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QUANTIFYING SEASONAL SHIFTS IN SOIL THERMO-HYDROLOGICAL COUPLING USING A TMS-4 SENSOR AND ERA5-LAND DATA

Dhananjana RAJAKARUNA[1] Samira ALHASSAN[1]
Petru T. STĂNCIOIU[2] Mihai D. NIȚĂ[1]

Abstract: *Forest ecosystem functions are influenced by the dynamic interplay between soil temperature and moisture. However, the lack of high-resolution temporal data has caused constraints in the comprehensive investigation of their association over time. This study uses a full annual cycle of 15-minute microclimate data, captured by a TMS-4 datalogger in Postăvaru, Romania, to quantify the correlation between soil temperature and moisture across different seasons, investigate seasonal regime shifts in soil thermo-hydrological processes, and quantify the thermal buffering capacity of soil moisture. Our analysis has shown a reversal in the soil temperature-moisture relationship across seasons. While the annual correlation was inverse (r = -0.42), a strong positive winter correlation (r = +0.606) was observed due to the melting of frozen water, which contrasted sharply with the strongly negative autumn correlation (r = -0.781) driven by evaporation. We further analysed the role of soil moisture as a thermal buffer, which reduces soil temperature by 0.31°C per 1% volumetric water content increase. The rate dynamics also showed how soil cooling and wetting were faster than warming and drying. These findings indicate the potential of high frequency monitoring in long-term continuous monitoring of the soil temperature-moisture relationship that may challenge the conventional static models. Also, this study may highlight that soil temperature-moisture coupling is seasonally dependent, with implications for predicting ecosystem responses to climate change and informing sustainable forest management.*

Key words: *ecosystem resilience, microclimate, seasonal variation, thermo-hydrological coupling.*

[1] Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven no. 1, Brasov 500123, Romania;
[2] Department of Forest Science, Faculty of Silviculture and forest engineering, Transilvania University of Brasov, Şirul Beethoven no. 1, Brasov 500123, Romania;
Correspondence: Mihai Daniel Niță; email: mihai.nita@unitbv.ro.

1. Introduction

Climate and land use factors continue to change due to the ecohydrological processes that take place in terrestrial and riverine ecosystems, causing a rise in stress of these systems and changing ecosystem service capacity, as well as watershed functioning [10, 20]. Soil moisture has become one of the variables that is prone to these changes, making soil moisture a valuable area of study due to its relevance to climate [5]. The significance of soil moisture interactions has the potential to regulate land surface warming [17]. This could potentially delay the expected crossing of critical temperature limits by more than 10 years [33.

Near-surface soil moisture controls both atmospheric and ecohydrological key processes at the land surface by regulating the allocation of energy and water [2]. This influences surface temperature and plant productivity through the means of runoff, infiltration, evaporation, and the equilibrium of sensible latent heat fluxes [21]. Beyond its role in hydrological and thermal regulation, soil moisture also contributes to environmental risk assessment. Integrating in situ, remote sensing, and model-based soil moisture information into fire-danger rating systems has been shown to improve fuel moisture estimation, enhance early-warning capability, and improve forecasts of wildfire occurrence and spread [12, 27].

The ecological relevance of soil moisture is revealed during the occurrence of droughts. For the majority of the world's land surface, the accessibility of soil water is determined by how fast ecosystems can recover, especially in mid-latitude areas, where moisture significantly reduces post-drought resilience [31]. Vegetation productivity is influenced by both moisture and soil temperature, although their proportional contributions show differences at the regional level. While soil moisture shows significant effects in semi-arid and arid zones, changes in temperature are more influential on vegetation activities in moist regions [4].

Given these different types of influences, soil moisture and soil temperature are recognised as essential climate variables, crucial for Earth system modelling and for understanding ecological responses to environmental change [14]. Despite this recognition, high-resolution observations capable of capturing short-term soil moisture and temperature interactions remain limited [1, 13, 18]. This can be seen in forest ecosystems with fine-scale heterogeneity that coarse resolution remote sensing models may find difficult to capture [23, 32]. Identifying these regional and local level shifts is important for advancing predictions of ecohydrological behaviour under ongoing climate change [22, 28].

The ERA5-Land dataset, produced by the European Centre for Medium-Range Weather Forecasts, is a state-of-the-art satellite-based reanalysis product that can be used to address this scale difference between localised ground conditions and regional climate models [7]. It provides a spatially and temporally consistent, global level reconstruction of historical land variables by utilizing various satellite and in-situ observations into a sophisticated numerical model [3, 9]. It has an approximately 9 km spatial resolution with soil variables, including moisture and temperature, providing important information for ecological models and historical climate trends analysis [16, 19]. However, despite its advanced architecture, ERA5-Land's reliability in complex forest environments is not yet fully established. The model faces several fundamental challenges when applied to forests, such as the "point-to-pixel" problem. A single TMS-4 sensor measures a soil volume of less than a litre, while an ERA5-Land grid cell covers approximately 81 km², averaging over immense topographic, soil, and canopy heterogeneity [23]. Therefore, validating these global models with high-resolution, ground-truth data from sensors like the TMS-4 may improve their utility in sustainable forest management [26].

