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SMAP Soil Moisture Measurement in Hungary over Agricultural Land

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Abstract

Monitoring spatial and temporal dynamics of soil moisture is essential for managing hydrological extremes such as droughts and inland excess water. This study assesses the accuracy of NASA's Soil Moisture Active Passive (SMAP) Level 3 soil moisture product using long-term in situ measurements (2016–2024) from the national drought monitoring network in Hungary. Two distinct 36 km satellite footprint cells were extensively analyzed, representing different land use and soil type conditions.

Daily averaged in situ soil moisture data measured in the upper 10 cm layer were compared to SMAP observations for both AM and PM overpasses. Statistical metrics used to evaluate performance include the Pearson correlation coefficient (*R*), bias, root mean square error (RMSE), and unbiased RMSE (ubRMSE). Results indicate that PM values generally exhibit stronger agreement with in situ measurements. The SMAP product met the <0.04 m^3/m^3 ubRMSE validation requirement threshold over several years and locations, particularly in areas with homogeneous soil conditions. However, variability in soil types and topography in more heterogeneous regions highlights the need for additional ground-based measurements and higher-resolution satellite data to enhance local-scale validation.

Keywords

soil moisture, SMAP validation, remote sensing in agriculture

1 Introduction

In the coming decades, ensuring a balanced water supply will pose an extraordinary challenge to humanity. The increasing frequency of localized, short-duration heavy rainfall, rising aridity of the climate and changes in land use have contributed significantly to the imbalance of the soil-plant-atmosphere system [1, 2].

Hungary has 5.3 million hectares of agricultural land, of which approximately 1.9 million hectares are considered potentially at risk of inland excess water. Under extreme hydrological conditions, an average of 100,000–150,000 hectares are flooded every 2–3 years, primarily in the Great Plain, the Little Hungarian Plain, the Drava Valley and the southern coast of Lake Balaton. The occurrence of inland excess water is influenced by both static factors (e.g., topography, soil conditions, abandoned riverbeds) and dynamic factors (e.g., meteorology, hydrology, groundwater movement). Anthropogenic activities, such as inappropriate cultivation practices or the deterioration of the drainage network, can further increase the risk [3].

Climate models predict that extremely hot days will become more frequent, while summer rainfall could decrease by more than 20% by the end of the century [4]. Due to the escalating drought hazard and the higher frequency of drought years, agricultural conditions are expected to degrade throughout the 21st century [5]. In 2022, approximately 1.4 million hectares of agricultural land in Hungary were affected by drought [6].

This fluctuating water balance is particularly sensitive to agriculture, as it can cause severe crop failure, soil degradation and cultivation problems. In cases of both extreme inland excess water and drought, the extent of damage is significantly influenced by soil moisture content and moisture transport [7]. Monitoring soil moisture via satellite remote sensing is therefore crucial for understanding the spatial and temporal dynamics of water balance extremes and predicting risks.

Since the early 2000s, several satellite soil moisture products and datasets have been made available, based on active and passive microwave sensors. The L-band (1–2 GHz)

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portion of the electromagnetic spectrum is particularly suitable for soil moisture estimation, as the effects of vegetation and the atmosphere are minimal within this frequency range. Currently, NASA's SMAP and ESA's SMOS satellites are the only L-band radiometer platforms designed specifically for soil moisture monitoring [8].

Over the past decade, significant development of retrieval algorithms has increased the accuracy and consistency of data. Consequently, product validation and understanding of error characteristics have become essential for reliable use and for providing feedback for further improvements [9–13].

In this study, we examine SMAP satellite soil moisture data and validate it using field measurements from a representative national ground-based network. The aim of this research is to evaluate whether passive microwave remote sensing data are suitable for estimating the moisture status of the upper soil layer and for filling the gap in missing data over agricultural areas of Hungary, given the varied soil and extreme precipitation conditions. We analyze the capabilities and limitations of the large footprint and daily temporal resolution of SMAP satellite -data in correlation with in situ soil moisture measurements. Furthermore, we examine the sensitivity of drought and vegetation effects across interannual and seasonal variations.

2 Materials and methods

2.1 Study area and ground-based observation database

The General Directorate of Water Management (OVF) began installing an in-situ drought monitoring network in 2016. The objective was to establish a nationwide soil moisture monitoring network to support drought detection, the determination of defence levels, and the calculation of the daily water deficit index (HDI). Station locations were selected based on several criteria: in addition to ensuring national coverage, sites were situated on agricultural (primarily arable) land, representing the dominant soil types of the surrounding area. Furthermore, only non-irrigated plots were selected, located away from operational meteorological stations, in areas with relatively flat topography and free from excessive surface water effects [14]. The soil moisture ground-based stations were installed in a 2.5 × 2.5 m fenced area protected against wildlife and vandalism (Fig. 1). Currently, ther network of 144 stations is operational and constantly maintained. These stations primarily monitor the soil and vegetation conditions. In addition to fundamental meteorological parameters such as precipitation, humidity, air temperature, relative humidity lately leaf surface moisture, soil moisture and temperature are recorded every hour at six different depths (10 cm, 20 cm, 30 cm, 45 cm, 60 cm and 75 cm) at the monitoring sites.


Fig. 1 Drought monitoring station in Apaj

The ground-based drought monitoring system measures soil moisture using Decagon 5TM sensors, which determine volumetric water content based on the soil's dielectric permittivity. The station network has been gradually expanded since 2016 [14]. Starting in 2022, the sensors at the Gádoros and Tótkomlós study sites were upgraded to modern TEROS 12 models, subsequent replacements took place at Nagybánhegyes in 2023 and Kunszentmiklós in 2024. Compared to the 5TM sensors, these sensors offer a larger measurement volume, more stable data, integrated electrical conductivity (EC) measurement, and a longer service life [15]. However, the differing technical characteristics of these sensors may influence the comparability of the long-term data series.

