Validation of Remotely Sensed and Modeled Soil Moisture at Forested and Unforested NEON Sites

Edward Ayres, Rolf H. Reichle, Andreas Colliander, *Senior Member, IEEE*, Michael H. Cosh, *Senior Member, IEEE*, and Lucas Smith

***Abstract*—Soil moisture (SM) is an important driver for forest ecosystems, creating a need for globally extensive SM information that can only be achieved with satellite-based sensors and/or process-based model. However, the reliability of remotely sensed or modeled SM data in forests is poorly understood due to a lack of suitable validation sites and interference with remote sensing caused by vegetation water content. Here, we examine three multiyear SM products: remotely sensed surface (0–5 cm) SM from combined soil moisture active passive (SMAP) and Sentinel-1 observations (SMAP/Sentinel); the SMAP Level-4 surface (0–5 cm) and root-zone (0–1 m) SM data assimilation product (SMAP-L4); and simulated surface (0–10 cm) and root-zone (0–1 m) SM from the North American land data assimilation system (NLDAS). These estimates were compared with in situ measurements from 39 National Ecological Observatory Network sites throughout the U.S. At 21 unforested sites, the performance of the three products was similar for surface SM, and all three were able to track temporal changes in surface SM. The performance of the three products declined at 18 forested sites; however, while the performance declined modestly for SMAP-L4 and NLDAS, SMAP/Sentinel performance declined so much that it was largely unable to track changes in surface SM. The SMAP-L4 and NLDAS products also reliably captured temporal changes in root-zone SM at both forested and unforested sites. Our findings indicate that both SMAP-L4 and NLDAS can be used to track surface and root-zone SM changes in forests (unbiased root-mean-square deviation: 0.03–0.06 m^3 m^{-3}).**

***Index Terms*—Forests, in situ validation, National Ecological Observatory network (NEON), North American land data assimilation system (NLDAS), soil moisture (SM), soil moisture active passive (SMAP).**

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I. Introduction

Forests cover 20%–30% of the global land surface, including 3.3 million km^2 in the U.S. [1], and soil moisture influences several important forest processes and disturbances, including tree growth, the occurrence and extent of fires, and insect and pathogen impacts [2], [3], [4]. Satellite-based sensors and process-based models driven with remotely sensed observations are the only feasible way to generate regular, globally extensive soil moisture estimates encompassing forested regions; however, the reliability of soil moisture data in forests is not well understood due to a lack of suitable validation sites, especially relative to unforested ecosystems, and due to uncertainties in remotely sensed measurements caused by high vegetation water content.

Until recently, remotely sensed and modeled soil moisture data were only available at relatively coarse spatial resolutions, typically of tens of kilometers. For example, the –3 dB footprint of the *L*-band (1.4 GHz) radiometer on the NASA soil moisture active passive (SMAP) satellite covers an area of $\sim 40^2$ km^2 [5], [6]. While such data are undeniably useful for assessing large-scale patterns, they are generally too coarse to be directly actionable for most land managers. Moreover, few soil moisture monitoring networks have a similar scale to validate such data.

Over time, remotely sensed and modeled soil moisture data have achieved finer resolutions on the order of 1–10 km. Simulated soil moisture is available from the North America land data assimilation system (NLDAS) at ~12 km resolution [7]. The SMAP Level-4 (SMAP-L4) soil moisture product assimilates the coarse-resolution SMAP radiometer observations into a higher resolution land-surface model, thereby producing soil moisture estimates at ~9 km resolution [8], [9]. Another example is the SMAP/Sentinel soil moisture product, which uses *C*-band (5.4 GHz) radar backscatter observations from the European Space Agency's Sentinel-1 satellite to downscale the coarse-resolution SMAP radiometer observations to a resolution of ~3 km [10], thereby approaching scales appropriate for land-management applications. However, these higher resolution data have only been validated for a very small number of forested sites. The ultrafine (200 m) spatial resolution soil moisture data that will be generated by the upcoming NASA–ISRO synthetic aperture radar (NISAR) [11] satellite will be compatible with the scale of many land-management decisions, and in situ soil moisture monitoring networks will be needed to assess the

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reliability of the NISAR products across a wide range of ecosystems, including forests.

To date, forested sites have been extremely under-represented in soil moisture validation studies due to the relative paucity of forested soil moisture monitoring stations compared with grassland and agricultural sites. For example, none of the densely instrumented core validation sites used for the validation of SMAP soil moisture products were forested (although 3–5 "candidate" validation sites were forested) [12], [13], and only 1% of the sparse validation sites were forested [14]. In addition, SMAPs original objective was to measure soil moisture in ecosystems with vegetation water content ≤ 5 kg$\cdot$m^{-2}, which excludes all forests. Given the importance of soil moisture information in forested ecosystems, however, there is a need to validate performance in forests. New in situ sensor installations are beginning to address this, with three densely instrumented forested core validation sites recently established [15], [16], but the level of effort required to establish and maintain such sites means that they will always be rare and unable to capture the diversity of forested systems. Sparsely instrumented forested validation sites, consisting of one or a small number of nearby in situ measurement locations, complement densely instrumented validation sites by expanding the range of ecosystems, soil types, and management practices that are included in validation networks, albeit by accepting a lower level of spatial representativeness. Such sites are increasingly used to validate soil moisture measurements in forested systems [17], [18] but have yet to be used to validate soil moisture data products with intermediate spatial resolutions (i.e., ~10 km or less) across a wide range of forest types.

In part, the under-representation of forested sites in soil moisture validation studies is due to the design of continental-scale soil moisture networks that have historically focused on unforested locations and contain few forested sites, such as the agriculturally focused soil climate analysis network (SCAN) [19] and the climatologically focused U.S. climate reference network [20], although the snow telemetry network in the western U.S. does include several forested sites where soil moisture is measured. In contrast, the U.S. National Ecological Observatory Network (NEON) was designed to monitor ecological processes in natural and managed ecosystems throughout the U.S. and encompasses a wide diversity of both unforested and forested sites. At each of the terrestrial NEON sites, soil moisture is measured at a range of depths down to 2 m in five soil plots separated by tens of meters. This design supports surface and root-zone soil moisture measurements that can capture some of the local-scale spatial variability in soil moisture, albeit at a scale that is much smaller than currently available remotely sensed or modeled soil moisture data products. In addition to soil moisture, NEON provides over 170 other data products that can be leveraged to better understand how the performance of remotely sensed and modeled soil moisture data products varies in relation to ecosystem properties. This is particularly useful for interpreting the performance of remotely sensed soil moisture due to its known sensitivity to vegetation water content.

Here, we validate the performance of multiyear remotely sensed (SMAP/Sentinel), remotely sensed data assimilation modeled (SMAP-L4), and modeled (NLDAS) surface and "root-zone" (0–1 m) soil moisture datasets with data from in situ sensors at 39 NEON sites throughout the contiguous U.S. (CONUS). Due to differences in spatial resolution, NEON soil moisture (~0.2 km measurement zone) correlations were expected to be stronger with the SMAP/Sentinel product (3 km resolution) than with coarser resolution SMAP-L4 (9 km resolution) or NLDAS products (~12 km resolution). Given the sensitivity of satellite measurements to vegetation water content, we expected to observe a deterioration in the correlations based on remotely sensed measurements (SMAP/Sentinel and, to a lesser extent, SMAP-L4) as indicators of vegetation water content increase. In contrast, the model-based data (NLDAS) was expected to be largely insensitive to differences in vegetation. In addition, we investigated seasonal changes in the performance of the three data products in estimating soil water content at both unforested and forested sites, with the expectation that the performance of the SMAP/Sentinel product, and to a lesser extent, the SMAP-L4 product, would deteriorate during the summer months at forested sites due to SMAPs known sensitivity to vegetation water content. The performance of remotely sensed and modeled soil moisture products was assessed for both forested and unforested sites, but we place a greater emphasis on the results from forested sites since much less is known about the products' performance in these ecosystems, while many previous studies have assessed performance in unforested systems [12], [13], [14].

II. Data and Methods

A. NEON Sites

NEON monitors ecosystem properties at 47 terrestrial sites across the United States. The analysis conducted here used the 39 NEON sites in CONUS because SMAP/Sentinel and NLDAS data were unavailable for Alaska and because proximity to the ocean prevents reliable SMAP soil moisture retrievals for Puerto Rico and Hawaii. The 39 sites span a wide range of latitudes (28–47°N), elevations (13–3490 m), mean annual temperature (0.3–22.5 °C), mean annual precipitation (271–2451 mm), and many different vegetation and soil types (see Fig. 1 and Table II). The large differences in spatial scale between the NEON sites and the SMAP footprint mean the dominant vegetation for the NEON plots sometimes differs from the dominant vegetation in the larger SMAP footprint, although, in most cases, the vegetation is similar at the two scales (see Table II). In addition, a prior analysis showed strong positive correlations for both canopy height and an index of vegetation water content between the smaller NEON sites and the larger SMAP footprints [18]. Although it was not assessed, it is likely that there are also some differences in soil properties (e.g., soil texture and soil organic carbon content) between the NEON plots and the larger SMAP footprint. In most cases, however, the soil properties are expected to be broadly similar at the two scales.

1) NEON Soil Moisture: At each site, soil moisture is measured in five soil plots. The soil plots are spaced up to approximately 40 m apart and are typically arranged in a transect in the locally dominant soil type immediately surrounding the

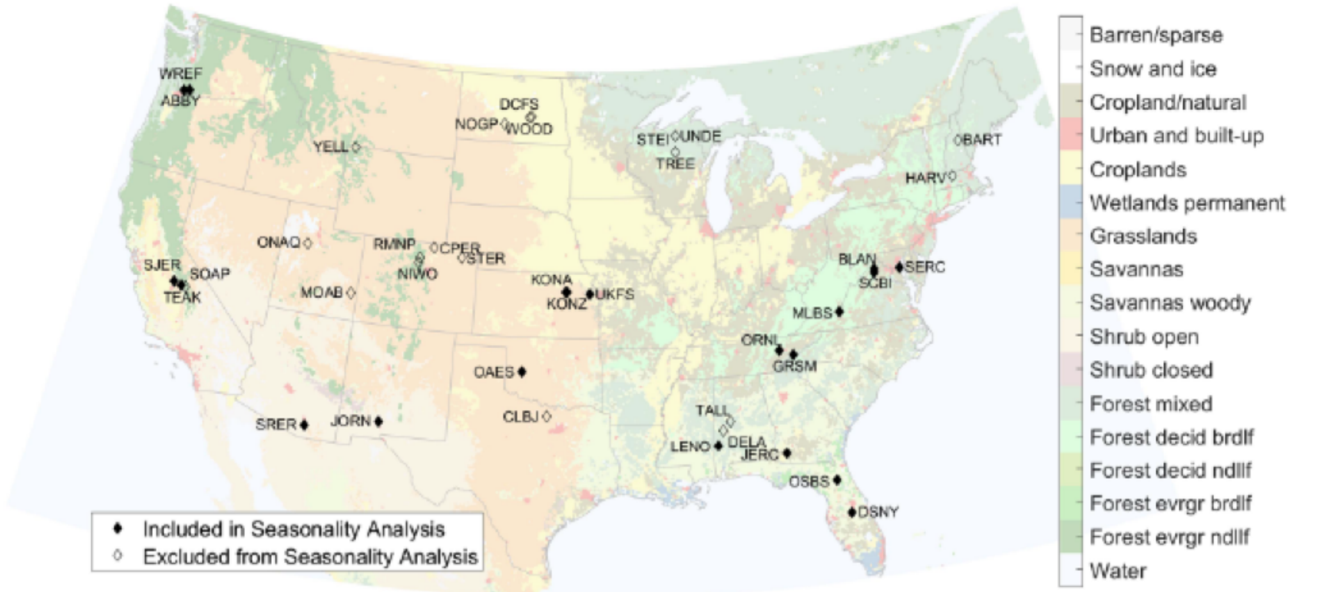

Fig. 1. NEON sites used to validate the three soil moisture data products over MODIS-based IGBP land cover.