To address this need, we deployed a TOMST TMS-4 sensor, a state-of-the-art microclimate datalogger, in Postăvaru, a temperate forest in Romania. The TMS4 is uniquely suited for this task, as it provides integrated, long-term, high frequency measurements of both soil temperature and moisture in a single, robust device [30]. Our specific goals were to: *i)* quantify the correlation between soil temperature and moisture across different seasons using high frequency data; *ii)* identify and explain seasonal regime shifts in the temperature-moisture coupling; *iii)* quantify the thermal buffering capacity of soil moisture and the asymmetries in its warming/cooling and wetting/drying rates, and *iv)* evaluate the performance of the ERA5-Land reanalysis dataset in replicating observed soil temperature and moisture seasonal patterns in a forested environment. By utilising the capabilities of the TMS 4 sensor, this research provides a fine-temporal-scale perspective on soil microclimate dynamics.

2. Methodology

2.1. Study Site

This study was conducted in Postăvaru, Romania (Figure 1). The site is characterised by a mixed forest canopy with dominant species of *Fagus sylvatica* (L.) and *Abies alba* (Mill.). The site, located at 1,215 m above Black Sea level, was selected for its representative forest structure, providing an ideal setting for studying soil microclimate processes.

2.2. Sensor Deployment and Data Collection

The TMS-4 is an integrated, battery-powered sensor designed for long-term microclimate monitoring [30]. The soil moisture probe indirectly measures volumetric water content in the upper 0–15 cm of soil as humidity signal values. Three temperature sensors with an accuracy of ±0.5°C, positioned at approximately -6 cm (soil), 0 cm (surface), and +15 cm (air) relative to the ground, measure soil and air temperatures, respectively. The logger was programmed to record measurements at 15-minute intervals by using basic mode [CM2.1] (Figure 2). The data presented here cover a full annual cycle from October 2024 to October 2025 of temperature and soil water content in the Postăvaru study site, capturing complete seasonal dynamics.

2.3. Data Processing

Raw data from the TMS-4 were processed and quality-controlled before analysis. Humidity signal values were calibrated to calculate the volumetric water content. The entire dataset of over 33,000 observations was visually screened for outliers and sensor errors. The data were partitioned into meteorological seasons for subset analysis as winter (December-February), Spring (March-May), Summer (June-August), and Autumn (September-November).

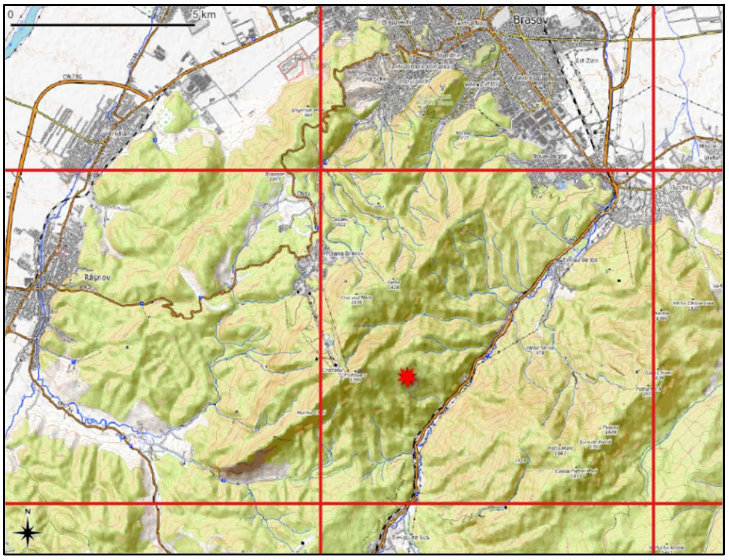


Fig. 1. *Location of TMS4 Sensor and the ERA5 Grid*

Fig. 2. *A TMS-4 sensor installed in the study site covered with a wire mesh to protect from wildlife*

2.4. ERA5-Land Reanalysis Dataset Integration

To provide a climatological context and validate the physical consistency of the in situ measurements, we retrieved hourly data from the ERA5-Land reanalysis dataset for the grid cell corresponding to the study site. The extracted variables included: Air Temperature (2 m) used to compare against the TMS-4 T2 (surface) and T3 (air) sensors, Soil Temperature Level 1 (0-7 cm) used for comparison with the TMS-4 T1 (-6 cm) sensor, Soil Temperature Level 2 (7-28 cm) used to assess deeper soil thermal inertia and lag effects, and Volumetric Soil Water Layer 1 (0-7 cm) converted to percentage for comparison with TMS-4 soil moisture.

ERA5 data were aligned temporally with the aggregated hourly TMS-4 data to facilitate the direct comparison of seasonal trends and weekly averages.

2.5. Statistical Analysis

We conducted several statistical analyses to characterize the soil temperature-moisture relationship. Pearson correlation coefficients (*r*) were calculated between soil temperature and volumetric water content for the entire dataset and for each seasonal subset. A simple linear regression was performed with soil temperature as the dependent variable and volumetric water content as the independent variable to quantify the thermal buffering effect. The rates of change for both temperature and moisture were calculated on an hourly basis to investigate asymmetries in warming/cooling and wetting/drying dynamics. All the above analyses were repeated on the seasonal subsets to identify and quantify seasonal regime shifts.