Ten monitoring stations were selected from the drought monitoring network for a detailed comparison over a period of nearly ten years (2016–2024). The data is available via open access on their website [16]. The selection of the study areas was based on the number of stations falling within a specific raster cell; a higher station density allows for more reliable evaluation and validation, and furthermore, it helps to reduce potential errors in remote sensing estimations. Since the SMAP L3 soil moisture product has a daily temporal resolution and a spatial resolution of 36 km, a maximum of five stations were located within individual raster cells in the two areas of interest (Raster1 and Raster2). The 36 km product was evaluated because the 9 km downscaled product would have allowed only one station per cell. Fig. 2 shows the locations of the stations within the drought monitoring network on a land use map, while also indicating the satellite raster cell coverage for the two investigated areas.

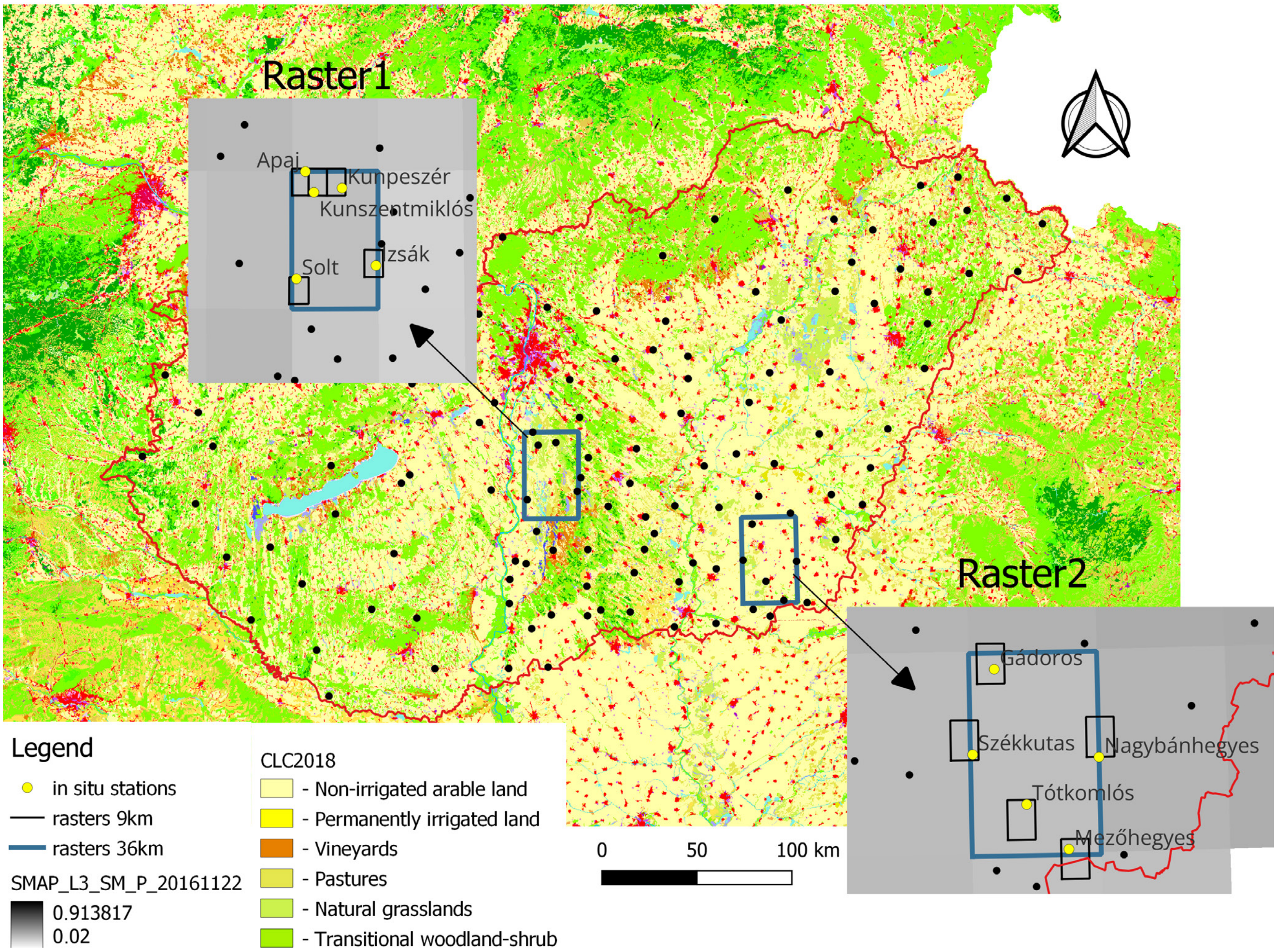

Fig. 2 Location of mnitoring stations within the SMAP raster cells (Raster1 and Raster2) overlaid on a land-use map

In the Raster 1 area, the average annual precipitation is 500 mm, and the average annual temperature of 12 °C. According to the 2018 CORINE Land Cover (CLC) databse, the land use is distributed as follows: 41.8% is non-irrigated arable land; 15.4% consists of complex cultivation patterns (arable land and pastures), and 7% belongs to other categories, primarily semi-natural areas such as transitional forest-shrubland, deciduous forest, vineyards and natural grasslands. The average elevation of the five in situ monitoring stations is 97.2 m a.s.l. One station (Izsák) is located in a vineyard at a higher elevation of 104.5 m a.s.l., while the others are situated on non-irrigated arable land. According to the USDA soil taxonomy, the soil texture classes at the stations vary within the topsoil layer (5–15 cm): Apaj and Solt are characterized by sandy loam, Izsák by sand, Kunpeszér by clay loam, and Kunszentmiklós by loam [17]. Soil water management is characterized by field capacity at pF = 2.5, reflecting the moisture content of the upper 10 cm of soil. Based on these values, sandier soils exhibit faster water movement and lower water retention capacity, whereas fine-grained loamy and clayey soils retain higher moisture content.

