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Seasonal differences between FAO-56 crop evapotranspiration and lysimeter measurements in Slovakia: The role of soil water availability

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Crop evapotranspiration is a key variable in agricultural water management and hydrological studies. In Central Europe, direct evapotranspiration measurements remain scarce due to the limited availability of lysimeter and eddy covariance stations. This study quantified the seasonal difference between crop evapotranspiration (ET_c) estimated using the FAO-56 Penman-Monteith method with climatically adjusted crop coefficients and actual evapotranspiration (ET_a) measured by weighing lysimeters at two research stations in Slovakia, Borovce and Petrovce nad Laborcom, with particular focus on the role of seasonal water availability and antecedent dry periods as controls on this difference.

The comparison revealed substantial seasonal variability in the ET_c-ET_a relationship. At Borovce, daily weighted absolute percentage error (WAPE) reached 38.1%, decreasing to 31.6% at the monthly scale. The largest discrepancies occurred during summer, when water availability became the dominant limiting factor. A post-rainfall analysis showed that the differences between ET_c and ET_a increased systematically with the duration of rain-free periods, with mean daily BIAS increasing from 0.27 mm one day after rainfall to more than 1.1 mm after four consecutive dry days. Analysis of satellite-derived soil moisture data (ESA CCI SM) confirmed that near-surface soil moisture was the strongest predictor of daily ET_c-ET_a differences (Pearson R=−0.556, p<0.001), fully mediating the effect of antecedent dry periods and identifying a soil moisture threshold of SM*=0.262 m^3 m^{-3} below which FAO-56 ET_c systematically overestimates lysimeter ET_a. The seasonal pattern of differences was consistent across both stations.

The results demonstrate that the agreement between FAO-56 ET_c and lysimeter-measured ET_a is strongly controlled by seasonal conditions and soil moisture availability. While ET_c provides a reasonable approximation of actual evapotranspiration under well-watered conditions, it systematically overestimates ET_a during dry periods.

KEY WORDS: evapotranspiration, lysimeter, FAO-56 Penman–Monteith, soil water availability, antecedent rainfall

Introduction

Evapotranspiration (*ET*) is a fundamental component of the terrestrial water cycle and a key process governing the exchange of water and energy between the land surface and the atmosphere. It integrates the combined water loss through soil evaporation and plant transpiration and plays a crucial role in hydrological balance, climate processes, and agricultural water management.

Accurate estimation of evapotranspiration (*ET*) is essential for assessing crop water use, irrigation requirements, and the overall water balance (Allen et al., 1998; Nolz, 2016; Pereira et al., 2015). The FAO-56 Penman-Monteith (P-M) method (Allen et al., 1998) is widely recognized as the global standard for estimating reference evapotranspiration (Soussi et al., 2024) due to its strong physical basis and proven reliability across diverse climatic conditions. Crop evapotranspiration (ET_c), derived from reference evapotranspiration (ET_o) using crop coefficients (K_c), is therefore frequently applied as a substitute for actual evapotranspiration (ET_a). However, under conditions of soil moisture stress, local microclimatic variability, and heterogeneous vegetation cover, ET_c can substantially deviate from measured ET_a (Glenn et al., 2010; Irmak and Mutiibwa, 2010; Tolk et al., 1999). Quantifying and understanding these deviations is crucial for improving water management practices and for validating model-based evapotranspiration estimates. Weighing lysimeters represent one of the most precise instruments for the direct measurement of actual evapotranspiration, as they enable continuous monitoring of water mass changes in a controlled soil-plant system (Evett et al., 1995; Howell et al., 1991; Vaughan et al., 2007). Abedinpour (2015) also confirmed that weighing lysimeters are well suited for measuring crop evapotranspiration (ET_c) throughout the growing season. Consequently, lysimeter data provide a robust benchmark for evaluating model-based

evapotranspiration estimates and for analyzing their temporal dynamics. They remain indispensable for detailed investigations of soil-plant-atmosphere water exchange and for validating both physical models and remote-sensing-based ET products (Gao et al., 2025; Nolz, 2016).

Recent advances in lysimeter technology, including automation, improved weighing precision, and intelligent real-time calibration and data processing systems, have significantly enhanced the temporal resolution and accuracy of water balance measurements worldwide (Gao et al., 2025). Despite their high precision, lysimeter measurements are affected by high-frequency noise caused by wind, mechanical vibrations, and electronic instability. To separate physical hydrological signals from noise, advanced filtering and denoising algorithms have been developed. Peters et al. (2014) introduced a method to distinguish precipitation and evapotranspiration signals in high-resolution lysimeter records, which was further improved through interpolation schemes in the AWAT filter (Peters et al., 2016). Classical smoothing approaches, such as the Savitzky-Golay digital filter (Savitzky and Golay, 1964), are also widely used to preserve short-term ET variability while reducing random noise.