3. Results

3.1. Seasonal Patterns

The occurrence of cool periods with wet conditions and warm periods with dry conditions can be seen over the period from October 2024 to October 2025 (Figure 3). The correlation of -0.42 between soil temperature also indicated this inverse relationship. The soil temperature ranged from 17.1 to -1.1°C, while the soil water content ranged from 54 to 18.9%. Furthermore, a strong positive association was observed between air temperature and soil temperature, with a correlation of *r* = 0.903 within the period monitored.

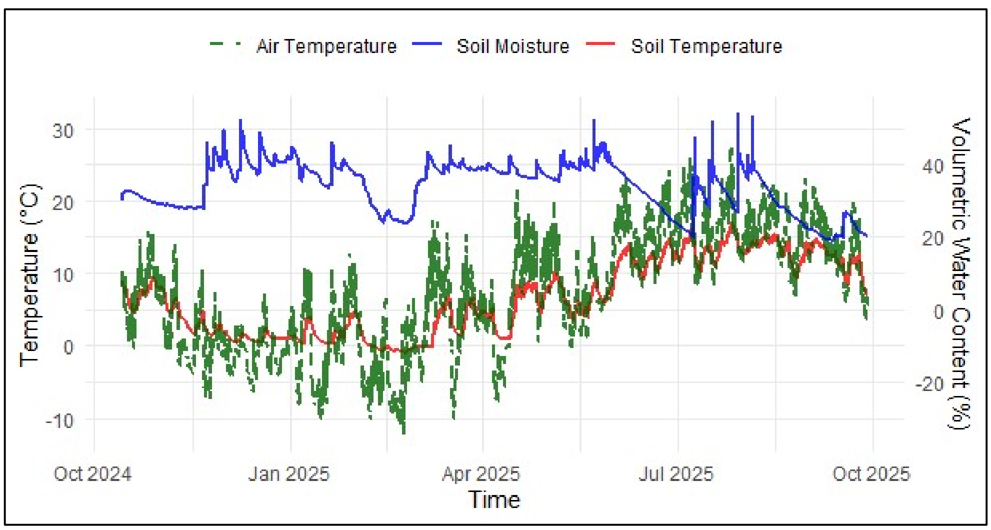


Fig. 3. *Temporal variation of air and soil temperatures and soil moisture*

3.2. Seasonal Correlation Reversal

The variation of soil temperature and soil moisture by season is shown in Figure 4. Although the annual correlation was negative, the season-wise analysis showed different results. Autumn had the strongest association between soil temperature and moisture (*r* = -0.781) with drier soils and warmer conditions. Weak negative associations could also be seen in spring (*r* = -0.054) and summer (*r* = -0.117) in the soil temperature-moisture relationship. However, winter showed a positive correlation of +0.606 where warmer conditions provided wetter soils. This could indicate how rising temperatures melt ice, leading to an increase in soil water content.

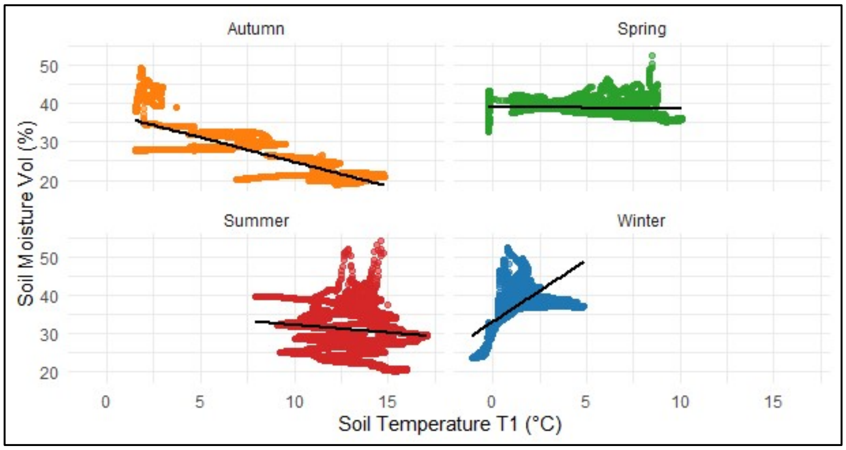


Fig. 4. *Variation of soil moisture vs soil temperature by seasons*

3.3. Thermal Buffering Effect

The linear regression model showed a significant relationship between soil temperature and soil moisture with an R^2 value of 0.17 ($p < 0.001$) (Figure 5). According to the model results, 1% increase in volumetric water content may reduce soil temperature by 0.31°C. This buffering effect may contribute to soil cooling during temperature extremes. However, the lower R^2 value may indicate that other factors, like soil properties, forest structure, and climatic factors, may affect this variation.