In the Raster 2 area, the average annual precipitation is slightly higher (520 mm) while the average temperature remains at 12 °C. Approximately 87.2% of the area is unirrigated arable land, and a further 4% is comprised of natural grassland and pasture. The average elevation of the stations is 91.4 m a.s.l., although relative differences in altitude of approximately 5 m can be observed. All stations are located on non-irrigated arable land. According to the USDA standard, the soil texture classes at the stations differ significantly in the topsoil layer (5–15 cm): Gádoros is characterized by sandy loam, Nagybánhegyes by clay loam, while Mezőhegyes, Székkutas and Tótkomlós have clay soil [17]. Based on the field capacity values at pF = 2.5, fine-grained clay soils can retain a higher moisture content in the top 10 cm of soil, whereas sandy loam exhibits faster water movement and a more moderate water retention capacity.

For the correlation analysis of satellite soil moisture estimates, surface precipitation and in situ moisture data from the top 10 cm of soil were used. Comparing multiple ground-based soil moisture measurements enables the assessment of the correlation between in-situ observations and satellite data for different land uses and soil types.

2.2 SMAP SM products

The NASA Soil Moisture Active Passive (SMAP) satellite mission was launched in January 2015 and became operational in April 2015. It was originally equipped with two instruments to measure soil moisture: an active Synthetic Aperture Radar (SAR) and a passive radiometer. Due to a hardware failure in the radar power supply, the radar instrument stopped working in July 2015. Despite this, the SMAP radiometer continues to provide valuable global soil moisture data for applications in climatology, hydrology, and agriculture.

NASA processes raw SMAP observations into four distinct product levels. Level 1 products consist of raw brightness temperature swath data. Level 2 products contain retrieved geophysical variables, such as surface soil moisture, at half-orbital resolution. Level 3 products are daily global composites generated by gridding and aggregating Level 2 data. Finally, Level 4 provide modelled, value-added data, estimating parameters such as root-zone soil moisture and land-atmosphere water and carbon fluxes. This hierarchical system enables users to select the most appropriate data level for their specific research objectives [18].

The SMAP L3 SM product is a daily composite that contains soil moisture observations from both descending (6:00 AM) and ascending (6:00 PM) overpasses. It features a spatial resolution of approximately 36 km and a revisit time of 2–3 days [18]. For our analysis, we utilized the SMAP L3 Radiometer Global Daily Soil Moisture, Version 9 (L3_SM_P) dataset, which is provided in both HDF5 (.h5) and georeferenced GeoTIFF formats by the National Snow and Ice Data Center (NSIDC).

2.3 Data processing

SMAP products provide multiple ways to assess quality. Each product contains bit flags, uncertainty measures, and file-level metadata that provide quality information. When processing SMAP L3 soil moisture data, we used the retrieval quality flag field as the primary quality indicator. This flag identifies whether the surface was frozen, snow-covered, flooded or experiencing precipitation at the time of satellite passage. This enables uncertain or erroneous retrievals to be filtered out [19]. The use of the retrieval quality flag is not only recommended by NASA, but is also common practice in several regional agricultural studies [20]. In the case of in situ data, we reduced measurement errors by applying quantile-based outlier filtering to the complete time series of each station.

Quantitative comparisons were enabled by harmonizing satellite and in situ data into a common daily time-series database across the Raster1 (Fig. 3) and Raster2 (Fig. 4). Fig. 3 and Fig. 4 reveal considerable variation in the data across different years and stations compared to the satellite data which are represented as points.

To evaluate the agreement between satellite and in situ data, we used the Pearson correlation coefficient (R) in Eq. (4), bias in Eq. (1), root mean square error (RMSE) in Eq. (2) and unbiased RMSE (ubRMSE) in Eq. (3). The R value describes the linear relationship between SMAP L3 SM and in situ SM. Since a single in situ point is not necessarily representative of an entire SMAP pixel, ubRMSE was adopted to evaluate the error after removing the mean bias [21, 22].

$$\text{Bias} = E\left[\theta_{est}\right] - E\left[\theta_{\text{true}}\right] \tag{1}$$

$$\text{RMSE} = \sqrt{E\left[\left(\theta_{est} - \theta_{\text{true}}\right)^2\right]} \tag{2}$$

$$\text{ubRMSE} = \sqrt{\text{RMSE}^2 - \text{Bias}^2} \tag{3}$$

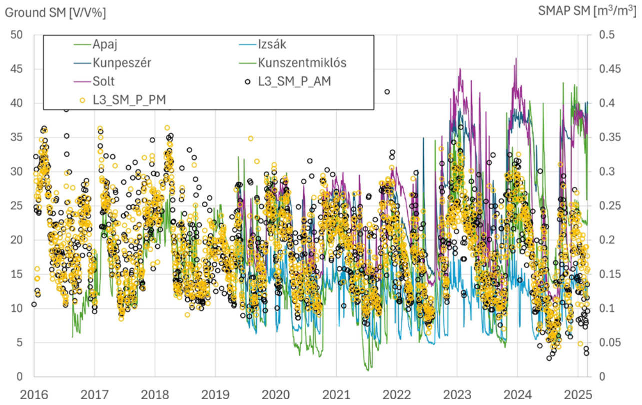

Fig. 3 Time series data in Raster1

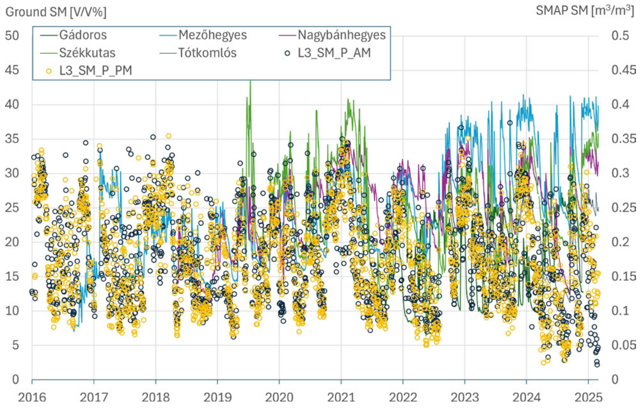

Fig. 4 Time series data in Raster2

$$R=\frac{E\left[\left(\theta_{est}-E\left[\theta_{est}\right]\right)\left(\theta_{\text{true}}-E\left[\theta_{\text{true}}\right]\right)\right]}{\sigma_{est}\sigma_{\text{true}}} \tag{4}$$