NEON tower. Where management activities occur in the immediate surrounding area (e.g., grazing, prescribed burns, and crop planting), the NEON plots are managed as similarly as feasible. In cases where the vegetation at the NEON site is cultivated crops, the soil moisture plots are located within the field (not at the field margin), and none of the fields are irrigated. A single vertical profile of soil moisture with up to eight sensor depths is measured in each of the five soil plots down to 2 m or a restrictive feature if the soil is shallower. The shallowest sensors are installed at depths of 6, 16, and 26 cm (all ± 1 cm), while installation depths for deeper sensors vary among sites based on soil horizon thicknesses and soil depth (see [18] for details). Data are processed using standardized algorithms that calculate soil water content, perform quality assurance and quality control (QA/QC) tests, and generate 1- and 30-min averages. The data are freely available for download (NEON data product ID: DP1.00094.001).

The 30-min soil water content data spanning 2016 to April 2022 were downloaded from the NEON data portal using the neonUtilities R package [21]. Since the calibration coefficients loaded on the sensors changed during the period of interest, raw sensor measurements were backcalculated and a soil-specific calibration was applied, thereby generating a consistent time series across the entire experimental period at each measurement location [22]. The soil-specific calibrations did not allow implausible soil moisture (i.e., $>0.6\,m^3\,m^{-3}$). A final quality flag was assigned to each datum based on the data product quality metrics, as well as a visual inspection of the time series. Only data with a final quality flag of 0 (i.e., considered trustworthy) were used.

Data from the shallowest NEON measurement level ($\sim$6 cm) were used to validate the SMAP and NLDAS surface soil moisture datasets, while multiple measurement levels within the 0–1 m layer were used to validate the root-zone datasets. Soil moisture for the 0–1 m layer of each soil plot was calculated as a depth-weighted average of measurements from the sensors within that layer, excluding data that failed the QA/QC tests. Within each soil plot, the group of sensors (i.e., depths) that most often passed the QA/QC tests at the same time over the experimental period were used to calculate the weighted vertical average. This avoids introducing artificial step changes in the time series caused by sensors dropping in and out of the averaging based on their QA/QC flags (see Table III for sensor measurement levels used in each soil plot). The weighted average for each time interval was only calculated when there was at least one valid soil moisture measurement within the 0–20 cm, 20–50 cm, and 50–100 cm depths to ensure that values were representative of the entire 0–1 m layer. As a result, 0–1 m soil moisture was not calculated for ONAQ soil plots 1–4 because there were no sensors in the 50–100 cm layer or at the following soil plots because the soil was too shallow: GRSM soil plots 1–4, HARV plot 1, OAES all plots, RMNP plot 1, SJER plot 1, TEAK plots 3 and 5, and YELL plots 2 and 5. The soil plots with the greatest coincidental data availability were used to calculate the site-average soil water content for validation of the SMAP and NLDAS datasets ($N = 39$ sites for the surface soil and $N = 38$ for the root zone; root-zone soil moisture could not be calculated for the OAES site because the soil was too shallow; Table III). Daily mean site-average soil moisture from the in situ sensors was used to validate the SMAP and NLDAS data products. The starting year varied based on when each site became operational. To avoid seasonal over- and under-representation within the NEON dataset, the start date for each site was cropped to 1 May of the first year with data, while the end date for all sites was 30 April 2022.

2) NEON Vegetation Properties: To investigate the impact of vegetation water content on the performance of the remotely sensed and modeled soil moisture data products, we used the data from [18] for three independent indicators of vegetation water content based on NEON data products: above-ground biomass, canopy height, and the normalized difference infrared index (NDII), which can serve as an index of vegetation water content. This was done for all sites in both forested and unforested ecosystems. Briefly, 1-m^2-resolution remotely sensed (airborne) canopy height and NDII data were averaged across years over the entire flight area for each site (~200 km^2) to generate a site-level mean. The above-ground biomass was calculated from the measurements of live herbaceous biomass from clip harvests, woody biomass (if present) allometrically estimated from the measurements of the tree diameter at breast height, and allometrically estimated biomass of other nonwoody growth forms (e.g., ferns and palms; if present) from plots throughout the NEON sites (mean site size: 34 km^2; see [18] for details).

B. Remote Sensing and Model Soil Moisture Products

The SMAP/Sentinel-1 L2 radiometer/radar (SMAP/Sentinel) product provides surface soil moisture on the 1 and 3 km equal-area scalable Earth version 2.0 grids. This study used version 3 of the product, as it was the latest at the time of the analysis [23]. The product downscales the coarse-scale SMAP radiometer brightness temperatures with the fine-resolution backscatter from the ESA/Copernicus Sentinel-1 satellites [10]. The SMAP/Sentinel product has a lower temporal resolution than the other products because of the requirement that a SMAP overpass (2–3-day return interval) and a Sentinel overpass (6–12-day return interval) must occur within ±24 h of each other resulting in an overall temporal resolution of ~12 days for most regions [10]. The SMAP/Sentinel algorithm is based on the original SMAP active/passive downscaling algorithm (discontinued upon the failure of the SMAP radar), which demonstrated satisfactory temporal performance (<0.06 m^{-3} m^{-3} ubRMSE) at the 3-km resolution over core validation sites with low-to-moderate vegetation [12], [24]. Similarly, the SMAP/Sentinel product exhibited satisfactory temporal performance over core sites with low-to-moderate vegetation [13]. The temporal performance of the active/passive products is closely tied to the radiometer's sensitivity to soil moisture changes as the downscaled brightness temperature is normalized to the coarse-resolution brightness temperature [10]. Importantly, the temporal changes have relatively strong autocorrelation over large spatial scales; therefore, the coarse-resolution brightness temperature has the first-order ability to capture the soil moisture changes, regardless of the downscaling approach (e.g., [25], [26], and [27]).

The 3-km SMAP/Sentinel soil moisture was applied in this study because of the larger noise in the 1-km soil moisture [10]. Soil moisture from the closest 3-km grid cell was matched with each NEON station. The data can be flagged for several reasons, including vegetation water content and terrain slope, but the retrieval quality flag was ignored to retain values for the forested sites, which are flagged based on the high expected vegetation water content (>5 kg m^{-2}).

The SMAP-L4 product provides global, 9-km, 3-h estimates of surface (0–5 cm) and root-zone (0–1 m) soil moisture and related land-surface fields from 31 March 2015 to the present [8]. This study used version 7, as it was the latest at the time of the analysis [28], [29]. The L4 estimates are based on the assimilation of SMAP *L*-band brightness temperature (*Tb*) observations into the NASA catchment land-surface model [30] using a stochastic ensemble Kalman filter [9], [31], [32]. The catchment model simulates spatial variations in soil moisture and water table depth within each 9-km grid cell based on its topographic statistics. A subsurface heat diffusion model tracks ground heat content and soil temperature, and snow processes are modeled with a physically based, three-layer snow accumulation and ablation model that accounts for snow aging and compaction [33]. In CONUS, the model's precipitation forcing, arguably the most important driver of soil moisture variations, is based on the Climate Prediction Center unified gauge-based, daily, 0.5° product [34]. A zero-order ("tau-omega") *L*-band microwave radiance transfer model maps the simulated soil moisture and temperature states into the space of the *Tb* observations [35], [36]. Observation-minus-forecast *Tb* residuals and ensemble-based, dynamic error covariance estimates are used to correct the catchment-simulated soil moisture. In this process, the radiative transfer model also encodes the sensitivity of the soil moisture corrections to the observation-minus-forecast *Tb* residuals. In densely vegetated locations (e.g., forests), *Tb* is largely insensitive to soil moisture, and the SMAP L4 soil moisture estimates are, thus, primarily determined by the catchment model, with a relatively smaller impact from the SMAP *Tb* observations at forested sites than at unforested sites.

The NLDAS Noah land-surface model L4 hourly 0.125° × 0.125° V002 product is a simulated series of land-surface variables with hourly temporal resolution and one-eighth degree (~12 km) grid spacing [7]. The surface meteorological forcing data for the simulation are based on the observations to the extent possible. Most importantly, NLDAS uses precipitation estimates that are based on both gauge and radar observations. Soil moisture content data for the cells containing the NEON towers were used. Root-zone (0–1 m) soil moisture was determined by vertically aggregating soil moisture data from the 0–10, 10–40, and 40—100 cm layers.

For SMAP-L4 and NLDAS, the soil parameters and other model parameters are from global and continental databases, respectively, and may differ from the parameters measured at the NEON sites. This represents one aspect of the upscaling error and may affect the performance metrics to some degree.

C. Performance Metrics and Data Analysis

The validation against the NEON in situ measurements is based on the standard performance metrics, including the mean difference (MD) (satellite or model minus NEON soil moisture), the absolute MD, the root-mean-square deviation (RMSD), the unbiased RMSD (ubRMSD), also known as the standard deviation of the error [37], and the Pearson correlation coefficient (r) defined as

$$\mathrm{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2} \quad (1)$$

$$\mathrm{MD} = \frac{1}{n} \sum_{i=1}^{n} (x_i - y_i) \quad (2)$$

$$\mathrm{ubRMSD} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} ((x_i - \bar{x}) - (y_i - \bar{y}))^2} \quad (3)$$

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (4)$$

where x and y represent the satellite (or model) estimates and NEON measurements for a given site, respectively, n is the number of coincidental samples for that site, and $\bar{x}$ and $\bar{y}$ represent the mean of the satellite (or model) estimates and NEON measurements for the site, respectively.

Metrics were computed separately for each site and then averaged across the sites. We also report the total number of coincidental NEON and SMAP-L4, NLDAS, or SMAP/Sentinel observations (n), and the average number of observations per site. The performance metrics were calculated using all available data for each site as well as for each meteorological season (December–February, March–May, June–August, and September–November).

NEON surface soil moisture data from as early as May 2016 through April 2022 were correlated at daily intervals with 4821 SMAP/Sentinel values, 38298 SMAP-L4 measurements, and 39051 NLDAS values (see Table IV; the minor discrepancy in the total number of SMAP-L4 and NLDAS data was caused by a few corrupted SMAP-L4 files and does not impact our key findings). The daily mean was calculated for the SMAP-L4 and NLDAS comparisons even though they provide more frequent soil moisture estimates because of the relatively large temporal autocorrelation of soil moisture over subdaily timescales, and the discontinuities in the NEON time series. The smaller size of the SMAP/Sentinel dataset was due to its lower temporal resolution [10]. NEON root-zone (0–1 m layer) measurements were correlated with over 22 000 SMAP-L4 and NLDAS values (see Table V). The smaller size of the root-zone datasets reflects the necessity of having simultaneous good-quality NEON measurements from in situ soil moisture sensors at several depths to calculate the 0–1 m average (see Section II-A1).

Summary statistics (mean and standard deviation) were calculated for the SMAP/Sentinel, SMAP-L4, and NLDAS performance metrics across all sites for surface and root-zone soil moisture. Similar to [18], the dominant IGBP vegetation class for the SMAP radiometer footprint that contained each NEON site was used to classify the sites as either forested (deciduous broadleaf forest, mixed forest, or evergreen needleleaf forest) or unforested (grassland, cropland, cropland/natural mosaic, open shrubland, savanna, or woody savanna). Summary statistics were calculated separately for the forested and unforested sites. Linear regressions were fitted to explore relationships between the performance metrics and ecosystems properties (above-ground biomass, NDII, and canopy height) using the lm() function in R.