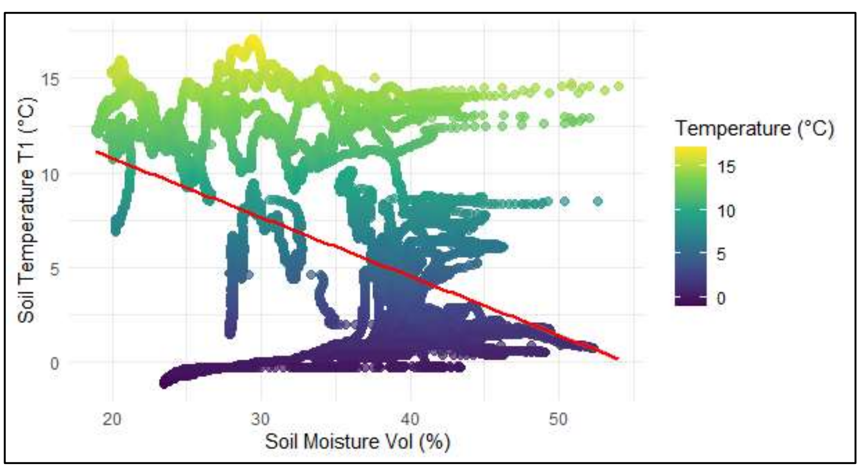


Fig. 5. *Variation of soil temperature vs soil moisture*

3.4. Rate Dynamics

The analysis of hourly change rates showed how soil moisture and temperature change rates were distributed across seasons (Figure 6). Most observations fell into the cooling and wetting zone and drying and warming zone. The overall correlation between soil moisture and temperature rate changes was -0.199 which aligns with the previous finding of their negative relationship. Also, the hourly cooling rates (-0.5 to -2.0°C/h) were faster than the warming rates (+0.1 to +0.4°C/h), while the wetting rates (+2% to +8%/h) were higher than the drying rates (-0.5% to -2%/h).

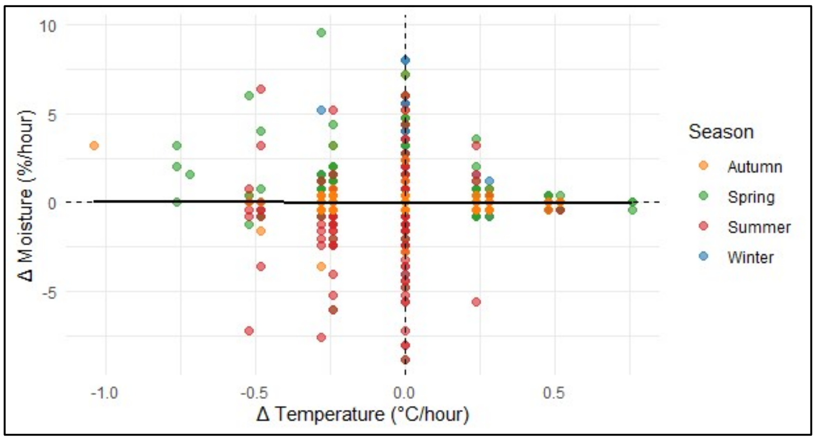


Fig. 6. *Variation of the hourly change rates of soil moisture vs soil temperature*

3.5. Comparison with ERA5 Reanalysis Data

To assess the consistency between the local and regional datasets, we compared the in-situ TMS-4 measurements with ERA5-Land reanalysis data, focusing on the identification of synchronous trends and magnitude discrepancies.

3.5.1. Long-term Coherence and Amplitude Differences

The analysis of weekly averages for the full monitoring period (Figure 7) demonstrated that both datasets captured the same fundamental seasonal trajectory. However, a distinct divergence was observed in the amplitude of thermal fluctuations. The ERA5 Soil Level 1 (0-7 cm) displayed high-frequency volatility (standard deviation 7.36°C) that was not present in the in situ T1 records. Conversely, the TMS-4 soil temperature (T1 0 to -6 cm) exhibited a significantly dampened signal (standard deviation 4.60°C) that closely paralleled the stability of the deeper ERA5 Soil Level 2 (7-28 cm, standard deviation 6.54°C). While the temporal trends were identical, the in-situ sensor data showed a mean negative bias of approximately -2.5°C compared to the model, likely reflecting the shading effect of the forest canopy, which is not fully resolved at the reanalysis grid scale.

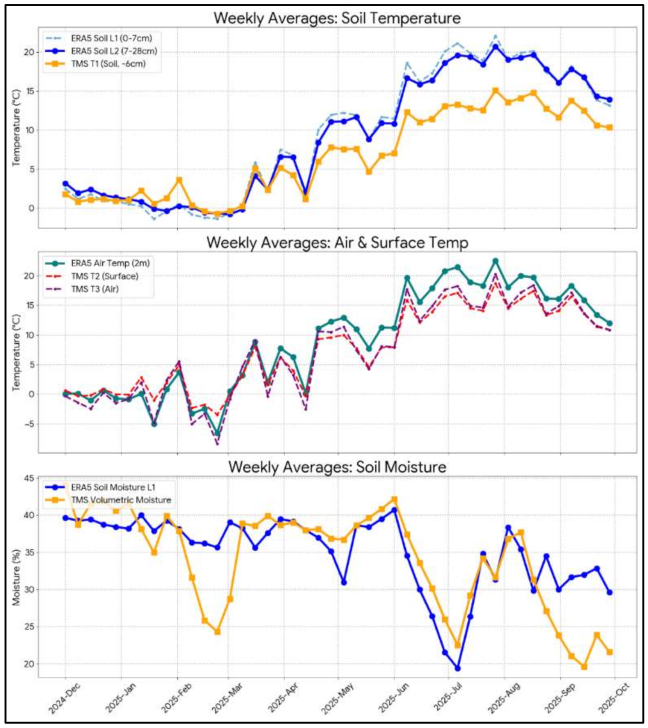


Fig. 7. *Comparison of weekly averages (December 2024-September 2025); the orange line (TMS T1) follows the trend of the solid blue line (ERA5 Soil Level 2)*