Marek et al. (2014) applied denoising techniques as a preprocessing step for lysimeter data and showed that noise associated with wind and lysimeter operation is generally higher during daytime and lower during late evening and morning hours. They further compared smoothing functions based on different moving-average window lengths to assess their effect on high-frequency mass data. While smoothing effectively suppresses random noise, the authors emphasized that it may also influence the interpretation of short-term *ET* dynamics, particularly during winter conditions with snow cover. Gebler et al. (2015) reported that up to 36% of the annual water balance discrepancy occurred during periods with snow cover but no recorded snowfall, when snow bridging and drifting led to substantial overestimation of precipitation by lysimeters.

In Slovakia, lysimeter research has been expanding over the past decade, particularly through facilities such as the Borovce and Petrovce n. Laborcom stations operated by the Institute of Hydrology of the Slovak Academy of Sciences (Tall et al., 2023). These stations, equipped with high-resolution weighing systems and comprehensive meteorological instrumentation, enable detailed analyses of water balance components under the soil and climatic conditions of the Slovak Lowlands. Previous studies have shown that the FAO-56 Penman-Monteith model provides highly accurate evapotranspiration estimates when compared with lysimeter measurements (Tofigh et al., 2020), a finding also confirmed for Central European conditions, including Slovakia (Kandra et al., 2023). Consequently, the FAO-56 P-M method is frequently used as a reference for evaluating the agreement of remote sensing-based *ET* datasets and other evapotranspiration models (Chen et al., 2023), particularly in the absence of direct ET measurements such as lysimeters, eddy covariance systems, or surface energy balance methods. Anapalli et al. (2018) further demonstrated that reference crop evapotranspiration for alfalfa, calculated from measured data, represents one of the best alternatives for irrigation management in regions where water availability is not the limiting factor. Moreover, the FAO-56 Penman-Monteith model is widely recommended for estimating evapotranspiration under varying soil moisture conditions (Foken, 2008).

The objective of this study was to quantify and characterize the seasonal discrepancy between crop evapotranspiration estimated by the FAO-56 Penman–Monteith method (ET_c) and actual evapotranspiration measured by weighing lysimeters (ET_a) under the climatic conditions of Slovakia, with particular attention to the role of seasonal water availability and antecedent dry periods as controls on the magnitude and direction of this discrepancy. Crop coefficients were adjusted for the climatic characteristics of each station rather than applied as fixed tabulated values, as detailed in the Methods section, ensuring that the observed difference primarily reflects soil moisture limitation of actual transpiration rather than systematic methodological bias.

Material and methods

Available data from lysimeter stations

For analyses, we used data from two lysimeter stations in Slovakia- Borovce and Petrovce nad Laborcom (Fig. 1). These lysimeter stations are two of the three existing lysimeter facilities in Slovakia (Matusek et al., 2017). Both are also equipped with a small meteorological station, from which meteorological measurements were used to calculate reference and crop evapotranspiration.

The lysimeter station in Petrovce nad Laborcom, operated by the Institute of Hydrology of the Slovak Academy of Sciences (Tall et al., 2025), was constructed in 2014 and has been fully operational since 2015 (Tall and Pavelková, 2020). Annual statistics for the station are presented in Table 1. The station comprises five weighing lysimeters and a meteorological station. Due to construction constraints, the upper rim of the lysimeters is located approximately 1 m above the surrounding terrain, which slopes gently toward the station. Each lysimeter contains an undisturbed soil monolith collected from different sites to represent the typical soil types of the Eastern Slovak Lowland. The system allows regulation of the groundwater level, which was maintained at a constant depth of −1 m throughout the observation period. The mass of each lysimeter is continuously recorded with a resolution corresponding to 0.01 mm of water column per 1 m² surface area, and the total measurement error is reported to be 0.02%. The lysimeter data used in this study were processed following the methodology described by Tall in the annually published station reports (Tall et al., 2023) and available only for March-November 2019.