Sites were only used to explore seasonal changes in the performance metrics if at least 10% of match-up pairs for that site were present in each meteorological season to avoid metrics based on just a few data points biasing the results. This reduced the number of sites available for the seasonal analysis to 20 and typically excluded higher latitude and high elevation sites, where few data points were available from December to February when the soil was often frozen (neither NEON nor SMAP sensors can reliably measure soil moisture when it is frozen; Fig. 1). For each site, the seasonal performance metrics (ubRMSD, absolute MD, and RMSD) were normalized relative to their average value across all four seasons. The median ubRMSD, absolute MD, and RMSD across all sites were calculated for each season for unforested and forested sites for both surface and root-zone soil moisture. The median, rather than the mean, was used in the seasonal analyses to minimize the influence of outliers, given the relatively small number of sites.

While the approaches used here are similar to most previous soil moisture validation studies, it is important to highlight potential shortcomings that may impact the quality of the validation [38]. Besides the clear mismatch in the spatial scale of the NEON and remotely sensed or modeled data products, the depth representation of datasets also differs (NEON surface soil moisture measurements: ~1–11 cm; NLDAS: 0–10 cm; and SMAP/Sentinel and SMAP-L4: 0–5 cm). In addition, the in situ sensors have a relatively small measurement zone (5 cm above and below the center of the sensor and up to 14 cm horizontally [39]), which makes them sensitive to unusual features within the measurement zone, such as voids or rocks. The depth-weighted approach to calculate 0–1 m root-zone soil moisture may not represent true 0–1 m moisture if a hydrologically significant feature in the soil profile was not appropriately captured by the in situ sensor depths. Finally, the soil pit from which soil-specific calibrations were determined may not fully represent the soil surrounding the in situ sensors, despite the pit location being selected to broadly represent the soil plot locations. At any given site, the impact of these shortcomings is more likely to be apparent in the bias-sensitive performance metrics (MD, absolute MD, and RMSD) than the bias-insensitive metrics (ubRMSD, r, and regression slope). However, averaging the performance metrics across multiple sites is expected to average out many of these impacts, thereby providing a reasonable measure of the performance of each data product, including the bias-sensitive metrics.

NEON data used in this study are listed in Table I, and the code scripts are available.[1]

III. Results

A. Surface Soil Moisture

Averaging the performance metrics across all sites showed that surface soil moisture from all three satellite and model products was positively correlated with NEON measurements [see Fig. 2(e)], but the agreement between the datasets and the NEON measurements varied substantially. The SMAP mission considers ubRMSD to be the primary performance metric [13], and it was substantially smaller for the SMAP-L4 and NLDAS products (0.05 $m^3 m^{-3}$) than the SMAP/Sentinel product

[1][Online]. Available: https://doi.org/10.6084/m9.figshare.24424762.v1

TABLE I
NEON DATA PRODUCTS USED IN THE ANALYSES

Data product ID	Data product name	DOI	Date range (YYYY-MM-DD)
DP1.00094.001	NEON Soil water content and water salinity	https://doi.org/10.48443/7exd-n727	2016-05-01 – 2022-04-30
Derived from DP3.30019.001	Site mean NDII[1]	https://doi.org/10.6084/m9.figshare.14599968.v1	2013-06-01 – 2020-10-01
Derived from DP3.30015.001	Site mean canopy heights[1]	https://doi.org/10.6084/m9.figshare.14599968.v1	2013-06-01 – 2020-10-01
DP1.10023.001	Herbaceous clip harvest	https://doi.org/10.48443/xjxw-2p18	2013-07-01 – 2019-12-31
DP1.10045.001	Non-herbaceous perennial vegetation structure	https://doi.org/10.48443/pgdv-wd42	2014-01-01 – 2019-12-31
DP1.10098.001	Woody vegetation structure	https://doi.org/10.48443/e3qn-xw47	2014-01-01 – 2019-12-31

[1]NDII and canopy height data were not available for the ORNL site.
Data were downloaded for all CONUS NEON sites ($n = 39$).

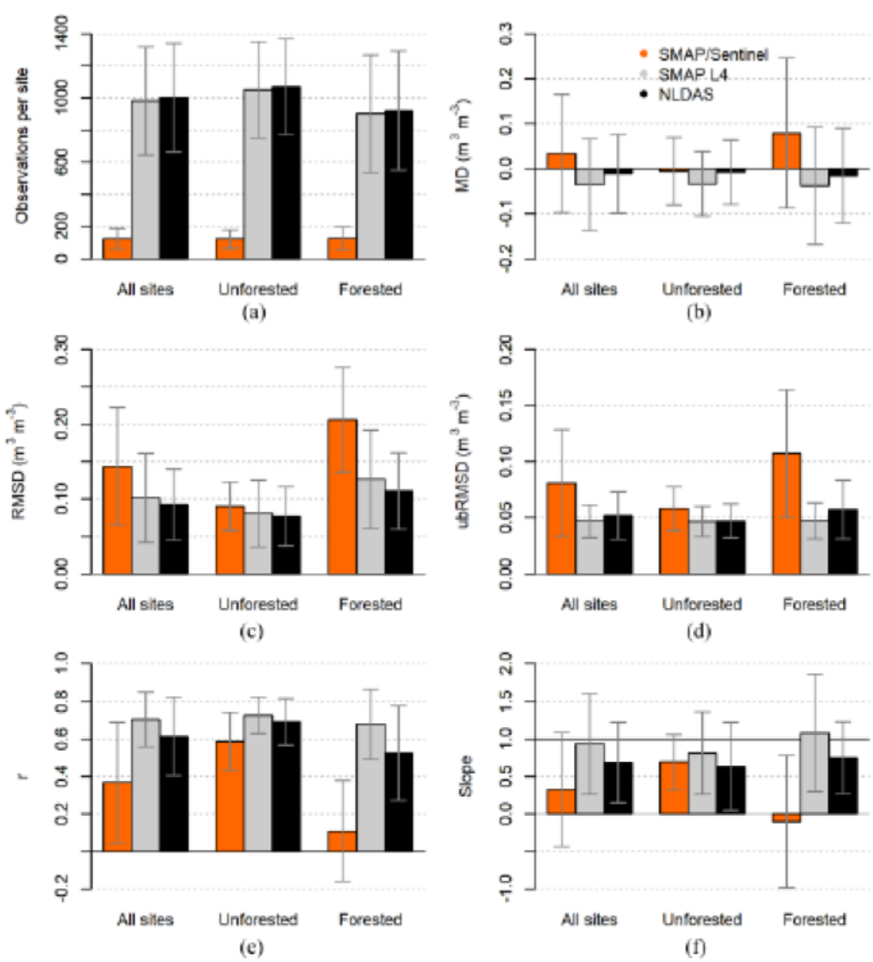

Fig. 2. Performance metrics for SMAP/Sentinel, SMAP-L4, and NLDAS surface soil moisture versus NEON in situ measurements averaged across all sites ($N = 39$), unforested sites ($N = 21$), and forested sites ($N = 18$). Performance metrics include (a) number of observations per site, (b) MD computed as the satellite (or model) minus NEON soil moisture, (c) RMSD, (d) ubRMSD, (e) r, and (f) slope. Note the differences in ordinate range for MD, RMSD, and ubRMSD. Error bars show the standard deviation of the metric across the individual sites. The graphic shows that all three products performed reasonably well at unforested sites, but SMAP/Sentinel performance deteriorated at forested sites.

(0.08 m^3 m^{-3}; see Fig. 2(d) and Table IV). The NLDAS product had an MD, which includes bias and spatial representativeness errors, that was closest to zero, while MDs were similar in magnitude for SMAP-L4 and SMAP/Sentinel but differed in their sign. SMAP-L4 was generally drier than indicated by NEON measurements, and SMAP/Sentinel was generally wetter than NEON. The SMAP/Sentinel product had the greatest absolute MD, and this combination of larger ubRMSD and absolute MD resulted in a substantially larger RMSD (0.14 m^3 m^{-3}) than for SMAP-L4 (0.10 m^3 m^{-3}) or NLDAS (0.09 m^3 m^{-3}).

Separate performance metrics were calculated for each data product at unforested and forested sites because of SMAPs known sensitivity to vegetation water content in forest ecosystems [40]. At the unforested sites, the performance of all three data products was relatively similar, although the SMAP-L4 and NLDAS products slightly outperformed the SMAP/Sentinel product (see Fig. 2 and Table IV). In most cases, the mean performance of the three data products was worse at forested than at unforested sites. The reduction in performance was most pronounced for the SMAP/Sentinel product (e.g., 84% larger mean ubRMSD at forested sites), while changes were more modest for the SMAP-L4 (no difference in ubRMSD) and NLDAS products (21% larger ubRMSD at forested sites). In particular, the SMAP/Sentinel product had a large ubRMSD (0.11 m^3 m^{-3}) and a very low correlation coefficient (0.1), indicating that it was largely unable to detect changes in soil moisture at forested sites, presumably due to its sensitivity to vegetation water content. Conversely, the other two data products were typically able to track changes in soil moisture at forested sites (mean ubRMSD: $<$0.06 m^3 m^{-3} and mean $r>$0.5), albeit at a somewhat degraded level relative to performance at unforested sites.

At both unforested and forested sites, the SMAP-L4 product slightly outperformed the NLDAS product at capturing temporal changes in soil moisture, as indicated by the bias-insensitive metrics [i.e., lower ubRMSD, higher r, and a slope close to 1; Fig. 2(d)–(f)]. The reason for the slightly better performance of the SMAP-L4 product is likely the assimilation of the (anomaly) time-series information provided by the SMAP brightness temperature observations (see Section II-B). In contrast, the NLDAS product slightly outperformed SMAP-L4 for the bias-sensitive metrics [i.e., MD closer to zero, lower absolute MD, and lower RMSD; Fig. 2(b) and (c)].

The relationship between the surface soil moisture performance metrics at each site and three site-specific indicators of vegetation water content (above-ground biomass, NDII, and canopy height) was assessed for the satellite and model data products. Consistent with the analysis of unforested and forested sites, there was a significant deterioration in the performance of the SMAP/Sentinel product for almost every performance metric with an increase in each of the ecosystem properties (see Fig. 3), demonstrating that performance is particularly unreliable in the densest forests but has already deteriorated in relatively low biomass/low canopy water content ecosystems. In contrast, performance metrics for the SMAP-L4 and NLDAS products were largely insensitive or only weakly related to these ecosystem properties, indicating that the performance remains similar in even the densest forests. For SMAP-L4, this is presumably because the skill SMAP-L4 derives from combining the land model estimates with the information from the assimilated SMAP brightness temperatures. While the latter provides less information about soil moisture with increasing vegetation density, the quality of the observation-based precipitation forcing—which largely determines the skill of the land model estimates—does not similarly depend on vegetation density. However, since the NLDAS performance metrics were likewise only weakly related to these ecosystems' properties, the results suggest that the benefit of incorporating the SMAP brightness temperature in the SMAP-L4 product is relatively small compared with the skill of the underlying models in regions, such as CONUS, where the surface meteorological forcing data and precipitation, in particular, are of high quality [41].

B. Root-Zone Soil Moisture

Results for the 0–1 m root-zone soil moisture are limited to the performance of SMAP-L4 and NLDAS because SMAP/Sentinel does not produce a root-zone product. Across all sites, most of the root-zone performance metrics were very similar for the SMAP-L4 and NLDAS products; however, NLDAS had a lower absolute MD, which also resulted in a lower RMSD than SMAP-L4 (see Fig. 4 and Table V). The mean ubRMSD was lower for root zone (0.03 m^3 m^{-3}) than for surface soil moisture (0.05 m^3 m^{-3}) for both data products, but this reduction appeared to be primarily due to the more stable temporal dynamics of root-zone soil moisture rather than improved model performance in the root zone. The other bias-insensitive performance metrics (r and slope) remained similar to values observed for surface soil moisture, although modest improvements in r and slope were observed for NLDAS in the root-zone layer versus the surface layer.

