the history of the microwave remote sensing community generally offering a simplified view of a shallow observing depth of satellite-based retrievals. For example, 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- and X-band frequencies) are thought to observe only the top 2 cm of soil. Other contributors to this viewpoint include the prevalent use of the top-most in-situ sensors for assessing satellite soil moisture products, and a common intuition that the maximum rooting depth defines the relevant water uptake profile.

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 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). As a result, many researchers avoid the use of these microwave satellite soil moisture products, instead often favoring rootzone moisture products from model reanalysis or precipitation-based wetness indices. We avoid calling attention to specific references, but argue that such a viewpoint is widely held and is stated across the peer-reviewed literature. If satellite soil moisture retrievals were to hold more information about the rootzone, they would be considered more desirable than reanalysis products for some 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 and Crow, 2019).

In fact, recent studies do not support the idea that microwave satellites are limited to seeing only a shallow (0-5 cm) surface soil layer. The same L-band microwaves used to retrieve surface soil moisture have been previously used to detect subsurface geologic features in drylands beyond depths of one meter (Farr et al., 1986; Paillou et al., 2010). Even if soil moisture satellites only observed the upper soil layers, surface and rootzone moisture dynamics are almost always hydraulically connected and correlated (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 (Albergel et al., 2008; McColl et al., 2017). Hydraulic redistribution by plants can also further couple the surface and deeper soil layers (Nadezhdina et al., 2010). As a result, the vertical depth of representation, or support scale, of L-band satellite surface soil moisture has been shown to be deeper than 5 cm (Akbar et al., 2018; Short Gianotti et al., 2019). Both surface and deeper soil layer support scales consequently have similar information content in explaining evapotranspiration fluxes and moisture thresholds between evaporative regimes (Dong et al., 2022; Qiu et al., 2016). Satellite surface soil moisture retrievals are thus recognized as a means to improve the characterization of rootzone soil moisture and evapotranspiration in model assimilation frameworks (Kumar et al., 2009; Purdy et al., 2018; Reichle et al., 2019).

Furthermore, a common emphasis on the fact that maximum rooting depths can extend plant water uptake meters into the soil (Nepstad et al., 1994) neglects that active water uptake is rarely uniform across the rooting profile. Specifically, global observations and optimally modeled rooting profiles indicate that most plants preferentially draw water from the upper soil layers to take advantage of these layers' pulse water and nutrient availability (Collins and Bras, 2007; Jackson et al., 1996; Nippert and Holdo, 2015). 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.

This perspective article evaluates the literature to determine (1) whether L-band satellite surface soil moisture products capture soil moisture dynamics deeper than 5 cm and (2) to what extent the vertical soil depth representation of satellite retrievals is relevant for global vegetation water uptake and evapotranspiration.

2. Satellite Soil Moisture's Effective Sensing Depth

The true vertical support of remote sensing-based soil moisture retrievals is dependent on both (1) the microwave emission properties of the soil column and (2) the vertical autocorrelation of typical soil moisture profiles and their dynamics (Njoku and Entekhabi, 1996; Short Gianotti et al., 2019). Both principles result in decay of soil moisture representation with depth (i.e., exponential distribution). Furthermore, these principles trade off in dominance from dry to wet conditions (Fig. 1).

For drier soils, L-band satellites directly detect soil moisture in a deeper soil column because microwave emission originates from deeper soil layers (Fig. 1). Specifically, modeling microwave emission from a soil layer that is assumed to be a homogenous, dielectric medium reveals that soil emission depth increases with aridity and vertically decays approximately exponentially (Njoku and Entekhabi, 1996; Njoku and Kong, 1977). Therefore, despite drier periods resulting in less coupling between surface and deeper layer soil moisture, satellites directly sample deeper into the soil column, often well below 5 cm (Fig. 1).

For wetter soils, despite shallower soil emission depths from an electromagnetic perspective, surface soil moisture has a greater hydraulic connectivity with deeper soil layers (Fig. 1). This is because soil moisture is a storage variable with strong spatiotemporal memory (McColl et al., 2017). As a result, satellite soil moisture from L-band satellites holds statistical information about the soil moisture magnitudes and variations deeper than 5 cm into the soil column, especially under wetter conditions (Akbar et al., 2018; Short Gianotti et al., 2019). Such vertical autocorrelation information decays approximately exponentially with depth, similarly to microwave soil emission.