The lysimeter station in Borovce consists of a weighable lysimeter with a surface area of 1 m² and a monolith depth of 1.5 m. Although the Borovce lysimeter surface is covered by grass originating from the original site, which closely corresponds to the cool-season grass

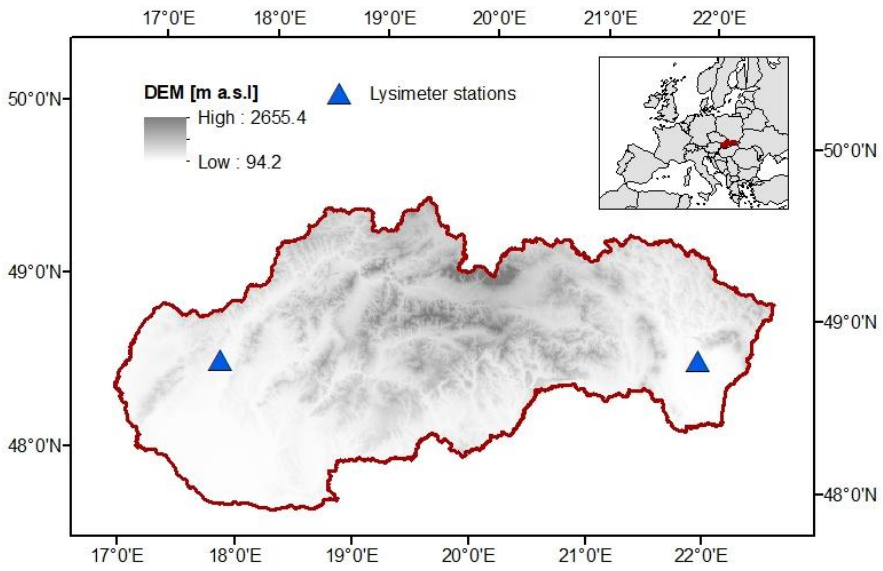


Fig. 1. Spatial distribution of the lysimeter stations within Slovakia.

Table 1. Annual mean air temperature, total precipitation, mean relative humidity, and mean wind speed at the Petrovce nad Laborcom station for the period 2014–2023

	2015	2016	2017	2018	2019	2020	2021	2022
mean daily temp. [°C]	11.3	10.6	10.3	11.6	11.4	10.7	9.8	10.8
precip. totals [mm]	421	535	315	401	450	539	458	326
mean relat. air. humid. [%]	76.7	80.1	76.8	76.3	77.3	78.6	78.1	75.5
mean dey. wind speed [m/s]	1.7	1.6	1.8	1.7	1.7	1.6	1.5	1.6

vegetation assumed in the FAO-56 crop coefficient approach, detailed canopy parameters were not continuously monitored. The lysimeter monolith is equipped with sensors for monitoring soil heat flux and soil moisture at three depths, as well as a weighing system and data logger. Water from the lysimeter is either pumped or drained to an external water tank with a diameter of 200 mm to ensure the same soil moisture conditions in the lysimeter as in the surrounding soil monolith. The lysimeter weight and the water level in the external tank are recorded at 15-minute intervals. A nearby climatological station operates at the same measurement interval and records air temperature at 2 m, wind speed, relative humidity, and solar radiation.

Processing of lysimeter measurements in Borovce

Raw data from the datalogger were transformed into a time series format, and the frequency of the time series was standardized across all datasets using linear interpolation based on the actual time intervals between observations. Lysimeter weight measurements were cleaned for outliers by removing values exceeding ±10 mm per 15-minute interval. For each 15-minute time step, the time delta was calculated. For the precipitation events, when the precipitation on meteorological instruments were measured (>0.1mm), the precipitation totals from meteorological measurements replaced the weight change of lysimeter, what arises from the assumption that precipitation and evapotranspiration does not occur at the same time. Values lower and equal to 0.1 mm can be caused by sensitivity of precipitation sensors (measurement errors) and this small value usually representing slight drizzle or non-rainfall water can't be only measured by precipitation sensors. To estimate measurement noise, a subset of "physically quiet" conditions was selected, defined by no precipitation, wind speed <2 m s^{-1}, relative humidity <85%, and global radiation >50 W m^{-2}. Slow instrumental drift was removed using a 2-hour (8×15 min) rolling median filter, and the residuals were analyzed to quantify random noise. The median absolute deviation (MAD) of the residuals was converted to a robust standard deviation (σ=1.4826×MAD). The resulting noise level was σ=0.0889 mm per 15 min, based on 56 261 data points. Using of σ as lower threshold for physical meaning of lysimeter measurements removes 68% of high-frequency random noise Mass changes smaller than this threshold during precipitation-free periods were considered instrumental noise or sensor drift and excluded from subsequent analyses. This step does not implement the full AWAT filter, but it follows a similar principle of accuracy-based thresholding used in the AWAT method by Peters et al.