Unlike for surface soil moisture, the performance metrics for root-zone soil moisture were not universally worse at forested sites versus unforested sites. In fact, the mean MD was slightly closer to zero at forested sites for both SMAP-L4 and NLDAS. SMAP-L4 and NLDAS estimates are generally drier than NEON soil moisture at unforested sites and wetter at forested sites. The mean absolute MD was lower and the mean ubRMSD was higher at forested sites than unforested sites for SMAP-L4, while for NLDAS, these metrics remained essentially unchanged between the two site types. These differences resulted in slightly lower mean RMSD at forested sites than at unforested sites for both SMAP-L4 and NLDAS.

With the notable exception of the ubRMSD metric, at unforested sites, the root-zone soil moisture performance of both SMAP-L4 and NLDAS tended to be similar to, or worse than, that of the corresponding surface soil moisture estimates. In contrast, at forested sites, the performance metrics of both SMAP-L4 and NLDAS were more often better for root-zone soil moisture than surface soil moisture.

As with surface soil moisture, the SMAP-L4 and NLDAS root-zone soil moisture performances were largely insensitive to the indicators of vegetation water content (see Fig. 5). However, there was some indication of increased ubRMSD at sites with

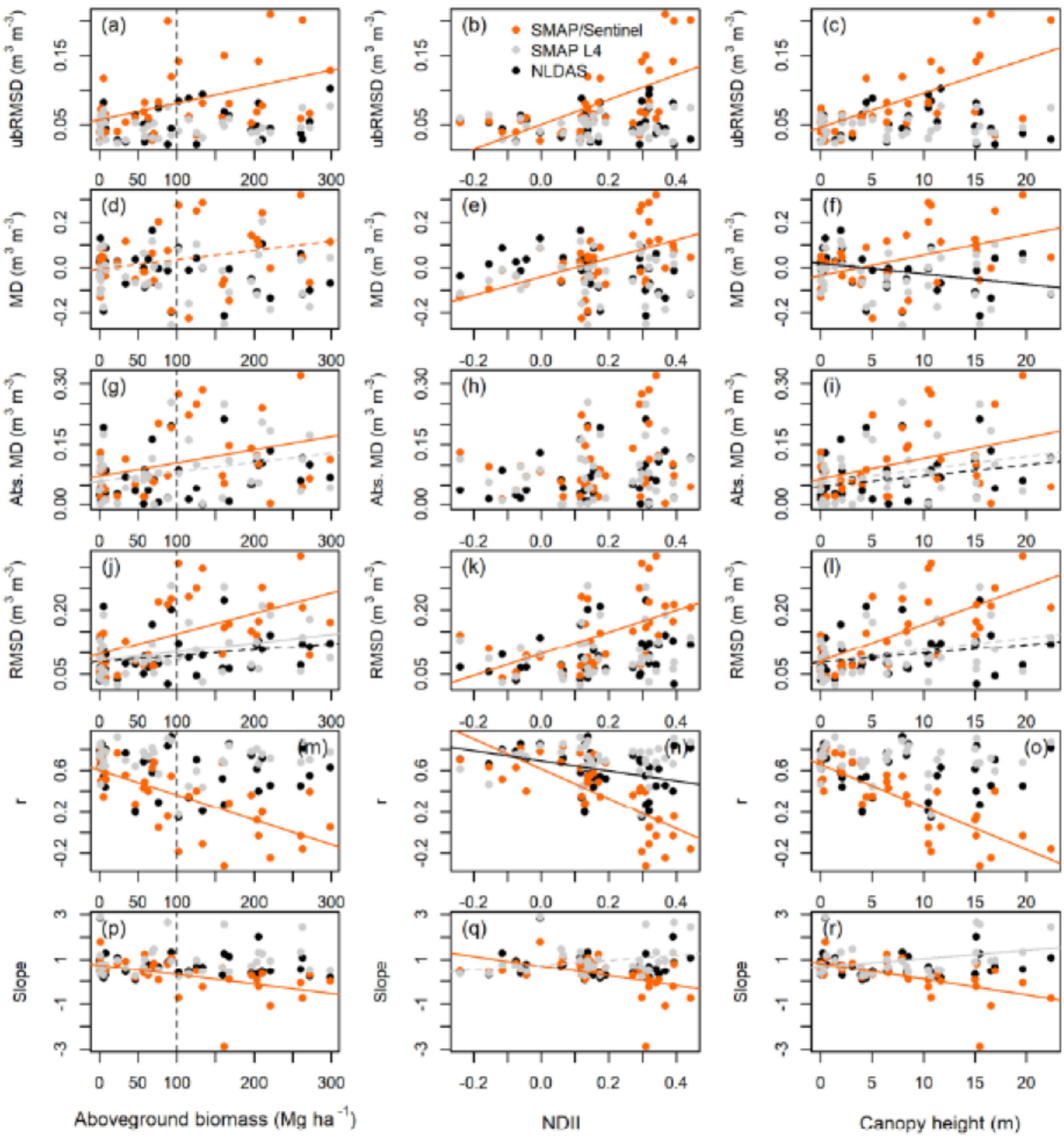

Fig. 3. Relationship between surface soil moisture performance metrics and indicators of vegetation water content (above-ground biomass, NDII, and canopy height) for SMAP/Sentinel, SMAP-L4, and NLDAS. Vertical dashed line indicates the maximum biomass where SMAP considers the radiometer data reliable assuming 50% vegetation water content. Solid fitted slope lines are significant at $p < 0.05$, and dashed fitted slope lines are significant at $p < 0.1$. SMAP/Sentinel performance generally decreased as vegetation biomass, water content, and canopy height increased, while SMAP-L4 and NLDAS performance was less sensitive to these ecosystem properties.

taller and wetter canopies, particularly for the SMAP-L4 product, although the magnitude was relatively small [see Fig. 5(a)–(c)]. No changes in RMSD, MD, the correlation coefficient, or the slope of the correlation were associated with the three indicators of vegetation water content [see Fig. 5(d)–(r)], suggesting consistent performance based on these metrics across vegetation types.

C. Seasonality

While seasonal changes in the performance metrics for all three data products for surface soil moisture were often large at individual sites (dotted lines in Fig. 6), there were few consistent patterns across the unforested or forested sites (solid lines in Fig. 6). The ubRMSD metric showed the greatest seasonal variation, and this was largest for the NLDAS product at forested sites, where ubRMSD was typically lowest in summer months and higher in the winter. Our hypothesis that SMAP/Sentinel, and to a lesser extent SMAP-L4, performance would be degraded at forested sites in summer months (i.e., when the canopy water content is greatest) was not supported.

Similar to the performance of surface soil moisture, the root-zone soil moisture performance metrics also varied seasonally at individual sites, but there were few consistent seasonal patterns

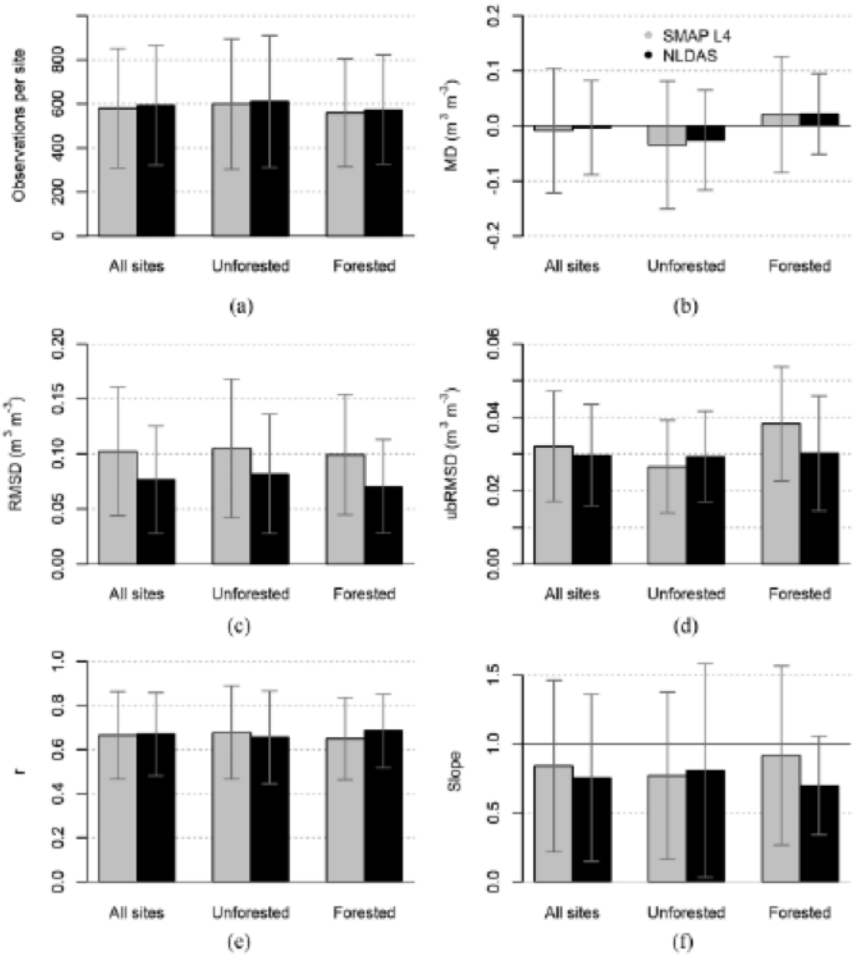

Fig. 4. As in Fig. 2, but for root-zone soil moisture from (gray bars) SMAP-L4 and (black bars) NLDAS. All sites ($N = 38$), unforested sites ($N = 20$), and forested sites ($N = 18$). Overall, SMAP-L4 and NLDAS performance was broadly similar in forested and unforested sites.

among the unforested or forested sites (see Fig. 7). The median performance metrics for the SMAP-L4 product remained almost constant at unforested sites, while there were slightly larger seasonal changes at forested sites (i.e., greater absolute MD and RMSD from March to May and lower values from June to November). The normalized ubRMSD for the NLDAS product tended to be greater from June to November at unforested sites and lower during those months at forested sites, while the normalized absolute MD and RMSD exhibited less seasonal variability.

IV. Discussion

A. Unforested Sites

Although the focus of this study was to investigate the performance of the remotely sensed and modeled soil water content data products at forested sites, it is useful to first compare our results at the unforested NEON sites with those of the previous validation studies, which have focused almost exclusively on unforested sites. Overall, the performance metrics for the products at the unforested NEON sites were similar to the results from previous SMAP and NLDAS validation studies. For example, a recent study [13] showed that the 3 km SMAP/Sentinel product had a ubRMSD of 0.05 $m^3\ m^{-3}$ ($r = 0.54$) at grassland and 0.07 $m^3\ m^{-3}$ ($r = 0.63$) at cropland sparse-network validation sites (i.e., sites typically with a single soil moisture measurement location), which is similar to the performance at unforested NEON sites that include both grassland and cropland sites (ubRMSD of 0.06 $m^3\ m^{-3}$ and $r = 0.59$). Colliander et al. [13] also reported a ubRMSD of ~0.06 $m^3\ m^{-3}$ ($r \sim 0.7$) for SMAP-L4 surface soil moisture performance and ubRMSD of ~0.04 $m^3\ m^{-3}$ ($r \sim 0.6$) for the root zone, which is also similar to performance relative to the NEON data at unforested sites. Previous NLDAS validation studies have not calculated the same performance metrics that we report here. However, they have shown strong root-zone anomaly correlations ($r = 0.7$), reasonable correlations for surface soils in most regions (i.e., $r > 0.5$), and a positive MD at SCAN sites throughout the U.S. [42], which is consistent with our findings.