Combining these electromagnetic and statistical considerations shows that, under a wide range of soil moisture conditions, L-band satellites effectively sample soil moisture dynamics deeper than 5 cm - realistically the top 15 to 25 cm (Fig. 1). This deeper "effective sensing depth" 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, the full depth of which is under investigation. Deeper layers between 25 to 100 cm are still integrated but contribute progressively less to the signal with depth (Fig. 1). 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.

Note that, in the case of drier soils, the microwave emission depth directly observes 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 nearer to 5 cm are directly observed by L-band satellite sensors (Fig. 1). Nevertheless, the typically high hydraulic connectivity between shallow and deeper layers in these wetter conditions allows indirect observation of the soil moisture magnitude and variations in the deeper layers.

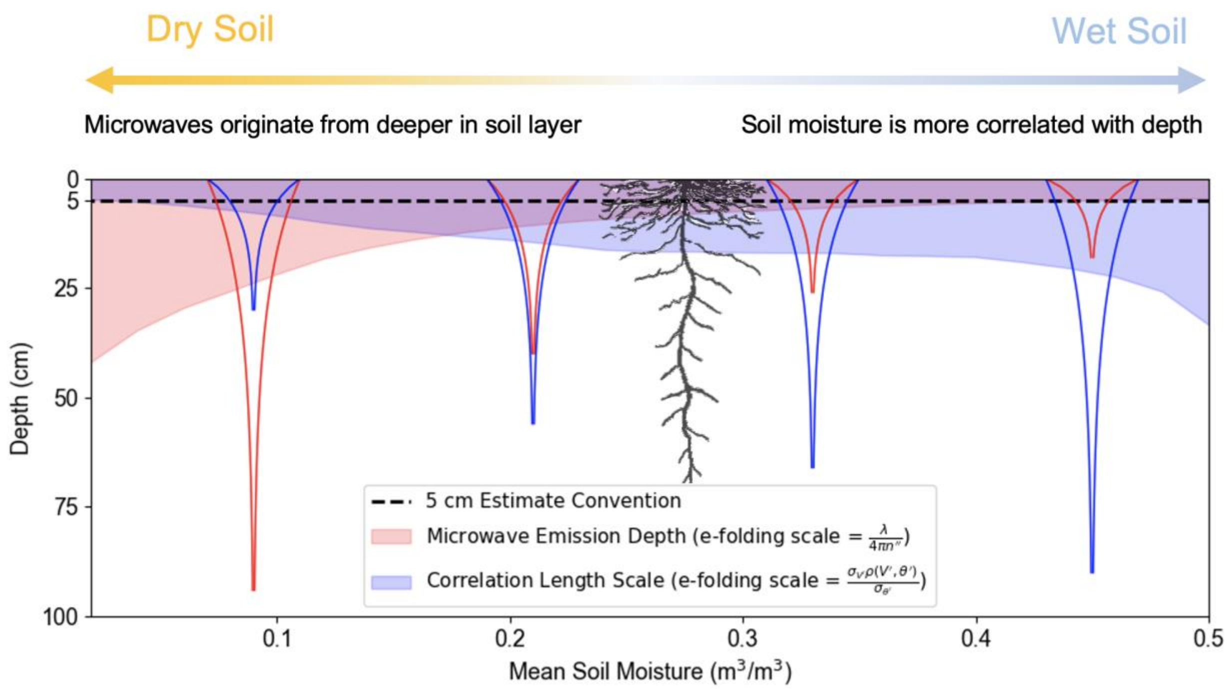

Figure 1. Effective sensing depth of microwave satellite soil moisture based on consideration of both L-band (1.4 GHz) microwave soil emission physics and vertical hydraulic connectivity of soil moisture. Satellite effective sensing depths of soil moisture range between 15 cm to over 25 cm, 3-5 times deeper than commonly thought, while integrating some deeper soil information. Effective sensing depths (shading) are e-folding scales determined from distributions (solid lines) of microwave soil emission and soil moisture information with depth. Microwave emission depth e-folding scale (red shading) and example emission profiles (red solid lines) are computed based on the soil emission model in Njoku and Entekhabi, (1996). Note that changes in soil texture have minimal influence on microwave emission depths compared to variations in soil moisture (not shown). E-folding vertical correlation length scales (blue shading) are computed by averaging global vertical length scale estimates, obtained with permission from Short Gianotti et al., (2019), binned based on mean annual soil moisture. Corresponding example profiles of degree of hydraulic connectivity with the surface (blue solid lines) are estimated from these averaged e-folding length scales. For equation details, see Appendix A. The displayed root profile image, adapted with permission from Nippert and Holdo, (2015), has a commonly-observed structure of decreasing root biomass with depth. The exact dimensions vary globally.