Where the true surface volumetric soil moisture (at a given scale) is defined as θ_{true} and the corresponding estimated retrieval is θ_{true}, $E[]$ is the expectation operator, σ^2_{est} and σ^2_{true} are the time variances of the estimated and true soil moisture for the remote sensing pixel, respectively. The SMAP surface (0–5 cm) soil moisture products must satisfy the mission requirement; specifically, the mean of the unbiased RMSE (ubRMSE) across all N_i validation areas must be less than 0.04 cm^3/cm^3, as shown in Eq. (5) [19].

$$\frac{1}{N_i}\sum_{i=1}^{N_i}\left[\text{ubRMSE}(i)\right]\le 0.04\ \text{m}^3/\text{m}^3 \tag{5}$$

3 Results

Section 3 presents the assessment results of the SMAP L3 SM product using box plots, table and line charts. Statistical indicators were calculated on an annual basis to examine the extent to which daily average in situ soil moisture measurements follow AM and PM satellite soil moisture retrievals. Fig. 5 and Fig. 6 present the distribution of yearly statistics for Raster1 and Raster2, respectively, using box plots. Orange and blue colors indicate the descending (AM) and ascending (PM) product results. The study period extended from 1 January 2016 to 28 February 2025. However, as the monitoring stations were installed at different times, their temporal coverage varies significantly.

The box plots show the distribution of the yearly statistics for Raster1 in Fig. 5. and for Raster2 in Fig. 6. Orange and blue colours indicate descending (AM) and ascending (PM) product results, respectively. The study period extended from 1 January 2016 to 28 February 2025. However, as the in situ monitoring stations were installed staggered in time, their temporal coverage and data availability vary significantly.

Based on the results, it can be concluded that the PM retrievals generally outperform the AM values. According to the bias (Fig. 5 (a)) calculations, the satellite data underestimate the in situ measurements in the most cases. While RMSE (Fig. 5 (b)) measures the total error between the estimates and the true values, ubRMSE (Fig. 5 (c)) captures the random error after removing the mean bias. A significantly larger RMSE compared to the ubRMSE indicates a systematic bias. For SMAP soil moisture products, an ubRMSE below 0.04 m^3/m^3 is considered acceptable, reflecting low random error relative to in situ measurement. This criterion was met in the Raster1 area by the Izsák station 0.038 m^3/m^3 the entire study period. However, when examined annually, several

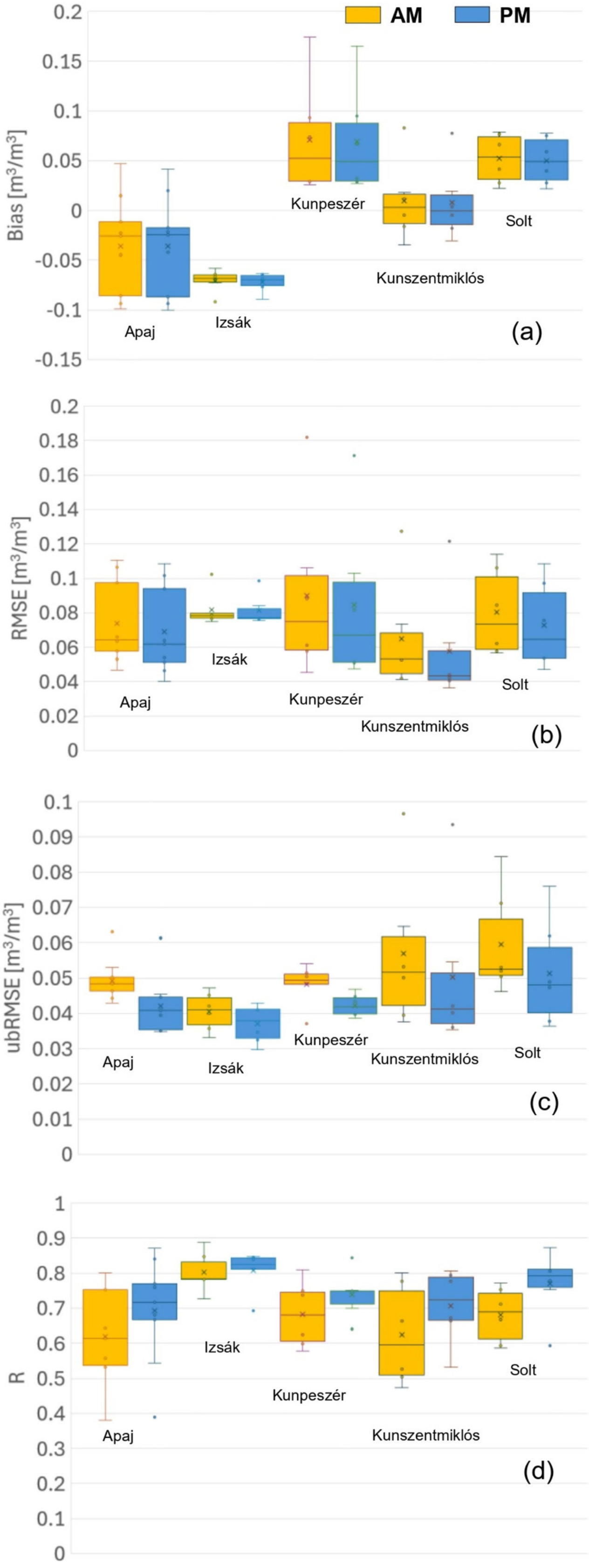

Fig. 5 SM assessment statistics for Raster 1 in terms of (a) bias, (b) RMSE, (c) ubRMSE and (d) *R*