Previous validation studies have shown that the bias-insensitive performance metrics (ubRMSD and r) for the SMAP-L4 surface and root-zone soil moisture improve when validated at densely instrumented sites (i.e., multiple soil moisture sensors distributed across the footprint) than at sparsely instrumented

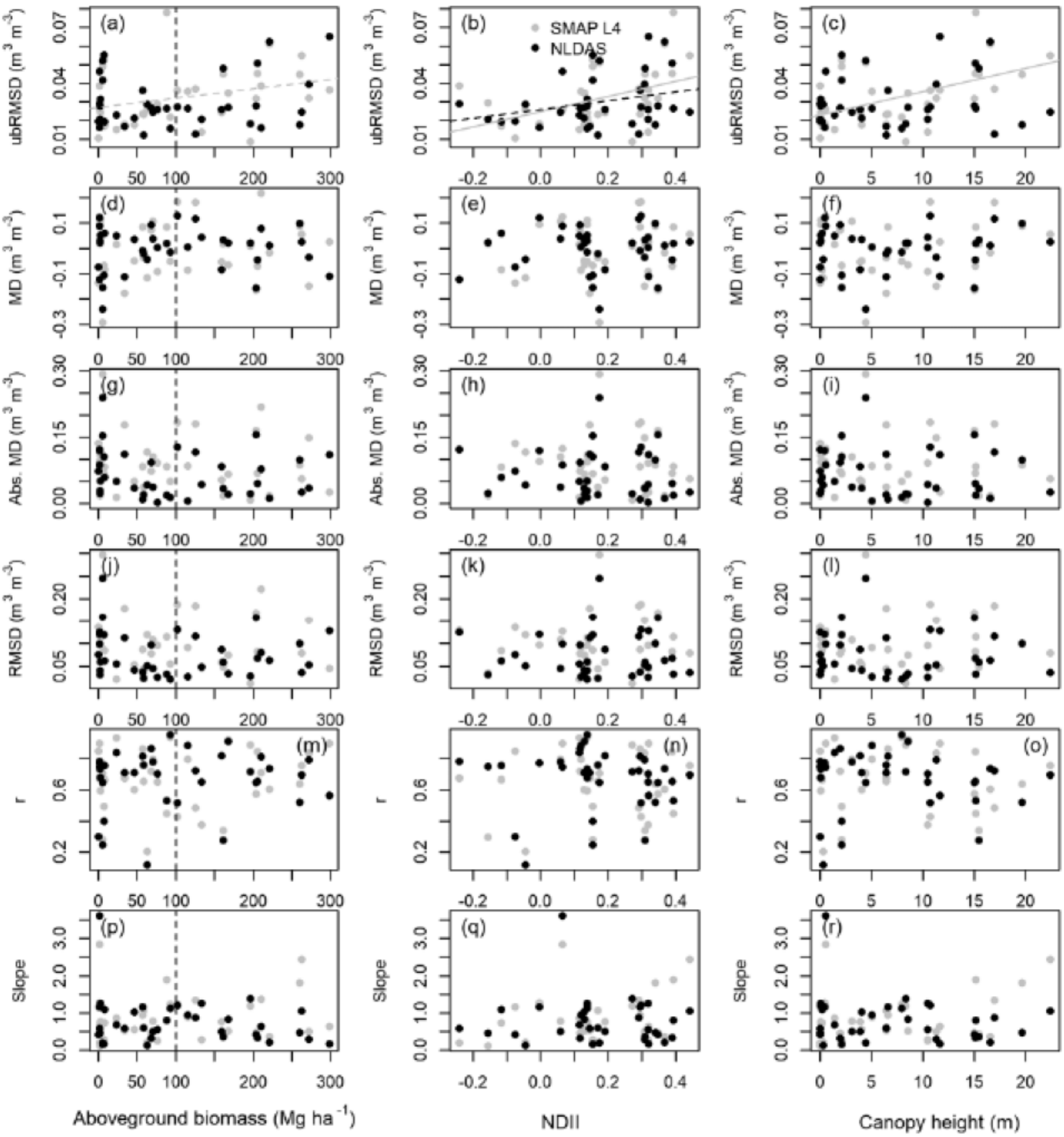

Fig. 5. As in Fig. 3, but for root-zone soil moisture from (gray dots) SMAP-L4 and (black dots) NLDAS. Overall, SMAP-L4 and NLDAS performance was largely unrelated to differences in vegetation properties among the sites.

sites (typically with a single soil moisture profile) due to improved spatial representativeness of the in situ validation data [13]. It is interesting to note that the bias-insensitive metrics based on the NEON validation data reported here lie between the performance metrics previously reported for sparsely and densely instrumented sites [13], perhaps reflecting the additional spatial information that is gained from having five soil plots spaced tens of meters apart even though that is still much smaller than the 9 km product footprint. Similar results were found in a previous analysis of the 33 km SMAP radiometer soil moisture product [18]. In contrast, performance metrics for the 3 km SMAP/Sentinel product based on NEON data were more similar to metrics from other sparsely instrumented sites than densely instrumented sites, possibly indicating that the additional spatial information associated with the NEON data is less important as the product footprint decreases in size, although it should also be noted that the difference in performance when validated at sparsely versus densely instrumented sites was relatively small for the 3 km SMAP/Sentinel product [13]. Since the performance metrics we report here have not been calculated in previous NLDAS validations, it is unclear if the greater spatial variability captured by the NEON data improves the estimates of NLDAS performance relative to other sparse validation networks.

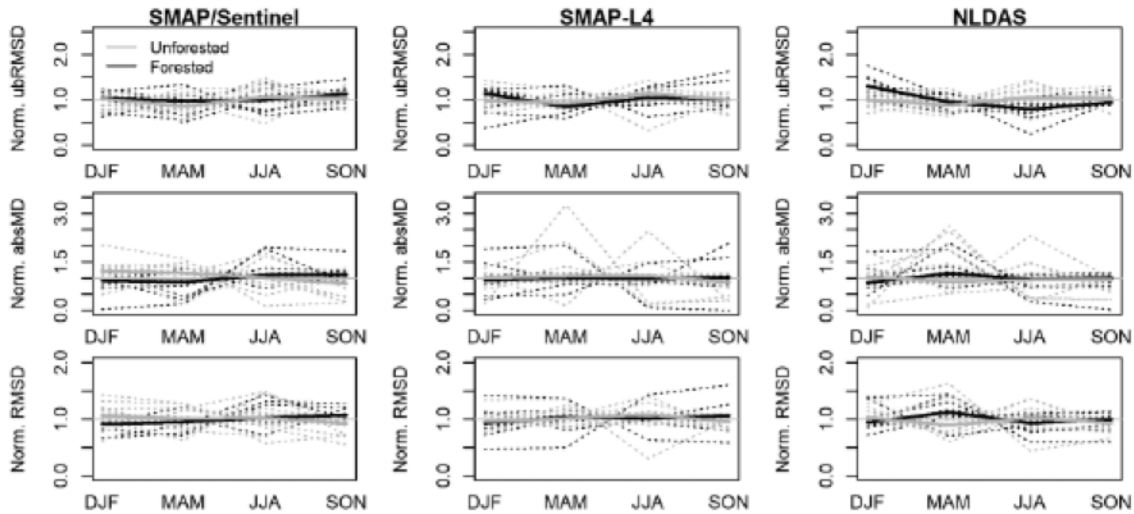

Fig. 6. Seasonal changes in normalized (top row) ubRMSD, (middle row) absolute MD, and (bottom row) RMSD for surface soil moisture at unforested and forested sites from (left column) SMAP/Sentinel, (middle column) SMAP-L4, and (right column) NLDAS. Dashed lines represent the individual sites where the metric could be calculated for every season, while thick solid lines represent the median normalized value ($N = 12$ for unforested sites and $N = 8$ for forested sites).

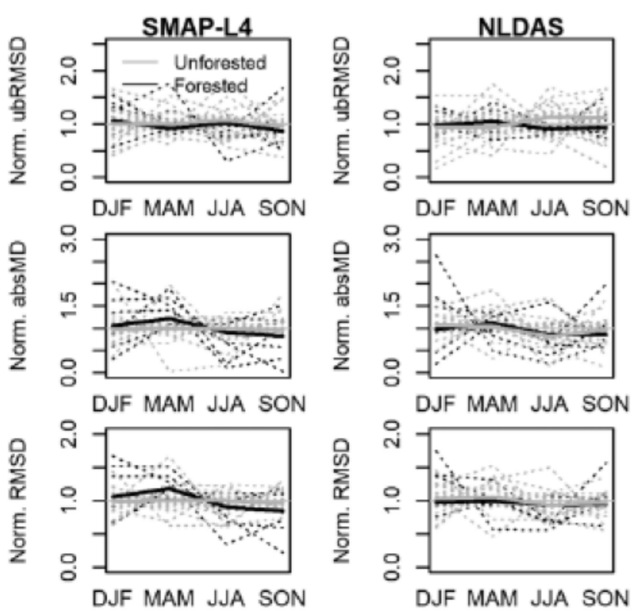

Fig. 7. As in Fig. 6 but for root-zone soil moisture from (left column) SMAP-L4 and (right column) NLDAS ($N = 11$ for unforested sites and $N = 8$ for forested sites).

The NEON-based bias-sensitive metrics (MD and RMSD) calculated for surface soil moisture were not too dissimilar to values reported for densely instrumented validation sites for SMAP/Sentinel, indicating consistency between the metrics assessed at the pixel level and those averaged across multiple NEON locations despite the limited within-site spatial sampling. For instance, the 3 km SMAP/Sentinel product had MD = 0.00 m^3 m^{-3} and RMSD = 0.07 m^3 m^{-3} based on the densely instrumented core validation sites [13], while the corresponding values for NEON were MD = −0.01 m^3 m^{-3} and RMSD = 0.09 m^3 m^{-3}. Similar MD results were reported for the SMAP radiometer soil moisture data product at NEON sites when averaging across multiple sites [18]. In contrast, MD and RMSD for the surface soil and root-zone SMAP-L4 product were not as consistent with the results from the core validation sites. For example, the MD was similar in magnitude (∼0.03 m^3 m^{-3}) but had the opposite sign, and root-zone soil moisture RMSD was 0.11 m^3 m^{-3} at NEON sites but only 0.06 m^3 m^{-3} (albeit $N = 7$) at core validation sites. However, the SMAP-L4 RMSD for surface soil moisture was similar at NEON sites (0.08 m^3 m^{-3}) and core validation sites (0.07 m^3 m^{-3}). At least some of the difference in the bias-sensitive metrics is likely due to differences in vegetation, soil texture, soil organic matter content, and other ecosystem properties at the scale of the NEON soil plots versus the larger footprints of the remotely sensed and modeled data products. While the NEON sites are typically broadly representative of the larger SMAP/Sentinel, SMAP-L4, and NLDAS pixels (see Table II and [18]), any differences that do exist are likely to inflate the absolute MD metric, which, in turn, would inflate RMSD. As a result, it is likely that the large differences in spatial scale between the NEON sites and the three soil moisture data products caused some inflation of the bias-sensitive performance metrics, and their "true" performance is likely to be somewhat better than indicated by this analysis. However, the reasonable level of consistency between the results reported here and those based on the densely instrumented core validation sites suggests that the impact of the spatial scale differences was relatively small when averaging across multiple sites.

Focusing on ubRMSD as the primary performance metric shows that, at unforested sites, the SMAP-L4 and NLDAS products slightly outperformed the SMAP/Sentinel product at tracking changes in soil water content despite SMAP/Sentinel's higher spatial resolution, which is consistent with results from SMAPs densely instrumented core validation sites [13]. However, it should be noted that the differences in performance were small, and all three products were reasonably reliable across a range of unforested sites.