3. Revised View of Plant Water Uptake Depths

A common viewpoint across the Earth science community is that rootzones are (qualitatively) “deep,” which strongly argues against using a 0-5-cm or even a 0-20-cm soil moisture dataset 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 and surface topography (Fan et al., 2017; Nepstad et al., 1994; H. J. Schenk and Jackson, 2002; 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 and survive under severe water-limitation (Stocker et al., 2021). 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 and their relevance to the global water cycle. Specifically, global rooting profiles are typically concentrated in the upper soil layers and decrease in root density with depth (Jackson et al., 1996). For example, some estimates indicate that 90% of global vegetation has more than half of their roots in the top 30 cm of soil (J. H. Schenk and Jackson, 2002).

Shallow preferential soil water uptake and deeper roots can exist concurrently - the existence of a deep maximum rooting depth does not imply low plant utilization of shallow soil moisture. The deepest roots are indeed important for survival under seasonal or severe water limitation. However, the frequency and volumetric proportion of use of these deeper water stores is small, often much less than 10% of annual plant water uptake (McCormick et al., 2021; Miguez-Macho and Fan, 2021). This lower contribution of water uptake from the deeper layers is, 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 and Fowkes, 1978; Nippert et al., 2012). Additionally, essential limiting nutrients are typically highly concentrated in the upper soil layers due to decaying organic matter, which prevents sole plant reliance on deeper moisture sources (Jobbágy and 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, the maximum rooting depth is often of limited importance for evaluating nominal plant water uptake throughout the year (Nippert and Holdo, 2015). This is true even in water-limited ecosystems (Nippert and Holdo, 2015), where rainfall infiltration is often shallow (<30 cm) and plants must rely on this more frequently wetted shallow zone for survival (Scott and Biederman, 2019).

Additionally, 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 and Boyer, 1995). Instead, isotopic tracers can be used to estimate the true range of primary water uptake, commonly called the functional rooting profile (Dawson and Pate, 1996; Ehleringer and 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 (Fig. 2). Values displayed in Fig. 2 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). We additionally searched citations within studies that initially met our criteria using these same keywords. Our search resulted in 45 references that met our criteria (Fig. 2 and Table S1).

We find that grass and crop species across global climates typically extract water from the upper soil layers (0-30 cm) over most of the year, with preferential uptake of water nearer to the surface (Figs. 2A and 2B). For grass species, 95% of the studies found grasses primarily use water from at least the top 50 cm with 65% of studies explicitly finding increased proportional uptake in the top-most soil layers (Fig. 2A). All sampled crop species either primarily use soil water within the top 25 cm or preferentially draw water from the upper soil layers with decreasing water use with depth (Fig. 2B). All crop studies that found water use extending deeper than 50 cm also found proportionally higher water use in the upper soil layers. 88% of these same studies also found the primary plant water uptake zone transitioned temporarily to the upper soil layers (see diamond symbols in Fig. 2B).

Shrub and tree species show a larger vertical range of water uptake, with water uptake commonly extending to well below 50 cm (Figs. 2C and 2D) 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 isotopic studies 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 a lack of field measurements in the tropics (Schimel et al., 2015). More studies also take place in semi-arid and sub-humid environments because of their higher proportion of global land cover (about 70% of land surfaces receive <1,000 mm of annual rainfall according to Global Precipitation Measurement rainfall (Huffman, 2015)). While our search yielded few tropical forest studies, we expect these regions may have deeper functional rooting profiles similarly to those found in Fig. 2D (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.