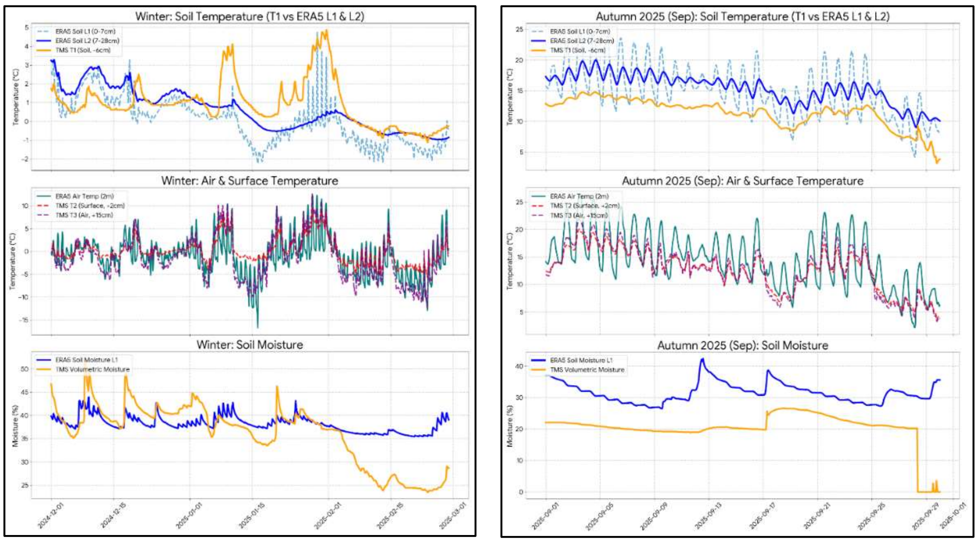
3.5.2. Seasonal Dynamics and Phase Shifts

The seasonal breakdown revealed specific periods of agreement and deviation between the datasets (Figure 8). For instance, during the winter months, the datasets captured a similar quasi-stationary thermal regime, with variances minimised in both records. However, a notable divergence occurred in the absolute temperature values. The ERA5 model maintained a persistent positive bias, with values staying strictly above 0°C. In contrast, the in situ TMS sensor captured distinct negative excursions, documenting freeze-thaw events that were absent in the reanalysis data.

The autumn period had the highest degree of concordance between the datasets. During September, the rate of soil cooling was identical across both the sensor and the model. Furthermore, the hydrological trends were captured with high similarity; the ERA5 volumetric soil water (Level 1) and the TMS volumetric moisture recorded simultaneous drying events. The magnitude of the soil moisture recession was comparable, indicating that the ERA5 model accurately represented the drying phase observed in the field during this specific window.

Regarding spring and summer both datasets successfully captured the decoupling of soil temperature from air temperature (Figure 9). A key difference was observed in the diurnal range: the

ERA5 2m Air Temperature showed a mean daily range of ~9.9°C, which was nearly double the ~5.4°C daily range recorded by the TMS T3 sensor. This highlights the significant buffering capacity of the canopy, which protects the understory from the peak solar heating simulated by the model.



ig. 8. *Seasonal comparisons of soil temperature (TMS T1 vs ERA5 L1/L2), air temperature (TMS T2/T3 vs ERA5 2m), and soil moisture: a. winter; b. autumn (September)*

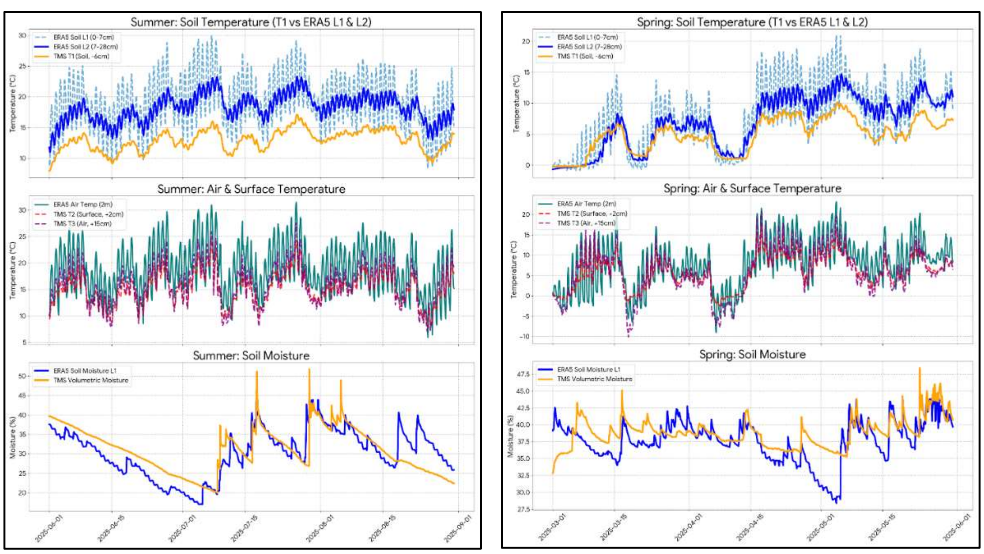


Fig. 9. *Seasonal comparisons of soil temperature (TMS T1 vs ERA5 L1/L2), air temperature (TMS T2/T3 vs ERA5 2m), and soil moisture: a. spring; b. summer*