B. Forested Sites

The similarity in the performance, particularly for the bias-insensitive metrics, of the SMAP/Sentinel, SMAP-L4, and NLDAS products at unforested sites when NEON or other validation networks were used as benchmarks provides a level of confidence for the NEON-based validation results we report for forested sites. This is important because there are few other forested validation studies with which we can compare our findings due to the general under-representation of forested sites in the existing soil moisture networks. SMAP-L4 and NLDAS ubRMSD were similar at forested and unforested sites. However, the performance of the SMAP/Sentinel product deteriorated markedly with increasing vegetation indicators to the point where it barely showed any correlation with the in situ data ($r = 0.1$ and ubRMSD = 0.11 m^3 m^{-3}). Some of this reduction in performance can be attributed to the SMAP *L*-band radiometer, which was previously shown to perform less well at measuring soil moisture at forested sites but still retains sufficient skill to provide some useful information [15], [16], [18], [43]. However, the *C*-band Sentinel data are likely causing the bulk of the reduction in performance because the *C*-band is known to be more sensitive to vegetation water content than the *L*-band [44]. In contrast to our findings, Andreadis et al. [17] observed strong agreement between the 3 km SMAP/Sentinel product and in situ soil moisture data from seven forested validation sites in New Zealand ($r = 0.8$ and ubRMSD = 0.03 m^3 m^{-3}). This difference in performance may be due to differences in forest type between the two studies: young (5–20-year-old) *Pinus radiata* plantations, presumably with relatively lower above-ground biomass, vegetation water content, and canopy heights, in the New Zealand study versus typically older and more diverse forests at the NEON sites. Consistent with this, we found that the performance of the SMAP/Sentinel product progressively deteriorated as above-ground biomass, an index of vegetation water content, and canopy height increased, suggesting that the New Zealand sites may simply represent less challenging forest conditions for remote sensing soil moisture than the range of forest types captured by the NEON sites. The relatively consistent performance of the SMAP-L4 product at unforested and forested sites indicates that it successfully compensates for the deterioration in SMAP radiometer data (see Section II-B). Since NLDAS does not rely on remotely sensed measurements (which experience interference from vegetation water content), it was expected to maintain a similar level of performance at unforested and forested sites, which we observed.

To our knowledge, no previous studies have quantified the performance of the SMAP-L4 and NLDAS products at forested sites. However, the performance of the SMAP radiometer product has been studied at three different densely instrumented forest sites with observed ubRMSDs of ~0.05–0.07 m^3 m^{-3} [15], [16], [43], as well as at forested NEON sites (ubRMSD = 0.06 m^3 m^{-3} [18]). Relative to the SMAP radiometer, the performance of the SMAP-L4 (ubRMSD: 0.05 m^3 m^{-3}) and NLDAS (ubRMSD: 0.06 m^3 m^{-3}) surface soil products was impressive, especially since both products have substantially higher spatial resolution (~10 km versus 33 km for the radiometer) as well as including root-zone soil moisture also with low ubRMSD. While the ~10 km resolution is likely too large for many land-management decisions, it is useful for assessing the health of forests and the likelihood of disturbance events (e.g., fires or pests). In particular, the inclusion of root zone rather than just surface soil moisture data is particularly valuable in the context of assessing drought status and potential impacts on forests. The majority of tree roots are in the 0–1 m layer, although they can extend beyond this depth [45], [46] and many trees have the ability to change water acquisition depths depending on soil moisture conditions [47].

While relatively sparsely instrumented validation sites, such as the NEON sites, cannot be used reliably to quantify bias-sensitive performance metrics (i.e., MD and RMSD) for coarser resolution products at individual sites, owing to the differences in spatial representativeness, averaging across multiple sites can provide information on the overall data product performance relative to these metrics. As expected, the SMAP/Sentinel product had a much larger MD at forested sites than at unforested sites, which was likely due to its sensitivity to vegetation water content, and this contributed to a very large RMSD (0.21 m^3 m^{-3}), indicating that only the most extreme differences in absolute water content could be gleaned from this product at forested sites. This was especially true for the tallest and densest forests with high vegetation water contents, where the SMAP/Sentinel soil water content values were particularly unreliable.

In contrast to SMAP/Sentinel, there was relatively little difference in SMAP-L4 and NLDAS MD for surface soil moisture between forested and unforested sites, suggesting little change in measurement bias between the two vegetation classes, although the greater variability of MD (corresponding to greater absolute MD) for both products at forested sites contributed to a 50% larger RMSD at the forested sites (0.11–0.13 m^3 m^{-3}). It is unclear why the absolute MD for surface soil moisture increased at forested sites, although we did observe weak (i.e., $p < 0.1$) correlations between absolute MD and at least one of the indicators of vegetation water content for SMAP-L4 and NLDAS. Without a strong correlation or mechanistic basis for the increase in absolute MD, we are unable to offer a pathway to reduce this potential measurement bias in forested sites. In the root zone, although SMAP-L4 and NLDAS MD changed from typically underestimating (unforested sites) to overestimating (forests) soil water content, the absolute MD remained similar, as did RMSD (0.07–0.10 m^3 m^{-3}). While the magnitude of the SMAP-L4 and NLDAS RMSD is too large to reliably determine the absolute water content of surface and root-zone soils, the products can reliably determine relative soil water content (e.g., dry, moist, or wet) when averaging across a number of sites. Moreover, as with the unforested sites, any differences in vegetation, soil, and ecosystem properties between the NEON

TABLE II
NEON SITE PROPERTIES [50] AND SMAP IGBP LAND COVER CLASSIFICATION

Site ID, U.S. State	Latitude (°)	Longitude (°)	Elevation (m)	MAT [1] (°C)	MAP [2] (mm)	SMAP footprint IGBP land cover classification[3]	NEON site dominant NLCD vegetation class[3]	Soil subgroup	Mean greenness increase DOY[4]	Mean maximum greenness DOY[4]	Mean greenness decrease DOY[4]
ABBY, WA	45.762	−122.330	365	10.0	2451	Mixed forest	Evergreen forest	Andic Humudepts	110	165	205
BART, NH	44.064	−71.287	274	6.2	1325	Mixed forest	Mixed forest, Deciduous forest	Aquic Haplorthods	120	170	220
BLAN, VA	39.034	−78.042	183	12.1	983	Cropland/ natural mosaic	Shrub/Scrub	Ultic Hapludalfs	75	150	210
CLBJ, TX	33.401	−97.570	272	17.5	926	Grassland	Deciduous forest	Udic Paleustalfs	60|215	135|230	175|265
CPER, CO	40.816	−104.746	1654	8.6	344	Grassland	Grassland/herbaceous	Aridic Argiustolls	90	165	210
DCFS, ND	47.162	−99.107	575	4.9	490	Cropland	Grassland/herbaceous	Typic Haplustolls	120	180	205
DELA, AL	32.542	−87.804	25	17.6	1372	Woody savanna	Woody wetland, Deciduous forest	Aquic Paleudults	60	135	205
DSNY, FL	28.125	−81.436	20	22.5	1216	Woody savanna	Pasture/hay	Aeric Alaquods	60	140	190
GRSM, TN	35.689	−83.502	575	13.1	1375	Mixed forest	Deciduous forest	Typic Humudepts	90	155	215
HARV, MA	42.537	−72.173	348	7.4	1199	Mixed forest	Deciduous forest, evergreen forest	Oxyaquic Dystrudepts	110	160	220
JERC, GA	31.195	−84.469	47	19.2	1308	Cropland	Evergreen forest	Arenic Kandiudults	90	175	220
JORN, NM	32.591	−106.843	1324	15.7	271	Open shrubland	Shrub/scrub	Typic Petrocalcids	80	185	245
KONA, KS	39.110	−96.613	323	12.7	850	Grassland	Cultivated crops	Pachic Vertic Argiudolls	90	160	210
KONZ, KS	39.101	−96.563	414	12.4	870	Grassland	Grassland/herbaceous	Pachic Udertic Argiustolls	90	160	210
LENO, AL	31.854	−88.161	13	18.1	1386	Mixed forest	Deciduous forest, woody wetland	Vertic Epiaquepts	70	145	200
MLBS, VA	37.378	−80.525	1170	8.8	1227	Deciduous broadleaf forest	Deciduous forest	Fluvaquents	110	160	220
MOAB, UT	38.248	−109.388	1799	10.1	319	Grassland	Shrub/scrub	Ustic Haplocalcids	85	165	225
NIWO, CO	40.054	−105.582	3490	0.3	1005	Needleleaf evergreen forest	Grassland/herbaceous	Typic Haplocryolls	140	190	220
NOGP, ND	46.770	−100.915	589	5.9	457	Cropland	Grassland/herbaceous	Typic Argiustolls	115	170	200
OAES, OK	35.411	−99.059	519	15.5	779	Grassland	Grassland/herbaceous	Lithic Haplustepts	70|233	135|270	165|290
ONAQ, UT	40.178	−112.452	1662	9.0	288	Grassland	Shrub/scrub	Xeric Haplocalcids	75	130	170
ORNL, TN	35.964	−84.283	344	14.4	1340	Deciduous broadleaf forest	Deciduous forest	Typic Paleudults	90	140	210
OSBS, FL	29.689	−81.993	46	20.9	1302	Woody savanna	Evergreen forest	Typic Quartzipsam-ments	70	150	190
RMNP, CO	40.276	−105.546	2742	2.9	731	Needleleaf evergreen forest	Evergreen forest	Ustic Haplocryolls	120	180	210
SCBI, VA	38.893	−78.139	352	11.6	1126	Deciduous broadleaf forest	Deciduous forest	Ultic Hapludalfs	85	150	220
SERC, MD	38.890	−76.560	33	13.6	1075	Cropland/ natural mosaic	Deciduous forest	Aquic Hapludults	80	155	220
SJER, CA	37.109	−119.732	400	16.4	540	Savanna	Deciduous forest, grassland/herbaceous	Psammentic Haploxerolls	270	65	95
SOAP, CA	37.033	−119.262	1210	13.4	900	Needleleaf evergreen forest	Evergreen forest	Ultic Haploxeralfs	90	155	185
SRER, AZ	31.911	−110.835	997	19.3	346	Open shrubland	Shrub/scrub	Typic Torrifluvents	87|186	139|215	189|259
STEI, WI	45.509	−89.586	476	4.8	797	Mixed forest	Deciduous forest	Alfic Epiaquods	120	165	215
STER, CO	40.462	−103.029	1365	9.7	433	Grassland	Cultivated crops	Pachic Argiustolls	90	150	190
TALL, AL	32.950	−87.393	166	17.2	1383	Mixed forest	Mixed forest, evergreen forest	Typic Hapludults	75	135	195
TEAK, CA	37.006	−119.006	2149	8.0	1223	Needleleaf evergreen forest	Evergreen forest	Pachic Humixerepts	120	180	205
TREE, WI	45.494	−89.586	467	4.8	797	Mixed forest	Deciduous forest, evergreen forest	Alfic Haplorthods	120	165	215
UKFS, KA	39.041	−95.192	322	12.7	990	Cropland/ natural mosaic	Deciduous forest	Pachic Argiudolls	75	160	210
UNDE, MI	46.234	−89.537	521	4.3	802	Mixed forest	Mixed forest, deciduous forest, woody wetland	Argic Fragiaquods	120	170	215
WOOD, ND	47.128	−99.241	591	4.9	494	Cropland	Grassland/herbaceous	Typic Haplustolls	120	180	210
WREF, WA	45.820	−121.952	351	9.2	2225	Needleleaf evergreen forest	Evergreen forest	Typic Hapludands	115	165	210
YELL, WY	44.953	−110.539	2133	3.4	493	Needleleaf evergreen forest	Evergreen forest, scrub/shrub	Pachic Argiustolls	125	169	193

[1]Mean annual temperature.
[2]Mean annual precipitation.
[3]NEON uses the USGS National Landcover Database for vegetation classification while SMAP uses the International Geosphere–Biosphere Program classification.
[4]For greenness increase, maximum greenness, and greenness decrease day-of-year (DOY) values, sites with two growing seasons have two DOY values separated by |.

site scale and the scale of the remotely sensed and modeled data products likely inflated the bias-sensitive performance metrics (MD and RMSD), suggesting that the "true" performance of these products is better than indicated in this analysis.