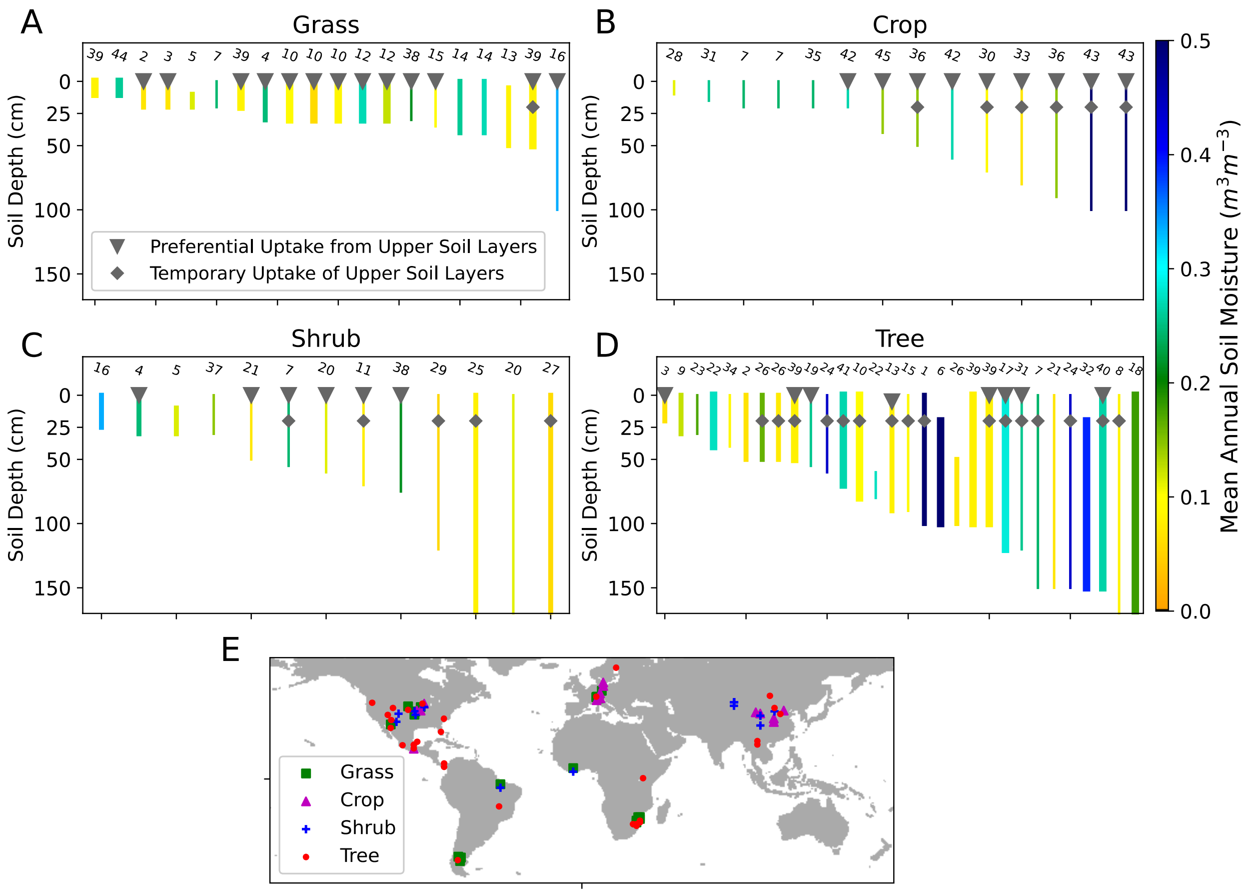

Figure 2. Primary root water uptake profiles (or functional rooting profile) based on field stable isotope tracer studies for species binned in (A) grass, (B) crop, (C) shrub, and (D) tree categories based on Table S1. The triangle symbol means the study found preferential water uptake nearer to the 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 (<~30cm) 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). Mean annual SMAP soil moisture is displayed for each field site using the nearest 36 km pixel. (E) Locations of the isotopic field measurements.

4. Recommendations

Our findings convey that satellite L-band radiometry captures global soil moisture dynamics at least as deep as the top 15-25 cm of soil (Fig. 1), which is more than three times deeper than commonly stated as well as more relevant for evaluating plant function than commonly appreciated. L-band satellite soil moisture estimates appear optimal for studying most grasslands and croplands, which cover more than a third of global vegetated surfaces. This proportion is higher when including non-vegetated surfaces, given that bare surfaces are also dominated by upper soil layer processes (i.e., bare soil evaporation). Grass and crop water use also decreases with depth, much like the decreasing L-band satellite soil moisture representation with depth (Fig. 1). Therefore, soil moisture datasets that integrate rootzone dynamics between 0-100 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. 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 Fig. 2) 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, and will increase in utility if global functional root profiles become shallower under global change (Hauser et al., 2020).