4. Discussion

Our study revealed that soil temperature-moisture relationships are not static but can undergo seasonal reversals, showing shifts in soil hydrological processes. The correlation changes from strongly negative in autumn (r = -0.781) to positive in winter (r = +0.606) may challenge the understanding of a consistently inverse relationship between these variables. The strong negative correlation in autumn may suggest evaporation has dominated soil temperature-moisture variation. The positive winter correlation may reflect the freezing of soil water in cold periods. As temperatures rise above freezing, ice may melt and increase liquid water content detectable by sensor. This is further supported by the findings from studies in boreal regions that have shown similar changes in frozen soils using high-resolution loggers [11, 30]. The near-zero correlation in spring (r = -0.054) may represent a transitional period where processes like snowmelt, spring rains, and increasing of evaporation create conflicting signals that reduce effect each other. However, these seasonal transitions have been noted in microclimate research but rarely quantified with the high-temporal resolution data enabled by sensors [8].

Our quantification of the thermal buffering effect (-0.31°C per 1% increase in soil moisture) provides empirical support for the role of soil moisture in regulating microclimate supporting root systems, soil organisms, and nutrient cycling processes in the study site [6, 24]. With the high specific heat in soil moisture increasing in soil water, the thermal buffering capacity of soil increases as well [29]. The R^2 value (0.17) shows that soil moisture can influence soil temperature, which may also be affected by additional factors like topography, canopy cover, and air temperature, making soil thermal dynamics a result of complex interactions between moisture, energy fluxes, and site characteristics [8, 32].

The observed rate changes in soil cooling were 4-5 times faster than warming, and the wetting rates were 3-4 times faster than drying. The rapid cooling capacity may protect the forest during heatwaves. Fast wetting rates may suggest that soil can quickly capture precipitation inputs, reducing runoff and enhancing water retention. Slow drying rates may indicate sustained moisture availability between rainfall events, potentially supporting plant water uptake and microbial activity during dry periods [32].

The comparative analysis between the TMS-4 sensor and ERA5-Land reanalysis provides critical insights into the limitations of using gridded climate data for plot-scale forest applications. A primary finding is the vertical mismatch in thermal profiles; the in situ sensor at -6 cm had a Mean Absolute Difference (MAD) of 3.53°C when compared to the ERA5 surface layer (Level 1, 0-7 cm), but this discrepancy was significantly reduced when compared to the deeper ERA5 Level 2 (7-28 cm). This suggests that the "effective" thermal surface of the forest floor is vertically displaced relative to the model's definition. ERA5-Land, which often parametrises surface interactions based on broader vegetation classes, likely underestimates the specific insulating capacity of the thick litter layer and organic horizon present in this mixed forest stand [15].

Furthermore, the systematic negative

bias of approximately -2.53°C observed in the in-situ data compared to the model highlights the role of canopy shading. While ERA5 captures the synoptic weather patterns correctly (as evidenced by the identical temporal trends), it appears to overestimate the solar radiative heating reaching the soil surface. This is corroborated by the diurnal range analysis in spring and summer, where the model's air temperature amplitude (~9.9°C) was nearly double that of the forest understory (~5.4°C). Consequently, our results advocate for a cautious approach when using reanalysis data for ecological modelling: for forest understory microclimates, the "surface" layer of the model is often too volatile and coupled too strongly to atmospheric forcing. Instead, deeper model layers (e.g., 7-28 cm) may serve as a more accurate proxy for the actual root-zone conditions experienced by seedlings and soil biota.

Using single-sensor data, while providing detailed temporal information, limits our ability to assess spatial variability, and future studies need to integrate multiple TMS 4 sensors across different microsites to separate temporal patterns from spatial heterogeneity. Additionally, although we observed correlation shifts, the underlying mechanisms may be related to physical, chemical, and biological processes that require further investigation. Also, the sensor's limitation in detecting frozen water (it measures liquid water content) shows the need for complementary measurements of soil ice content in cold regions. Integration with soil physical properties and vegetation metrics would strengthen future interpretations of the observed patterns [25].

The seasonal reversals observed may suggest that models incorporating seasonally varying soil temperature-moisture relationships may better explain soil hydrological processes. Ground-truth data from high-resolution sensors like the TMS 4 are important for validating such models, including reanalysis products like ERA5-Land [23]. The quantified thermal buffering effect may encourage forest management practices that maintain soil moisture, while also indicating forests with higher soil moisture may maintain cooler root zones, which would increase their resilience to heat stress [8].

5. Conclusion

This study utilised high-frequency TMS-4 monitoring over a full annual cycle to investigate soil thermo-hydrological processes in a temperate mixed forest. The integration of in-situ data with ERA5-Land reanalysis enabled a comprehensive assessment of seasonal dynamics. The results identified a distinct seasonal shift in the soil temperature-moisture relationship, transitioning from a negative correlation in autumn), associated with evaporative processes, to a positive correlation in winter, associated with freeze-thaw cycles.