C. Seasonality

We did not observe a consistent seasonal pattern in the performance of the different products among the unforested or forested sites, although there was seasonal variability in performance at individual sites. The forested sites are often a mixture of evergreen and deciduous trees across the scales being considered, and forests typically are more resistant to soil moisture fluctuations over short time scales. This means that broadscale remote sensing algorithms have stable vegetation signals upon which the algorithms have been developed. Deep rooting and water storage capacity within the forest biomass will still influence the remote sensing signal without significant losses of moisture content over short time periods (inter-rain periods), in contrast to agricultural and rangeland landscapes, which are much quicker to respond to drought or flood conditions. Previous studies have observed modest seasonal differences in performance at a densely instrumented deciduous forest [43] and cropland [48] site. However, we cannot determine if this represents a consistent pattern or simply site-level variability consistent with our findings. To some extent, the wide range of climates and ecosystems encompassed in our analysis means that variation in phenological events (e.g., growing season start and end dates) among the sites may mask some seasonal variability in the performance of the data products. In addition, the exclusion of higher latitude and higher elevation sites, which typically have particularly pronounced seasonality, from the seasonal analysis due to limited December–February in situ soil moisture data may have reduced any seasonal differences in the performance of the three products. Furthermore, known SMAP biases that vary over time are expected to make the detection of seasonal changes in performance challenging [49]. Nonetheless, to date, there is little evidence of strong and consistent changes in the seasonal performance of these products across a range of sites. Seasonal differences in product performance warrant further investigation, and sensor networks that include a larger number of sites (e.g., USDA SCAN and USCRN) may be better able to identify seasonal patterns after grouping sites into different categories based on vegetation type (crops versus grassland), crop type, growing season, and climate.

V. Conclusion

Our findings indicate that both the SMAP-L4 and NLDAS products can be used with some confidence to track changes in soil water content in forests, at least when aggregating across a wide range of sites. Not only did these products outperform the SMAP/Sentinel product at forested sites but they also outperformed the SMAP radiometer soil moisture product across all metrics [18] while offering higher spatial resolutions and root-zone soil moisture estimates (in addition to surface soil moisture). Moreover, their performance was largely insensitive to season when averaging across sites, although seasonal variability was apparent for individual sites. In contrast, the SMAP/Sentinel product was not reliable at forested sites, particularly for forests with the tallest, densest, and wettest canopies, but its performance had already started to deteriorate at relatively small, low-density forests; it should be noted that forests are outside the range of conditions that guided the development of this product.

Appendix

Site metadata are presented in Table II. Information on the soil plots and measurement levels that were used to calculate the in situ site mean soil moisture can be found in Table III. Tables IV and V contain data product performance metrics for surface and root-zone soil moisture, respectively.

TABLE III
Soil Plots (Stations) and Measurement Levels (Root-Zone Only) Used for NEON Mean Soil Moisture at Each Site

Site	Surface soil No. stations	Surface soil NEON soil plots	Root zone (0–1 m) No. stations	Root zone (0–1 m) NEON soil plots (measurement levels)
ABBY	3	2, 3, and 4	2	2 (12456) and 4 (123456)
BART	2	2 and 4	2	4 (12345) and 5 (12345)
BLAN	5	1, 2, 3, 4, and 5	2	2 (123456) and 5 (123456)
CLBJ	3	1, 3, and 5	3	3 (123456), 4 (23456), and 5 (123456)
CPER	5	1, 2, 3, 4, and 5	4	1 (123456), 2 (123456), 4 (123456), and 5 (123456)
DCFS	4	2, 3, 4, and 5	2	2 (123456) and 4 (1234567)
DELA	3	2, 4, and 5	2	3 (1235) and 4 (123456)
DSNY	5	1, 2, 3, 4, and 5	5	1 (123456), 2 (123456), 3 (123456), 4 (123456), and 5 (123456)
GRSM	3	2, 3, and 5	1	5 (123456)
HARV	3	1, 4, and 5	2	4 (123456) and 5 (123456)
JERC	3	1, 2, and 3	3	1 (123456), 2 (123456), and 3 (123456)
JORN	3	1, 4, and 5	2	1 (12345) and 5 (1345)
KONA	4	1, 2, 4, and 5	3	1 (12456), 2 (123456), and 3 (123456)
KONZ	3	2, 3, and 5	3	1 (123456), 2 (123456), and 4 (1234567)
LENO	2	4 and 5	2	3 (12345) and 4 (12345)
MLBS	4	1, 2, 4, and 5	2	1 (1234567) and 5 (123456)
MOAB	2	1 and 3	2	1 (123456) and 3 (123456)
NIWO	3	1, 4, and 5	2	4 (1346) and 5 (123456)
NOGP	5	1, 2, 3, 4, and 5	2	4 (12356) and 5 (123456)
OAES	5	1, 2, 3, 4, and 5	NA	NA
ONAQ	3	1, 4, and 5	1	5 (12345)
ORNL	3	1, 3, and 5	3	1 (12345), 3 (1235), and 5 (1234)
OSBS	5	1, 2, 3, 4, and 5	3	2 (123456), 3 (123456), and 4 (123456)
RMNP	5	1, 2, 3, 4, and 5	2	2 (1234567) and 5 (1234567)
SCBI	3	1, 2, and 4	3	2 (12345), 3 (12345), and 5 (2345)
SERC	2	1 and 2	2	2 (123456) and 4 (123456)
SJER	2	1 and 3	3	2 (123456), 3 (123456), and 4 (123456)
SOAP	4	1, 2, 3, and 5	2	2 (123456) and 5 (123456)
SRER	5	1, 2, 3, 4, and 5	3	2 (12345), 3 (1234), and 4 (1235)
STEI	3	1, 3, and 5	2	3 (1235) and 5 (12356)
STER	3	1, 4, and 5	2	2 (123456) and 5 (123456)
TALL	3	1, 4, and 5	2	4 (12345) and 5 (12345)
TEAK	5	1, 2, 3, 4, and 5	2	1 (123456) and 2 (1234567)
TREE	3	2, 4, and 5	2	4 (12346) and 5 (12356)
UKFS	3	1, 3, and 5	2	1 (1234567) and 3 (123456)
UNDE	2	3 and 4	3	1 (23456), 3 (123457), and 4 (123456)
WOOD	4	2, 3, 4, and 5	2	2 (123456) and 4 (123456)
WREF	3	3, 4, and 5	2	3 (12345) and 4 (12345)
YELL	3	1, 3, and 5	1	3 (123456)

TABLE IV
PERFORMANCE METRICS FOR SMAP/SENTINEL, SMAP-L4, AND NLDAS SURFACE SOIL MOISTURE VERSUS NEON IN SITU MEASUREMENTS AVERAGED ACROSS ALL SITES, UNFORESTED SITES, AND FORESTED SITES

	All sites ($N = 39$)			Unforested sites ($N = 21$)			Forested sites ($N = 18$)		
	SMAP/Sentinel	SMAP-L4	NLDAS	SMAP/Sentinel	SMAP-L4	NLDAS	SMAP/Sentinel	SMAP-L4	NLDAS
Observations (n)	4821	38 298	39 051	2561	22 068	22 462	2260	16 230	16 589
Observations/site	124 ±64	982 ±336	1001 ±338	122 ±58	1051 ±299	1069 ±299	126 ±73	902 ±367	922 ±371
RMSD (m^3 m^{-3})	0.144 ±0.079	0.102 ±0.059	0.093 ±0.048	0.090 ±0.032	0.081 ±0.045	0.077 ±0.039	0.206 ±0.070	0.126 ±0.066	0.111 ±0.051
MD (m^3 m^{-3})	0.033 ±0.131	–0.036 ±0.102	–0.012 ±0.088	–0.006 ±0.075	–0.034 ±0.072	–0.008 ±0.072	0.079 ±0.167	–0.038 ±0.130	–0.016 ±0.106
Abs. MD (m^3 m^{-3})	0.105 ±0.084	0.083 ±0.068	0.066 ±0.058	0.063 ±0.038	0.059 ±0.052	0.053 ±0.047	0.154 ±0.097	0.111 ±0.075	0.082 ±0.066
ubRMSD (m^3 m^{-3})	0.081 ±0.048	0.047 ±0.015	0.052 ±0.021	0.058 ±0.020	0.047 ±0.014	0.047 ±0.015	0.107 ±0.057	0.047 ±0.016	0.057 ±0.026
Correlation coefficient, r	0.37 ±0.32	0.70 ±0.15	0.61 ±0.21	0.59 ±0.16	0.73 ±0.10	0.69 ±0.21	0.11 ±0.27	0.68 ±0.19	0.52 ±0.25
Slope	0.33 ±0.76	0.94 ±0.67	0.69 ±0.53	0.69 ±0.37	0.81 ±0.55	0.63 ±0.59	–0.10 ±0.88	1.08 ±0.78	0.75 ±0.48

MD is computed as the satellite (or model) minus NEON soil moisture.

TABLE V
AS IN TABLE IV BUT FOR ROOT-ZONE (0–1 M) SOIL MOISTURE FROM SMAP-L4 AND NLDAS

	All sites ($N = 38$)		Unforested sites ($N = 20$)		Forested sites ($N = 18$)	
	SMAP-L4	NLDAS	SMAP-L4	NLDAS	SMAP-L4	NLDAS
Observations (n)	22 053	22 533	11 984	12 218	10 069	10 315
Observations/site	580 ±270	593 ±273	599 ±296	611 ±298	559 ±245	573 ±248
RMSD (m^3 m^{-3})	0.102 ±0.058	0.077 ±0.049	0.105 ±0.063	0.082 ±0.054	0.099 ±0.054	0.071 ±0.042
MD (m^3 m^{-3})	-0.008 ±0.113	-0.003 ±0.085	-0.035 ±0.116	-0.026 ±0.091	0.021 ±0.105	0.022 ±0.073
Abs. MD (m^3 m^{-3})	0.094 ±0.062	0.066 ±0.053	0.100 ±0.064	0.074 ±0.056	0.087 ±0.060	0.078 ±0.048
ubRMSD (m^3 m^{-3})	0.032 ±0.015	0.030 ±0.014	0.027 ±0.013	0.029 ±0.012	0.038 ±0.016	0.030 ±0.016
Correlation coefficient, r	0.67 ±0.20	0.67 ±0.19	0.68 ±0.21	0.66 ±0.21	0.65 ±0.19	0.69 ±0.17
Slope	0.84 ±0.62	0.76 ±0.61	0.77 ±0.61	0.81 ±0.77	0.92 ±0.65	0.70 ±0.36

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REFERENCES

[1] S. N. Oswalt, W. B. Smith, P. D. Miles, and S. A. Pugh, "Forest resources of the United States, 2017: A technical document supporting the forest service 2020 RPA assessment," U.S. Dept. Agriculture, Forest Service, Washington, DC, USA, 2019.

[2] H. Jactel et al., "Drought effects on damage by forest insects and pathogens: A meta-analysis," *Glob. Change Biol.*, vol. 18, no. 1, pp. 267–276, 2012, doi: 10.1111/j.1365-2486.2011.02512.x.

[3] D. Jensen, J. T. Reager, B. Zajic, N. Rousseau, M. Rodell, and E. Hinkley, "The sensitivity of US wildfire occurrence to pre-season soil moisture conditions across ecosystems," *Environ. Res. Lett.*, vol. 13, no. 1, 2018, Art. no. 014021, doi: 10.1088/1748-9326/aa9853.

[4] P. Meir et al., "Threshold responses to soil moisture deficit by trees and soil in tropical rain forests: Insights from field experiments," *BioScience*, vol. 65, no. 9, pp. 882–892, 2015, doi: 10.1093/biosci/biv107.

[5] D. Entekhabi et al., "The soil moisture active passive (SMAP) mission," *Proc. IEEE*, vol. 98, no. 5, pp. 704–716, May 2010, doi: 10.1109/JPROC.2010.2043918.

[6] J. R. Piepmeier et al., "SMAP L-band microwave radiometer: Instrument design and first year on orbit," *IEEE Trans. Geosci. Remote Sens.*, vol. 55, no. 4, pp. 1954–1966, Apr. 2017, doi: 10.1109/TGRS.2016.2631978.