Given these considerations, our findings indicate a wider applicability of satellite soil moisture for the study of global climate. This encourages broader, more confident use of 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 (Akbar et al., 2020; Dong et al., 2020; Feldman et al., 2022, 2018b; Konings et al., 2017; Purdy et al., 2018; Santanello et al., 2019; Short Gianotti et al., 2020; Taylor et al., 2012; Tuttle and Salvucci, 2016).

While our assessment indicates wide applicability of L-band satellite soil moisture, 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 mixed (i.e., savanna) and forested landscapes.

Furthermore, we argue that there is no single soil moisture product that will globally 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 dataset. Potentially, multiple products and their synergistic use are needed depending on the complexity of root water uptake scenarios.

For example, for herbaceous ecosystems including most croplands, grasslands, and savannas with sparse tree cover, the L-band soil moisture products will likely optimally integrate the relevant rootzone moisture information. 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, datasets representing a uniform distribution of integrated soil moisture across the top 1-2 meters of soil (i.e., model reanalysis rootzone soil moisture products) may be optimal (Reichle et al., 2019). P-band (0.4 GHz) soil moisture remote sensing applications may be more useful for these scenarios as well with potentially twice as deep of effective sensing depths than at L-band (Konings et al., 2014). Finally, in scenarios where root water uptake extends well below one meter for consistent or transient use of deep moisture or groundwater (McCormick et al., 2021; Miguez-Macho and 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 et al., 2018a; 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 and Famiglietti, 2001).

In summary, we urge the community to consider using L-band soil moisture observations for applications involving vegetated landscapes. The value of satellite-based soil moisture beyond only a shallow (0-5 cm) surface layer emphasizes the urgent need to maintain continuity of L-band satellite remote sensing missions.

Appendix A

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

$$L_{Emission} = \frac{\lambda}{4\pi n''} \qquad \text{(Eq. A1)}$$

where λ is the emission wavelength (Njoku and Kong, 1977). 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). $L_{Emission}$ is the e-folding scale that represents the emission depth of microwaves. Measurements of these microwaves are used to estimate satellite soil moisture.

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

$$L_{Correlation} = \frac{\sigma_{V'}\rho(V',{\theta_s}')}{\sigma_{{\theta_s}'}} \qquad \text{(Eq. A2)}$$

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. $L_{Correlation}$ 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. $L_{Correlation}$ 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 $L_{Correlation}$ to be a support scale of the soil moisture magnitude and time dynamics (Akbar et al., 2018).

While Eq. A2 is an exact solution, total column volumetric moisture is not widely available to estimate $L_{Correlation}$ globally. Thus, Short Gianotti et al. (2019) estimate $L_{Correlation}$ 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 and SMAP soil moisture retrievals are used together to globally estimate $L_{Correlation}$, which are used in Fig. 1.

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Author Contributions

A.F.F. conceived of the study, performed the analysis, and drafted the manuscript. D.E. and A.F.F. led the study. D.J.S.G., J.D., R.A., W.T.C, and D.E. provided guidance and edits on the presentation of satellite sensing depth estimates. J.B.N., S.J.T.D, N.M.H., F.E.R., and R.L.S. provided guidance and edits on presentation of isotopic tracer studies and rooting depth information. K.A.M., R.H.R., A.C., J.J., and B.P. provided guidance on all components and, in particular, in framing the perspective in the context of their respective fields. All authors contributed substantial textual edits.

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Table S1. Field isotropic tracer studies across the globe as displayed in Fig. 2. Crop species are specified and partitioned in the table due to wide variability of cultivated vegetation types (includes both herbaceous and woody species). Decay of water uptake with depth found in the study (1 = yes, 0 = no). Temporary plant uptake of upper layer soil moisture found in the study (1 = yes, 0 = no).