The comparison with ERA5 reanalysis provided validation of the in situ measurements and highlighted the specific thermal characteristics of the forest floor. The analysis indicated that soil temperatures measured at -6 cm align more closely with the deeper ERA5 model layer (7-28 cm) than with the surface layer (0-7 cm). This alignment reflects the insulating effect of the litter layer, which dampens thermal fluctuations relative to surface-level model predictions. Quantitatively, the thermal buffering analysis indicated a soil temperature reduction of 0.31°C per 1% increase in volumetric water content. Additionally, the analysis of rate dynamics showed that soil cooling occurs 4-5 times faster than warming, while wetting occurs 3–4 times faster than drying.

Future research will expand on these findings by deploying a network of TMS-4 sensors to examine spatial heterogeneity within the Postăvaru area. This work will aim to determine the influence of topography, soil texture, and forest structure quantified through 3D segmentation on soil thermal and moisture dynamics, with the objective of improving site-specific ecosystem models.

References

1. Babaeian, E., Sadeghi, M., Jones, S.B., 2019. Ground, proximal, and satellite Remote Sensing of soil moisture. In: Reviews of Geophysics, vol. 57(2), pp. 530-616. DOI: 10.1029/2018RG000618.
2. Badea, C., Clinciu, I., Niță, M.D., 2014. Research on spatial distribution of soil moisture in a small, forested watershed from the mountainous area of Brașov. In: Revista Pădurilor, vol. 129(3-4), pp. 25-34.
3. Bernini, L., Lagasio, M., Milelli, M. et al., 2025. Convection-permitting dynamical downscaling of ERA5 for Europe and the Mediterranean basin. In: Quarterly Journal of the Royal Meteorological Society, vol. 151(772), ID article e5014. DOI: 10.1002/qj.5014.
4. Dang, C., Shao, Z., Huang, X. et al., 2022. Assessment of the importance of increasing temperature and decreasing soil moisture on global ecosystem productivity using solar-induced chlorophyll fluorescence. In: Global Change Biology, vol. 28(6), pp. 2066-2080. DOI: 10.1111/gcb.16043.
5. Furtak, K., Wolińska, A., 2023. The impact of extreme weather events as a consequence of climate change on the soil moisture and on the quality of the soil environment and agriculture – A review. In: Catena, vol. 231, ID article 107378. DOI: 10.1016/j.catena.2023.107378.
6. Gobatti, L., Bach, P.M., Maurer, M., 2025. Impact of soil moisture content on urban tree evaporative cooling and human thermal comfort. In: npj Urban Sustainability, vol. 5(1), ID article 26. DOI: 10.1038/s42949-025-00220-0.
7. Gomis-Cebolla, J., Rattayova, V., Salazar-Galán, S. et al., 2023. Evaluation of ERA5 and ERA5-Land reanalysis precipitation datasets over Spain (1951-2020). In: Atmospheric Research, vol. 284, ID article 106606. DOI: 10.1016/j.atmosres.2023.106606.
8. Greiser, C., Hederová, L., Vico, G. et al., 2024. Higher soil moisture increases microclimate temperature buffering in temperate broadleaf forests. In: Agricultural and Forest Meteorology, vol. 345, ID article 109828. DOI: 10.1016/j.agrformet.2023.109828.
9. Hersbach, H., Bell, B., Berrisford, P. et al., 2020. The ERA5 global reanalysis. In: Quarterly Journal of the Royal Meteorological Society, vol. 146(730), pp. 1999-2049. DOI: 10.1002/qj.3803.
10. Huang, L., Wang, H. Liu, Z.A. et al., 2024. Quantitatively linking ecosystem service functions with soil moisture and ecohydrology regimes in watershed. In: Science of The Total Environment, vol. 955, ID article 176866. DOI:

10.1016/j.scitotenv.2024.176866.