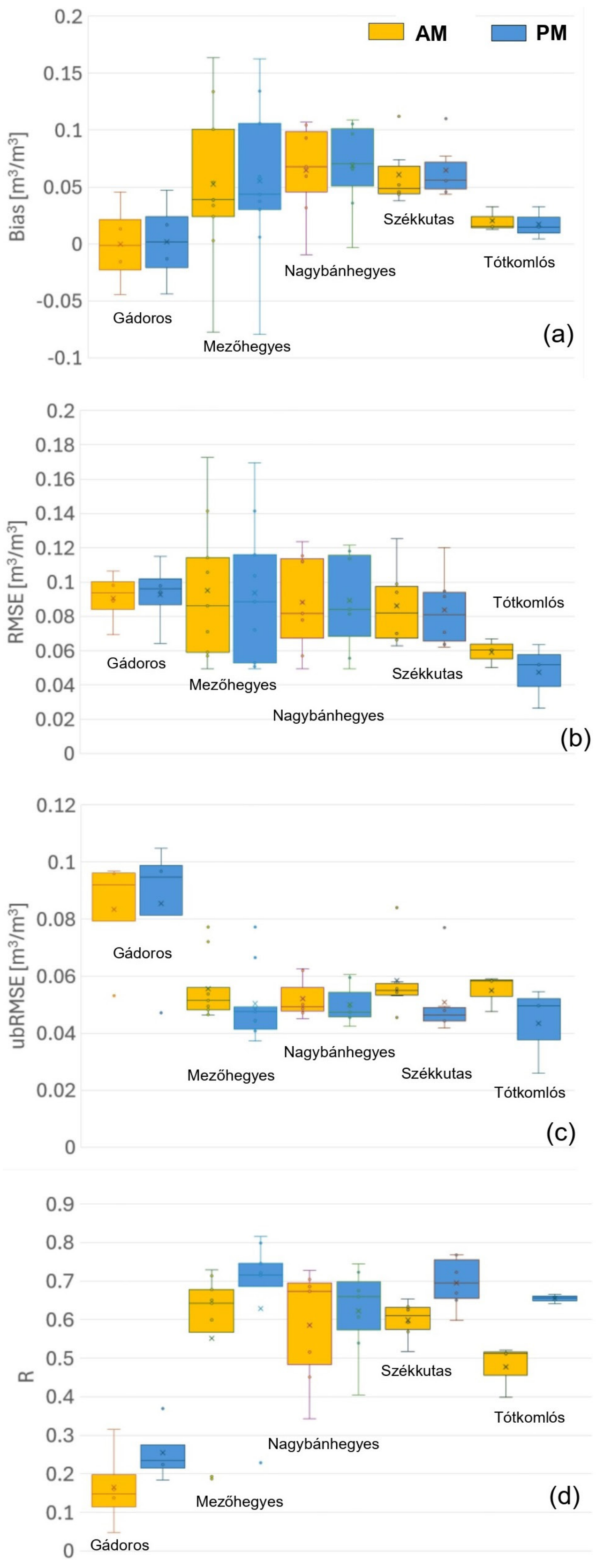

Fig. 6 SM assessments statistics for Raster2 in terms of (a) bias, (b) RMSE, (c) ubRMSE and (d) *R*

stations performed below this threshold for multiple years (Apaj 4 years, Izsák 3 years, Kunpeszér, Kunszentmiklós and Solt 2 years.

Fig. 6 shows that the discrepancy between satellite and in situ measurements is greater in Raster2 than in Raster1, characterized by lower correlations (Fig. 6 (d), *R*) and larger variation among the statistical indicators (Fig. 6 (a) bias; Fig. 6 (b) RMSE; Fig. 6 (c) ubRMSE) of the stations. The Gádoros station shows the lowest performance in this regard; therefore its inclusion in further analyses should be reconsidered.

The Person correlation coefficient (*R*) indicates the strength and direction of the relationship between satellite and ground-based measurements. The closer the coefficient is to 1, the stronger the correlation. In SMAP analyses an *R* value above 0.8 generally indicates strong agreement between the two data sources. The SMAP L3 product performance criteria are defined as ubRMSE ≤ 0.04 m^3/m^3 and $R \geq 0.8$ [11]. Table 1 provides tge calculated values in detail, distinguishing between AM and PM overpasses; results meeting the validation criteria are highlighted in bold, while the remaining results are indicated in grey. In the case of Raster1, the high correlation values are likely attributable to the geophysical characteristics of the area such as soil properties, topography and land use.

Due to the significant variation in soil moisture across large area, measurements taken at a single in situ station are generally not representative of the data retrieved from a satellite with large footprint. Averaging spatial measurements from multiple stations can minimize the effects caused by scale differences. Therefore, we averaged the daily ground-based measurements over the raster cells to evaluate how much it enhances the agreement between ground and satellite estimations. As shows in Fig. 7, the complete time-series shows an almost 30% improvement when we calculate the average of several in situ stations. This analysis was specifically performed on the Raster1 cell, as this area exhibited more favorable preliminary results.

We also studied seasonal variations by averaging multiple in situ station data within the a satellite raster footprints. Across the studied areas, higher correlation values (*R*) we obtained for the ascending (PM) passes, particularly in spring (0.61) and autumn (0.52), with Raster1 showing higher accuracy than Raster2 (Fig. 8). The improvement performance during these seasons is attributed to more favorable vegetation density, the absence of snow and frost, and reduced atmospheric attenuation. Furthermore, the radiometer is better able to capture dynamic changes in soil moisture under these moderate conditions.

Table 1 Correlation coefficient R per year at soil moisture stations (AM/PM values)

	2019	2020	2021	2022	2023	2024
Raster1						
Apaj	0.56 / 0.67	0.53 / 0.68	0.62 / 0.76	0.54 / 0.54	0.75 / **0.84**	**0.80 / 0.87**
Izsák	0.78 / 0.69	**0.85 / 0.85**	0.73 / **0.81**	**0.89 / 0.85**	0.79 / **0.81**	0.78 / 0.84
Kunpeszér	**0.81** / 0.75	0.60 / 0.70	0.63 / 0.75	0.74 / 0.75	0.75 / **0.84**	0.58 / 0.64
Kunszent-miklós	**0.80** / 0.79	0.50 / 0.66	0.53 / 0.68	0.78 / **0.81**	0.66 / 0.78	0.47 / 0.53
Solt	0.59 / 0.59	0.59 / 0.75	0.67 / 0.78	0.75 / **0.81**	0.71 / **0.81**	0.77 / **0.87**
Raster2						
Gádoros			0.16 / 0.22	0.05 / −0.18	0.32 / −0.37	0.14 / −0.24
Mezőhegyes	0.57 / 0.69	0.68 / **0.80**	0.74 / **0.82**	0.64 /0.72	0.71 / 0.72	0.60 / 0.75
Nagybán-hegyes	0.67 / 0.66	0.73 / 0.67	0.46 / 0.55	0.69 / 0.74	0.70 / 0.72/	0.52 / 0.61
Székkutas	0.63 / 0.65	0.57 / 0.67	0.53 / 0.61	0.65 / 0.77	0.63 / 0.72	0.59 / 0.77
Tótkomlós				0.40/ 0.66/	0.51/ 0.64	0.52/ 0.67