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
Meinzer et al. 1999	1	Tree	9	-79.5	2600	0	100	Jan. to May	0	1
Kulmatiski et al. 2010	2	Grass	-25	31.5	746	0	20	Oct., Nov., Feb., Apr.	1	0
Kulmatiski et al. 2010	2	Tree	-25	31.5	746	0	50	Oct., Nov., Feb., Apr.	0	0
Kulmatiski et al. 2013	3	Grass	-25	31.5	746	0	20	Nov., Feb., May	1	0
Kulmatiski et al. 2013	3	Tree	-25	31.5	746	0	20	Nov., Feb., May	1	0
Nippert and Knapp 2007	4	Grass	39	-96	850	0	30	Jun. to Aug.	1	0
Nippert and Knapp 2007	4	Shrub	39	-96	850	0	30	Jun. to Aug.	1	0
Le Roux et al. 1995	5	Grass	6.25	-5	1210	10	20	May, Nov., Jan.	0	0
Le Roux et al. 1995	5	Shrub	6.25	-5	1210	10	30	May, Nov., Jan.	0	0
Jackson et al. 1995	6	Tree	9	-79.5	2600	20	100	Dec. to May	0	0
Asbjornsen et al. 2008	7	Grass	41.5	-93	882	0	20	May to Sep.	0	0
Asbjornsen et al. 2008	7	Crop (Soybean)	41.5	-93	882	0	20	May to Sep.	0	0
Asbjornsen et al. 2008	7	Crop (Corn)	41.5	-93	882	0	20	May to Sep.	0	0
Asbjornsen et al. 2008	7	Shrub	41.5	-93	882	0	55	May to Sep.	1	1
Asbjornsen et al. 2008	7	Tree	41.5	-93	882	0	150	May to Sep.	0	1
Brooks et al. 2002	8	Tree	44	-121	550	0	200	Jul. to Sep.	0	1
Li et al. 2006	9	Tree	48	108.5	296	0	30	Jun. to Oct.	0	0
Schulze et al. 1996	10	Grass	-45.3	-69.8	125	0	30	Mar.	1	0
Schulze et al. 1996	10	Grass	-45.3	-70.3	160	0	30	Mar.	1	0
Schulze et al. 1996	10	Grass	-44.8	-71.3	290	0	30	Mar.	1	0
Schulze et al. 1996	10	Tree	-44.8	-71.6	770	0	80	Mar.	0	1
Ogle et al. 2004	11	Shrub	33	-107	230	0	70	Jul. to Aug.	1	1
Prechsl et al. 2015	12	Grass	47.2	8.3	1110	0	30	Apr. to Oct.	1	0
Prechsl et al. 2015	12	Grass	46.5	9.75	950	0	30	Apr. to Oct.	1	0