11. Kemppinen, J., Niittynen, P., Rissanen, T. et al., 2023. Soil moisture variations from Boreal forests to the tundra. In: Water Resources Research, vol. 59(6), ID article e2022WR032719. DOI: 10.1029/2022WR032719.
12. Krueger, E.S., Levi, M., Achieng, K. et al., 2023. Using soil moisture information to better understand and predict wildfire danger: a review of recent developments and outstanding questions. In: International Journal of Wildland Fire, vol. 32(2), pp. 111-132. DOI: 10.1071/WF22056.
13. Lekarkar, K.L., Lembrechts, J., Dondeyne, S., 2025. SoilMoist: A global network of soil moisture observations based on emerging low-cost technologies. In: European Geosciences Union General Assembly (EGU24), April 14-19, 2024 Vienna, Austria. DOI: 10.5194/egusphere-egu24-16181.
14. Li, Q., Zhu, Y., Shangguan, W., 2022. An attention-aware LSTM model for soil moisture and soil temperature prediction. In: Geoderma, vol. 409, ID article 115651. DOI: 10.1016/j.geoderma.2021.115651.
15. Marin, M., Clinciu, I., Tudose, N.C. et al., 2019. Analiza previziunilor privind regimul termic și pluvial din bazinul hidrografic Tărlungul Superior în contextul schimbărilor climatice. In: Revista de Silvicultură și Cinegetică, vol. 24(45), pp. 15-21.
16. Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A. et al., 2021. ERA5-Land: a state-of-the-art global reanalysis dataset for land applications. In: Earth System Science Data, vol. 13(9), pp. 4349-4383. DOI: 10.5194/essd-13-4349-2021.
17. Niță, M.D., Clinciu, I., 2011. Research on soil moisture geographic distribution in small forested watersheds.. In: Proceedings of the Biennial International Symposium, *Forest and Sustainable Development*, October 15-16, 2010, Brasov, Romania, pp. 453-458.
18. Ochsner, T.E., Cosh, M.H., Cuenca, R. et al., 2013. State of the art in large-scale soil moisture monitoring. In: Soil Science Society of America Journal, vol. 77(6), pp. 1888-1919. DOI: 10.2136/sssaj2013.03.0093.
19. Ouassanouan, Y., Simonneaux, V., Kharrou, M.H. et al., 2025. Downscaled ERA5 Land addresses agrometeorological data scarcity in North African basins. In: Scientific Reports, vol. 15(1), ID article 38533. DOI: 10.1038/s41598-025-20552-2.
20. Qiu, J., Huang, T., Yu, D., 2022. Evaluation and optimization of ecosystem services under different land use scenarios in a semiarid landscape mosaic. In: Ecological Indicators, vol. 135, ID article 108516. DOI: 10.1016/j.ecolind.2021.108516.
21. Rasheed, M.W., Tang, J., Sarwar, A. et al., 2022. Soil moisture measuring techniques and factors affecting the moisture dynamics: A comprehensive review. In: Sustainability, vol. 14(18), ID article 11538. DOI: 10.3390/su141811538.
22. Robock, A., 2015. Hydrology, floods and droughts – Soil moisture. In: Encyclopedia of Atmospheric Sciences, Elsevier, pp. 232-239. DOI: 10.1016/B978-0-12-382225-3.00169-9.
23. Schönauer, M., Ågren, A.M., Katzensteiner, K. et al., 2024. Soil moisture modeling with ERA5-Land retrievals, topographic indices, and in

situ measurements and its use for predicting ruts. In: Hydrology and Earth System Sciences, vol. 28(12), pp. 2617-2633. DOI: 10.5194/hess-28-2617-2024.

24. Sun, X., Li, J., 2025. Tree root-soil interaction: field study of the effect of trees on soil moisture and ground movement in an urban environment. In: Plant and Soil, vol. 512(1,2), pp. 153-173. DOI: 10.1007/s11104-023-06307-w.
25. Tyystjärvi, V., Kemppinen, J., Luoto, M. et al., 2022. Modelling spatio-temporal soil moisture dynamics in mountain tundra. In: Hydrological Process, vol. 36(1), ID article w14450. DOI: 10.1002/hyp.14450.
26. Vanella, D., Longo-Minnola, G., Belfiore, O.R. et al., 2022. Comparing the use of ERA5 reanalysis dataset and ground-based agrometeorological data under different climates and topography in Italy. In: Journal of Hydrology: Regional Studies, vol. 42, ID article 101182. DOI: 10.1016/j.ejrh.2022.101182.
27. Vogel, E., Lerat, J., Pipunic, R. et al., 2021. Seasonal ensemble forecasts for soil moisture, evapotranspiration and runoff across Australia. In: Journal of Hydrology, vol. 601, ID article 126620. DOI: 10.1016/j.jhydrol.2021.126620.
28. Von Büren, R.S., Zehnder, M., Von Oppen, J. et al., 2025. A novel method for monitoring above- and belowground microclimates in mountain ecosystems year-round. In: Journal of Vegetation Science, vol. 36(5), ID article e70063. DOI: 10.1111/jvs.70063.
29. Werner, W.J., Sanderman, J., Melillo, J.M. 2020. Decreased soil organic matter in a long-term soil warming experiment lowers soil water holding capacity and affects soil thermal and hydrological buffering. In: Journal of Geophysical Research: Biogeosciences Home, vol. 125(4), ID article e2019JG005158. DOI: 10.1029/2019JG005158.
30. Wild, J., Kopecký, M., Macek, M. et al., 2019. Climate at ecologically relevant scales: A new temperature and soil moisture logger for long-term microclimate measurement. In: Agriculture and Forest Meteorology, vol. 268, pp. 40-47. DOI: 10.1016/j.agrformet.2018.12.018.
31. Yao, Y., Liu, Y., Zhou, S., 2023. Soil moisture determines the recovery time of ecosystems from drought. In: Global Change Biology, vol. 29(13), pp. 3562-3574. DOI: 10.1111/gcb.16620.
32. Zignol, F., Lidberg, W., Greiser, C., 2025. Controls on spatial and temporal variability of soil moisture across a heterogeneous boreal forest landscape. In: Hydrology and Earth System Sciences, vol. 29(20), pp. 5493-5513. DOI: 10.5194/hess-29-5493-2025.
33. Zuo, Z., Qiao. L., Zhang, R. et al., 2024., Importance of soil moisture conservation in mitigating climate change. In: Science Bulletin, vol. 69(9), pp. 1332-1341. DOI: 10.1016/j.scib.2024.02.033.