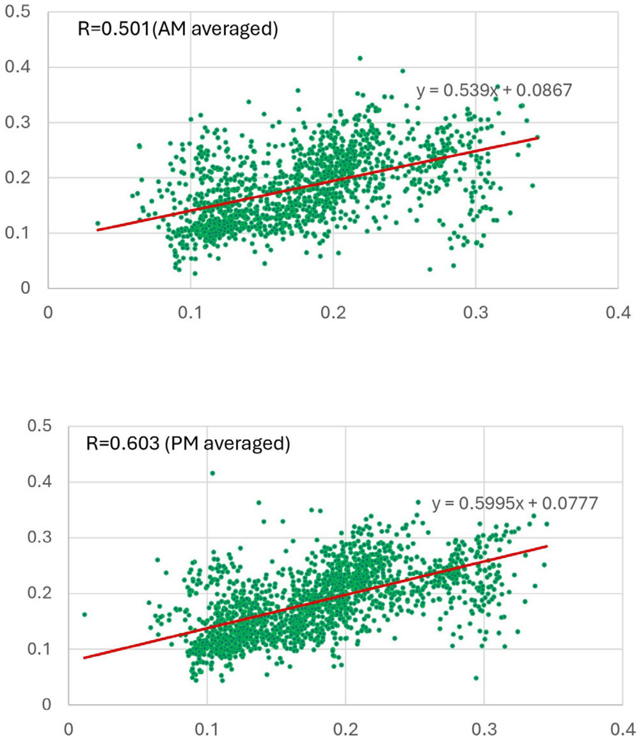

Fig. 7 Improvement of correlation coefficient (R) after averaging multiple in situ stations measurements in Raster1

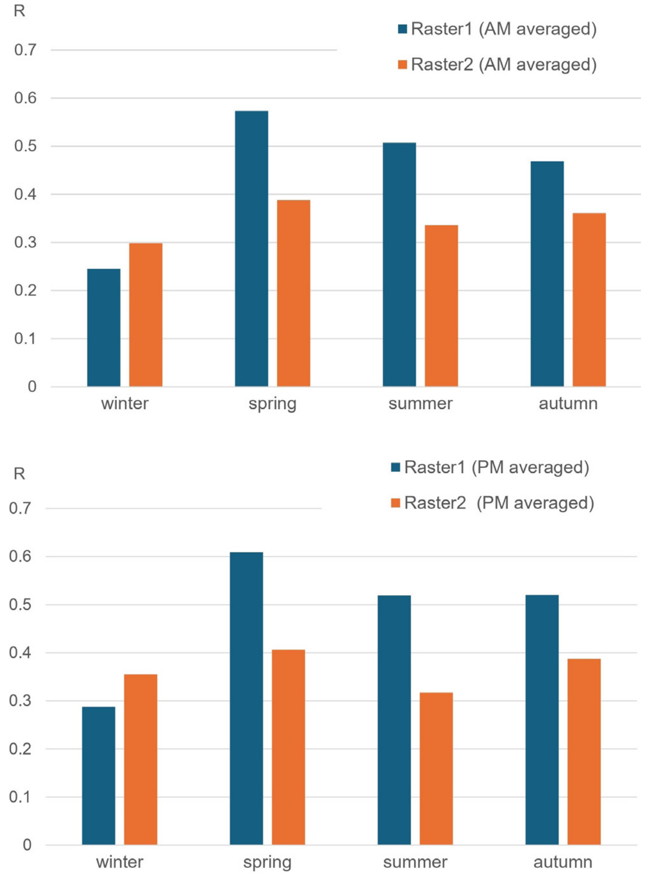

Fig. 8 Seasonal characteristics of averaging on correlation coefficient (R) in Raster1 and Raster2

The comparison of satellite and in-situ soil moisture measurements in this study revealed patterns consistent with findings in the literature. Specifically, ascending (PM) retrievals outperformed descending (AM) ones, while the satellite data tended to underestimate field measurements, reflecting the negative bias. The ubRMSE values frequently fell below the 0.04 m^3/m^3 threshold, confirming acceptable random error levels. Seasonal results also aligned with established literature [11], showing higher accuracy in spring and autumn due to favorable vegetation and surface conditions. Finally, averaging multiple in situ stations significantly improved correlations, supporting the established practice of reducing scale mismatch between ground-based and satellite data. These results align with several independent studies discussed in detail in Section 4.

4 Discussion

Several studies have reported systematic differences between SMAP ascending (PM) and descending (AM) overpasses when compared against in situ soil moisture observations [23–26]. In many cases, the descending morning passes show slightly better coincidence, while in other regions ascending passes provide higher correlations. These discrepancies can be attributed to several factors.

Diurnal effects in surface temperature and soil moisture influence the microwave signal at the satellite. During the morning overpass, surface conditions are usually more stable, whereas in the afternoon evaporation and stronger soil temperature gradients can introduce greater variability [23, 10]. The amount of water stored in vegetation and the structure of the plant canopy change over the course of the day, impacting the microwave signal. This affects the accuracy of soil moisture estimates, especially in agricultural areas or regions with dense vegetation [24]. The algorithms and supporting data used to produce the SMAP L3 product differ depending on whether the satellite passes in the morning (descending pass) or the afternoon (ascending pass). For example, uncertainties in soil temperature or freeze/thaw conditions may introduce biases that are stronger in one overpass than in the other [25]. Differences in scale between local in situ measurements and the 36 km SMAP spatial footprint can introduce a difference with daily changes in soil and surface water conditions. Since local variability is often greater during the day, this can lead to weaker agreement with the afternoon (ascending) satellite measurement [26].