Eggemeyer et al. 2009	13	Grass	41.9	-100.3	573	5	50	Jan. to Nov.	0	0
Eggemeyer et al. 2009	13	Tree	41.9	-100.3	573	5	90	Jan. to Nov.	1	1
Hoekstra et al. 2014	14	Grass	47.47	8.9	927	0	40	Jun. to Aug.	0	0
Hoekstra et al. 2014	14	Grass	47.4	8.5	1176	0	40	Jun. to Aug.	0	0
Weltzin et al. 1997	15	Grass	31.5	-110.3	602	0	35	Apr., Sep.	1	0
Weltzin et al. 1997	15	Tree	31.5	-110.3	602	0	90	Apr., Sep.	0	1
Moreira et al. 2000	16	Grass	-3	-47	1800	0	100	Apr. Jun., Jul., Dec.	1	0
Moreira et al. 2000	16	Shrub	-3	-47	1800	0	25	Apr. Jun., Jul., Dec.	0	0
Retzlaff et al. 2001	17	Tree	34.8	-79.6	1200	0	120	Mar. to Nov.	1	1
Jackson et al. 1999	18	Tree	-15.8	-47.8	1550	0	300	Aug., Sep.	0	0
Plamboeck et al. 1999	19	Tree	64.25	19.75	614	0	55	Jul., Aug.	1	0
Wu et al. 2014	20	Shrub	44.25	87.75	160	0	300	Mar. to Oct.	0	0
Wu et al. 2014	20	Shrub	44.25	87.75	160	0	60	Mar. to Oct.	1	0
Ohte et al. 2003	21	Tree	39	109.15	362	0	150	Sep.	0	0
Ohte et al. 2003	21	Shrub	39	109.15	362	0	50	Sep.	1	0
Goldsmith et al. 2012	22	Tree	19.75	-97	3186	0	40	Mar., May	0	0
Goldsmith et al. 2012	22	Tree	19.75	-97	3186	60	80	Mar., May	0	0
Hartsough et al. 2008	23	Tree	19.5	-103.5	1100	0	30	Mar., Nov.	0	0
Liu et al. 2010	24	Tree	21.9	101.25	1487	0	60	Mar., Dec.	0	1
Liu et al. 2010	24	Tree	21.9	101.25	1487	0	150	Mar., Dec.	0	1
Chimner et al. 2004	25	Shrub	37.7	-105.8	121	0	200	Jun., Aug.	0	1
Williams et al. 2000	26	Tree	34	-110	430	0	50	May to Sep.	0	1
Williams et al. 2000	26	Tree	39	-110	390	0	50	May to Sep.	0	1
Williams et al. 2000	26	Tree	39	-110	390	50	100	May to Sep.	0	0
Dai et al. 2015	27	Shrub	44.33	87.9	125	0	300	Apr. to Sep.	0	1
Yang et al. 2015	28	Crop (Corn)	38.5	100.33	129	0	10	Apr. to Sep.	0	0
Zhu et al. 2011	29	Shrub	38.5	103	111	0	120	May, Jul., Sep.	0	1
Ma et al. 2018	30	Crop (Wheat)	39.5	116.5	540	0	70	Jul., Aug.	1	1
Munoz-Villers et al. 2020	31	Crop (Coffee)	19.5	-97	1765	0	15	Jan. to May, Aug.	0	0
Munoz-Villers et al. 2020	31	Tree	19.5	-97	1765	0	120	Jan. to May, Aug.	1	1
Ellsworth et al. 2015	32	Tree	27.2	-81.33	1346	20	150	Jan. to Dec.	0	0
Wu et al. 2016	33	Crop (Corn)	37.8	102.9	164	0	80	Jun. to Aug.	1	1
Liu et al. 2019	34	Tree	37.5	114.5	521	0	40	Mar. to Sep.	0	0
Asbjornsen et al. 2007	35	Crop (Corn)	41.5	-93.25	882	0	20	Jul.	0	0

Wang et al. 2010	36	Crop (Corn)	34.9	110.75	590	0	50	May to Oct.	1	1
Wang et al. 2010	36	Crop (Cotton)	34.9	110.75	590	0	90	May to Oct.	1	1
Liu et al. 2011	37	Shrub	30.85	103	711	0	30	Aug.	0	0
Ratajczak et al. 2011	38	Shrub	39.1	-96.6	835	0	75	Jun. to Sep.	1	0
Ratajczak et al. 2011	38	Grass	39.1	-96.6	835	0	30	Jun. to Sep.	1	0
Case et al. 2020	39	Grass	-24	31.5	479	0	10	May, Jun.	0	0
Case et al. 2020	39	Tree	-24	31.5	479	0	50	May, Jun.	1	1
Case et al. 2020	39	Grass	-24	31.5	510	0	20	May, Jun.	1	0
Case et al. 2020	39	Tree	-24	31.5	510	0	100	May, Jun.	0	0
Case et al. 2020	39	Grass	-24	31.5	600	0	50	May, Jun.	1	1
Case et al. 2020	39	Tree	-24	31.5	600	0	100	May, Jun.	1	1
Hahn et al. 2021	40	Tree	0.5	35.3	1988	0	150	Sep. to Dec.	1	1
Brinkmann et al. 2019	41	Tree	47.5	8.3	1110	0	70	Apr. to Nov.	0	1
Sun et al. 2021	42	Crop (Pea)	47.5	8.5	994	0	20	May to Jul.	1	0
Sun et al. 2021	42	Crop (Barley)	47.5	8.5	994	0	60	May to Jul.	1	0
Clement et al. 2022	43	Crop (Alfalfa)	55.7	12.3	523	0	100	Jun. to Aug.	1	1
Clement et al. 2022	43	Crop (Wheatgrass)	55.7	12.3	523	0	100	Jun. to Aug.	1	1
Bachmann et al. 2015	44	Grass	50.9	11.5	587	0	10	Apr., Jun., Sep.	0	0
Penna et al. 2021	45	Crop (Apple Tree)	46.6	10.7	480	0	40	Jun. to Sep.	1	0

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