[7] Y. Xia et al., "NLDAS Noah land surface model L4 hourly 0.125 × 0.125 degree V002," NASA/GSFC/HSL, Goddard Earth Sci. Data Inf. Serv. Center, Greenbelt, ML, USA, doi: 10.5067/47Z13FNQODKV.

[8] R. H. Reichle et al., "Assessment of the SMAP level-4 surface and root-zone soil moisture product using in situ measurements," *J. Hydrometeorol.*, vol. 18, no. 10, pp. 2621–2645, 2017, doi: 10.1175/JHM-D-17-0063.1.

[9] R. H. Reichle et al., "Global assessment of the SMAP level-4 surface and root-zone soil moisture product using assimilation diagnostics," *J. Hydrometeorol.*, vol. 18, no. 12, pp. 3217–3237, 2017, doi: 10.1175/JHM-D-17-0130.1.

[10] N. N. Das et al., "The SMAP and Copernicus Sentinel 1A/B microwave active-passive high resolution surface soil moisture product," *Remote Sens. Environ.*, vol. 233, 2019, Art. no. 111380, doi: 10.1016/j.rse.2019.111380.

[11] K. Kellogg et al., "NASA-ISRO synthetic aperture radar (NISAR) mission," in *Proc. IEEE Aerosp. Conf.*, 2020, pp. 1–21, doi: 10.1109/AERO47225.2020.9172638.

[12] A. Colliander et al., "Validation of SMAP surface soil moisture products with core validation sites," *Remote Sens. Environ.*, vol. 191, pp. 215–231, 2017, doi: 10.1016/j.rse.2017.01.021.

[13] A. Colliander et al., "Validation of soil moisture data products from the NASA SMAP mission," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 15, pp. 364–392, 2022, doi: 10.1109/JSTARS.2021.3124743.

[14] P. O'Neill et al., "Soil moisture active passive (SMAP) project: Calibration and validation for the L2/3_SM_P version 7 and L2/3_SM_P_E version 4 data products," Jet Propul. Lab., Pasadena, CA, USA, 2020.

[15] A. Colliander et al., "SMAP detects soil moisture under temperate forest canopies," *Geophys. Res. Lett.*, vol. 47, no. 19, 2020, Art. no. e2020GL089697, doi: 10.1029/2020GL089697.

[16] J. T. Ambadan et al., "Evaluation of SMAP soil moisture retrieval accuracy over a boreal forest region," *IEEE Trans. Geosci. Remote Sens.*, vol. 60, Oct. 2022, Art. no. 4414611, doi: 10.1109/TGRS.2022.3212934.

[17] K. M. Andreadis, D. F. Meason, B. Höck, P. Lad, and N. Das, "Evaluation of multiscale SMAP soil moisture products in forested environments," *IEEE Geosci. Remote Sens. Lett.*, vol. 19, Jun. 2022, Art. no. 2505805, doi: 10.1109/LGRS.2022.3184177.

[18] E. Ayres, A. Colliander, M. H. Cosh, J. A. Roberti, S. Simkin, and M. A. Genazzio, "Validation of SMAP soil moisture at terrestrial National Ecological Observatory network (NEON) sites show potential for soil moisture retrieval in forested areas," *IEEE J. Sel. Topics Appl. Earth Observ. Remote Sens.*, vol. 14, pp. 10903–10918, Oct. 2021, doi: 10.1109/JSTARS.2021.3121206.

[19] G. L. Schaefer, M. H. Cosh, and T. J. Jackson, "The USDA natural resources conservation service soil climate analysis network (SCAN)," *J. Atmos. Ocean. Technol.*, vol. 24, no. 12, pp. 2073–2077, 2007, doi: 10.1175/2007JTECHA930.1.

[20] H. J. Diamond et al., "US climate reference network after one decade of operations: Status and assessment," *Bull. Amer. Meteorol. Soc.*, vol. 94, no. 4, pp. 485–498, 2013, doi: 10.1175/BAMS-D-12-00170.1.

[21] "neonUtilities: Utilities for working with NEON data," Nat. Ecol. Observatory Netw., Boulder, CO, USA, 2021. [Online]. Available: https://github.com/NEONScience/NEON-utilities

[22] J. A. Roberti et al., "A robust calibration method for continental-scale soil water content measurements," *Vadose Zone J.*, vol. 17, no. 1, pp. 1–19, 2018, doi: 10.2136/vzj2017.10.0177.

[23] N. Das et al., "SMAP/sentinel-1 L2 radiometer/radar 30-second scene 3 km EASE-grid soil moisture, version 3 [Data Set]," NASA Nat. Snow Ice Data Center Distrib. Active Archive Center, Boulder, CO, USA, doi: 10.5067/ASB0EQO2LYJV.

[24] N. N. Das et al., "The SMAP mission combined active-passive soil moisture product at 9 km and 3 km spatial resolutions," *Remote Sens. Environ.*, vol. 211, pp. 204–217, 2018, doi: 10.1016/j.rse.2018.04.011.

[25] F. Chen et al., "Uncertainty of reference pixel soil moisture averages sampled at SMAP core validation sites," *J. Hydrometeorol.*, vol. 20, no. 8, pp. 1553–1569, 2019, doi: 10.1175/JHM-D-19-0049.1.

[26] M. H. Cosh, T. J. Jackson, R. Bindlish, and J. H. Prueger, "Watershed scale temporal and spatial stability of soil moisture and its role in validating satellite estimates," *Remote Sens. Environ.*, vol. 92, no. 4, pp. 427–435, 2004, doi: 10.1016/j.rse.2004.02.016.

[27] W. T. Crow et al., "Upscaling sparse ground-based soil moisture observations for the validation of coarse-resolution satellite soil moisture products," *Rev. Geophys.*, vol. 50, no. 2, 2012, Art. no. RG2002, doi: 10.1029/2011RG000372.

[28] R. Reichle et al., "SMAP L4 global 3-hourly 9 km EASE-grid surface and root zone soil moisture geophysical data, version 7," NASA Nat. Snow Ice Data Center Distrib. Active Archive Center, Boulder, CO, USA, doi: 10.5067/EVKPQZ4AFC4D.

[29] R. H. Reichle et al., "Soil moisture active passive (SMAP) project assessment report for version 7 of the L4_SM data product," NASA Tech. Report Series Global Model. Data Assimilation, NASA/TM-2023-104606, Nat. Aeronaut. Space Admin., Goddard Space Flight Center, Greenbelt, MD, USA, 2023.

[30] R. D. Koster, M. J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar, "A catchment-based approach to modeling land surface processes in a general circulation model: 1. Model structure," *J. Geophys. Res., Atmos.*, vol. 105, no. D20, pp. 24809–24822, 2000, doi: 10.1029/2000JD900327.

[31] G. J. De Lannoy and R. H. Reichle, "Global assimilation of multiangle and multipolarization SMOS brightness temperature observations into the GEOS-5 catchment land surface model for soil moisture estimation," *J. Hydrometeorol.*, vol. 17, no. 2, pp. 669–691, 2016, doi: 10.1175/JHM-D-15-0037.1.

[32] G. J. De Lannoy and R. H. Reichle, "Assimilation of SMOS brightness temperatures or soil moisture retrievals into a land surface model," *Hydrol. Earth Syst. Sci.*, vol. 20, no. 12, pp. 4895–4911, 2016, doi: 10.5194/hess-20-4895-2016.

[33] M. Stieglitz, A. Ducharne, R. Koster, and M. Suarez, "The impact of detailed snow physics on the simulation of snow cover and subsurface thermodynamics at continental scales," *J. Hydrometeorol.*, vol. 2, no. 3, pp. 228–242, 2001, doi: 10.1175/1525-7541(2001)002%3C0228:TIODSP%3E2.0.CO;2.

[34] R. H. Reichle et al., "IMERG precipitation improves the SMAP level-4 soil moisture product," *J. Hydrometeorol.*, vol. 24, no. 10, pp. 1699–1723, 2023, doi: 10.1175/JHM-D-23-0063.1.

[35] G. J. De Lannoy, R. H. Reichle, and V. R. Pauwels, "Global calibration of the GEOS-5 L-band microwave radiative transfer model over nonfrozen land using SMOS observations," *J. Hydrometeorol.*, vol. 14, no. 3, pp. 765–785, 2013, doi: 10.1175/JHM-D-12-092.1.

[36] G. J. De Lannoy, R. H. Reichle, and J. A. Vrugt, "Uncertainty quantification of GEOS-5 L-band radiative transfer model parameters using Bayesian inference and SMOS observations," *Remote Sens. Environ.*, vol. 148, pp. 146–157, 2014, doi: 10.1016/j.rse.2014.03.030.

[37] D. Entekhabi, R. H. Reichle, R. D. Koster, and W. T. Crow, "Performance metrics for soil moisture retrievals and application requirements," *J. Hydrometeorol.*, vol. 11, no. 3, pp. 832–840, 2010, doi: 10.1175/2010JHM1223.1.

[38] A. Gruber et al., "Validation practices for satellite soil moisture retrievals: What are (the) errors?," *Remote Sens. Environ.*, vol. 244, 2020, Art. no. 111806, doi: 10.1016/j.rse.2020.111806.

[39] Sentek, "Calibration manual for Sentek soil moisture sensors," Stepney, SA, Australia, 2011.

[40] D. Entekhabi et al., "SMAP handbook–soil moisture active passive: Mapping soil moisture and freeze/thaw from space," Jet Propul. Lab., Calif. Inst. Technol., Pasadena, CA, USA, JPL CL#14-2285, 2014.

[41] R. H. Reichle et al., "The contributions of gauge-based precipitation and SMAP brightness temperature observations to the skill of the SMAP level-4 soil moisture product," *J. Hydrometeorol.*, vol. 22, no. 2, pp. 405–424, 2021, doi: 10.1175/JHM-D-20-0217.1.

[42] Y. Xia et al., "Evaluation of multi-model simulated soil moisture in NLDAS-2," *J. Hydrol.*, vol. 512, pp. 107–125, 2014, doi: 10.1016/j.jhydrol.2014.02.027.

[43] M. Abdelkader et al., "Assessing the spatiotemporal variability of SMAP soil moisture accuracy in a deciduous forest region," *Remote Sens.*, vol. 14, no. 14, 2022, Art. no. 3329, doi: 10.3390/rs14143329.

[44] T. Jackson and T. Schmugge, "Vegetation effects on the microwave emission of soils," *Remote Sens. Environ.*, vol. 36, no. 3, pp. 203–212, 1991, doi: 10.1016/0034-4257(91)90057-D.

[45] R. B. Jackson, J. Canadell, J. R. Ehleringer, H. Mooney, O. Sala, and E.-D. Schulze, "A global analysis of root distributions for terrestrial biomes," *Oecologia*, vol. 108, pp. 389–411, 1996, doi: 10.1007/BF00333714.

[46] M. Lu et al., "A continental scale analysis reveals widespread root bimodality," *bioRxiv*, 2002, doi: 10.1101/2022.09.14.507823.

[47] P. Jiang, H. Wang, F. C. Meinzer, L. Kou, X. Dai, and X. Fu, "Linking reliance on deep soil water to resource economy strategies and abundance among coexisting understorey shrub species in subtropical pine plantations," *New Phytologist*, vol. 225, no. 1, pp. 222–233, 2020, doi: 10.1111/nph.16027.

[48] V. A. Walker, B. K. Hornbuckle, M. H. Cosh, and J. H. Prueger, "Seasonal evaluation of SMAP soil moisture in the US corn belt," *Remote Sens.*, vol. 11, no. 21, 2019, Art. no. 2488, doi: 10.3390/rs11212488.

[49] S. Zwieback et al., "Estimating time-dependent vegetation biases in the SMAP soil moisture product," *Hydrol. Earth Syst. Sci.*, vol. 22, no. 8, pp. 4473–4489, 2018, doi: 10.5194/hess-22-4473-2018.

[50] NEON, "Explore field sites," Accessed on: Jun. 12, 2023. [Online]. Available: https://www.neonscience.org/field-sites/explore-field-sites

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