In addition, several studies have reported that the relative accuracy of morning and afternoon data queries is not consistent throughout the year, varying with vegetation phenology and surface hydrological dynamics. For example, site-specific assessments in northwestern China showed that ascending overpasses sometimes had stronger correlations in summer and fall, especially over alpine meadows, while descending data performed better in spring [27]. At a global scale, dry down analyses revealed that soil moisture retrieval accuracy can change during drought conditions, with diurnal moisture and temperature gradients exerting stronger influence under dry soils [28]. Futhermore, assessments of precipitation flagging demonstrated that ascending overpasses may achieve comparable or slightly better performance when atmospheric interference is minimized [29]. These results suggest that ascending SMAP data may provide estimates that are as reliable or even more reliable in certain cases, particularly during dry periods or for certain crop types. Therefore, separating the evaluation of ascending and descending retrievals is essential to determine the conditions under which the SMAP product achieves the highest accuracy.

Overall, the relative performance of SMAP observations during ascending and descending passes varies depending on multiple factors, including regional characteristics and seasonality. Evaluating the two overpasses separately therefore provides valuable insight into the conditions under which SMAP retrievals achieve optimal accuracy.

5 Conclusions

In this study, we evaluated the accuracy of the 36 km NASA SMAP L3 soil moisture product using ground-based measurements from the Hungarian drought monitoring network. The results indicate that SMAP data, especially from the afternoon (ascending) overpasses, show a strong correlation within situ observations, especially when spatial averaging over several stations is applied. In several cases, ubRMSE values remained below the satellite product's validation requirement of <0.04 m^3/m^3 during interannual variations, supporting the product's reliability even during variable hydro-meteorological periods, particularly in areas with homogeneous soil conditions. However, the inaccuracies found in more heterogeneous areas highlight the importance of incorporating higher resolution remote sensing data for detailed, local validations. Overall, SMAP soil moisture data prove to be a valuable tool for monitoring and managing extreme hydrological phenomena in agricultural regions, as demonstrated by this case study in Hungary.

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References

[1] Somlyódy, L., Aradi, C. "A hazai vízgazdálkodás stratégiai kérdései" (Strategic Issues of the Hungarian Water Resources Management), Magyar Tudományos Akadémia, 2002. ISBN 963-508-333-5 (in Hungarian)

[2] Tőkei, L., Juhos K. "A csapadékvíz, a vízkészletek és vízhasználat kapcsolatrendszerének agroklimatológiai vonatkozásai" (Some agroclimatic aspects of rainwater, water resources and water use), "KLÍMA-21" Füzetek, 61, pp. 33–43, 2010. (in Hungarian)

[3] Kajári, B., Tobak, Z., Túri, N., Bozán, C., Van Leeuwen, B. "Prediction of Inland Excess Water Inundations Using Machine Learning Algorithms", Water, 16(9), 1267, 2024. https://doi.org/10.3390/w16091267

[4] Lakatos, M., Zsebeházi, G. "Az éghajlat megfigyelt tendenciái és várható alakulása Magyarországon" (Observed trends and projected changes in the climate of Hungary), [pdf] In: Mérsékelt öv? Felelős cselekvési irányok a hatékony klímavédelemért, Klímabarát Települések Szövetsége, pp. 31–49, 2018. ISBN 978-615-00-1120-2 Available at: http://klimabarat.sreter.eu/images/kiadvany/kotet.pdf (In Hungarian)

[5] Mezősi, G., Blanka, V., Ladányi, Z., Bata, T., Urdea, P., Frank, A., Meyer, B. C. "Expected mid-and long-term changes in drought hazard for the South-Eastern Carpathian Basin", Carpathian Journal of. Earth and Environmental Sciences, 11(2), pp. 355–366, 2016.

[6] Áldorfai, Gy., Keszthelyi, Sz., Kovac, A. R., Lámfalusi, I., Péter, K., Szili, V., Hámori, J. "A mezőgazdasági kockázatkezelési rendszer működésének értékelése 2022" (Evaluation of the operation of the Hungarian Agricultural Risk Management System (HARMS) in 2022), [online], Agrárközgazdasági Intézet, Budapest, 2023. Available at: https://www.aki.gov.hu/termek/a-mezogazdasagi-kockazatkezelesi-rendszer-mukodesenek-ertekelese-2022/ (in Hungarian)

[7] Jolánkai, M., Birkás, M., "Szárazodás, aszály és a növénytermelés" (Crop production, soil tillage, cropping structure, harvest), "KLÍMA-21" Füzetek, 59, pp. 26–32, 2010. (in Hungarian)

[8] Cui, C., Xu, J., Zeng, J., Chen, K. S., Bai, X., Lu, H., Chen, Q., Zhao, T. "Soil Moisture Mapping from Satellites: An Intercomparison of SMAP, SMOS, FY3B, AMSR2, and ESA CCI over Two Dense Network Regions at Different Spatial Scales", Remote Sensing, 10(1), 33, 2018. https://doi.org/10.3390/rs10010033

[9] Zeng, J., Chen, K. S., Bi, H., Chen, Q. "A Preliminary Evaluation of the SMAP Radiometer Soil Moisture Product Over United States and Europe Using Ground-Based Measurements", IEEE Transactions on Geoscience and Remote Sensing, 54(8), pp. 4929–4940, 2016. https://doi.org/10.1109/TGRS.2016.2553085

[10] Chan, S. K., Bindlish, R., O'Neill, P. E., Njoku, E., Jackson, T., …, Fellow, Y. K. "Assessment of the SMAP Passive Soil Moisture Product", IEEE Transactions on Geoscience and Remote Sensing, 54(8), pp. 4994–5007, 2016. https://doi.org/10.1109/TGRS.2016.2561938

[11] Colliander, A., Jackson, T. J., Bindlish, R., Chan, S., Das, N., Kim, S. B., …, Yueh, S. "Validation of SMAP surface soil moisture products with core validation sites", Remote Sensing Environment, 191, pp. 215–231, 2017. https://doi.org/10.1016/j.rse.2017.01.021

[12] Jotisankasa, A., Torsri, K., Supavetch, S., Sirirodwattanakool, K., Thonglert, N., Sawangwattanaphaibun, R., Faikrua, A., Peangta, P., Akaranee, J. "Investigating Correlations and the Validation of SMAP-Sentinel L2 and In Situ Soil Moisture in Thailand", Sensors, 23(21), 8828, 2023. https://doi.org/10.3390/s23218828

[13] Zhu, L., Tian, G., Wu, H., Ding, M., Zhu, A. X., Ma, T. "Regional Assessment of Soil Moisture Active Passive Enhanced L3 Soil Moisture Product and Its Application in Agriculture", Remote Sensing, 16(7), 1225, 2024. https://doi.org/10.3390/rs16071225

[14] Fiala, K., Barta, K., Benyhe, B., Fehérváry I., Láng, I., Lábdy, J., Sipos, G., Győrffy, L. "Development of an Operational Drought and Water Scarcity Monitoring System in Hungary", [pdf] Global Water Partnership Central and Eastern Europe, Europe, 2018. Available at: https://www.gwp.org/globalassets/global/gwp-cee_files/idmp-cee/idmp-drought-monitoring-hungary.pdf

[15] Meter Group "TEROS 12 soil moisture, temperature, and EC sensor", [online] Available at: https://metergroup.com/products/teros-12 [Accessed: 05 September 2025]

[16] General Directorate of Water Management "Aszálymonitoring", [online] Available at: https://aszalymonitoring.vizugy.hu [Accessed: 11 February 2026],

[17] DOSoReMI "A talajok digitális térképezése Magyarországon" (Digital mapping of soils in Hungary), [online] Available at: https://dosoremi.hu/maps/textura-osztaly-usda-5-15-cm/ (in Hungarian)

[18] Entekhabi, D., Yueh, S., O'Neill, P. E., Kellogg, K. H., Allen, A., …, West, R. "SMAP Handbook – Soil Moisture Active Passive: Mapping Soil Moisture and Freeze/Thaw from Space", National Aeronautics and Space Administration, Pasadena, California, 2014.

[19] O'Neill, P. E., Chan, S., Njoku, E., Jackson, T., Bindlish, R., Chaubell, J. "SMAP L3 Radiometer Global Daily 36 km EASE-Grid Soil Moisture, Version 7", NASA National Snow and Ice Data Center Distributed Active Archive Center, Boulder, CO, USA, SPL3SMP. https://doi.org/10.5067/HH4SZ2PXSP6A

[20] Huang, X., He, Q., Hanasaki, N., Reichle, R. H., Oki, T. "Detecting irrigation signals from SMAP L3 and L4 soil moisture: A case study in California's Central Valley", [preprint] EGUsphere, 16 May 2025. https://doi.org/10.5194/egusphere-2025-2004

[21] Entekhabi, D., Reichle, R. H., Koster, R. D., Crow, W. T. "Performance Metrics for Soil Moisture Retrievals and Application Requirements", Journal of Hydrometeorology, 11(3), pp. 832–840, 2010. https://doi.org/10.1175/2010JHM1223.1

[22] Bai, J., Cui, Q., Chen, D., Yu, H., Mao, X., Meng, L., Cai, Y. "Assessment of the SMAPDerived Soil Water Deficit Index (SWDISMAP) as an Agricultural Drought Index in China", Remote Sensing, 10(8), 1302, 2018. https://doi.org/10.3390/rs10081302

[23] Entekhabi, D., Njoku, E. G., O'Neill, P. E., Kellogg, K. H., Crow, W. T., …, Van Zyl, J. "The Soil Moisture Active Passive (SMAP) Mission", Proceedings of the IEEE, 98(5), pp. 704–716, 2010. https://doi.org/10.1109/JPROC.2010.2043918

[24] Colliander, A., Jackson, T.J., Chan, S.K., O'Neill, P., Bindlish, R., Cosh, M. H., ..., Yueh, S. H. "Seasonal Dependence of SMAP Radiometer-Based Soil Moisture Performance as Observed Over Core Validation Sites", In 2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 2019, pp. 5320-5323. ISBN 978-1-5386-9155-7 https://doi.org/10.1109/IGARSS.2019.8899007

[25] Lyu, H., McColl, K. A., Li, X., Derksen, C., Berg, A., ..., Entekhabi, D. "Validation of soil moisture and landscape freeze/thaw from SMAP", Remote Sensing of Environment, 205, pp. 329–337, 2018. https://doi.org/10.1016/j.rse.2017.12.007

[26] Crow, W. T., Berg, A. A., Cosh, M. H., Loew, A., Mohanty, B. P., Panciera, R., deRosnay, P., Ryu, D., Walker, J. P. "Upscaling sparse ground-based soil moisture observations for the validation of coarse-resolution satellite soil moisture products", Reviews of Geophysics, 50(2), RG2002, 2012. https://doi.org/10.1029/2011RG000372

[27] Zhang, L., He, C., Zhang, M. "Multi-Scale Evaluation of the SMAP Product Using Sparse In-Situ Network over a High Mountainous Watershed, Northwest China", Remote Sensing, 9(11), 1111, 2017. https://doi.org/10.3390/rs9111111

[28] Sehgal, V., Gaur, N., Mohanty, B. P. "Global Surface Soil Moisture Drydown Patterns", Water Resources Research, 57(4), e2020WR027588, 2021. https://doi.org/10.1029/2020WR027588

[29] Neelam, M., Bindlish, R., O'Neill, P., Huffman, G. J., Reichle, R., Chan, S., Colliander, A. "Evaluation of GEOS Precipitation Flagging for SMAP Soil Moisture Retrieval Accuracy", Journal of Hydrometeorology, 22(5), pp. 1317–1332, 2021. https://doi.org/10.1175/JHM-D-20-0038.1