(2014) and later applications (e.g., Gebler et al., 2015). However, although thresholding efficiently suppresses low-amplitude random noise, it does not remove high-frequency oscillations, step-like mechanical disturbances, or wind-induced vibrations that remain above the noise level. Therefore, a second-stage signal-based filtering was applied using total variation denoising followed by Savitzky-Golay smoothing. This combined approach ensures both amplitude-based and structure-based noise suppression while preserving physically meaningful mass changes associated with evapotranspiration and precipitation fluxes. The time series of lysimeter mass change was corrected for measured variations in the external water tank to account for system-related water storage effects. As the lysimeter surface area is 1 m², a mass change of 1 kg corresponds directly to a water depth change of 1 mm. The corrected mass change series was subsequently converted into daily evapotranspiration rates. Unrealistic values outside the physically plausible range (ET<0 mm or ET>10 mm day^{-1}) were removed, and the remaining data were resampled to a daily time step for further analysis.

Calculation of Reference and Crop evapotranspiration

The calculation of reference evapotranspiration (ET_0) was based on meteorological measurements from the climatological station associated with the lysimeter site. All variables were originally recorded at a 15-minute time step. For the evapotranspiration analyses, wind speed, air temperature at 2 m height, global solar radiation, and relative air humidity were used. Data preprocessing primarily consisted of quality control, outlier detection, and resampling to a daily time step.
Reference and crop evapotranspiration were subsequently calculated using the FAO Penman-Monteith model according to the formulation proposed by Allen et al. (1998):

$$ET_0=\frac{0.408*\Delta*(R_N-G)+\Upsilon\frac{900}{T+273}*u_2+(e_s-e_a)}{\Delta+\Upsilon*(1+0.34*U_2)} \quad (1)$$

where ET_0 is the reference evapotranspiration [mm day^{-1}]; R_n is the net radiation at the crop surface [MJ m^{-2} day^{-1}]; G is the soil heat flux density [MJ m^{-2} day^{-1}]; T is the mean daily air temperature at 2 m height [°C]; u_2 is the wind speed at 2 m height [m s^{-1}]; e_s is the saturation vapor pressure [kPa];e_a is the actual vapor pressure [kPa]; D is the slope vapor pressure curve [kPa °C^{-1}]; Υ is the psychrometric constant [kPa °C^{-1}].
For calculation of crop evapotranspiration (ET_c), single crop coefficient method was used. This method recalculates crop evapotranspiration from reference evapotranspiration by crop coefficient (K_c) approach whereby the effect of the various weather conditions, but does not assume limitations on crop growth or evapotranspiration from soil water, crop density, weed infestation or low fertility, according equation:

$$ET_c=K_c \times ET_0 \quad (2)$$

For calculation of crop coefficient (Eq.3) we used table values for "cold season grass" want mostly correspond to land cover conditions in climatological stations. (Djaman and Irmak, 2013) also noted that grass and alfalfa have been used as the two reference surfaces for computing ET_a under a variety of climatic conditions from ET_0. Table coefficient values are divided according stage of vegetation growth; initial stage ($K_{c\ ini}$), the mid-season stage ($K_{c\ mid}$) and at the end of the late season stage ($K_{c\ end}$). Coefficients were adjusted for frequency of wetting or climatic conditions during the individual stage, calculated from meteorological measurements, by the equation:

$$K_c=K_{cb(tab)}+[0.04(u_2\text{-}2)\text{-}0.004(RH_{min}\text{-}45)]\left(\frac{h}{3}\right)^{0.3} \quad (3)$$

where $K_{cb\ (Tab)}$ is table value of crop coefficient [-]; u_2 is a daily mean wind speed in 2 m in the range between 1 m s^{-1} and 6 m s^{-1}; RH_{min} is mean seasonal value of daily minimum values of relative humidity (20%–80%), and h is mean height of grass cover over season.

Soil moisture data

Daily soil moisture data were obtained from the ESA Climate Change Initiative Combined Soil Moisture dataset version 8.1 (ESA CCI SM v8.1; Dorigo et al., 2017; Gruber et al., 2019). This dataset combines active and passive microwave satellite observations into a harmonized daily soil moisture product with a spatial resolution of 0.25°. For the analysis, soil moisture values were extracted from the grid cell closest to the Borovce lysimeter station (48.625°N, 17.625°E), whose centre is located approximately 5 km from the station. Only observations with the highest quality flag (flag=0) were used, while all other observations were excluded. The dataset provides volumetric soil moisture content of the near-surface soil layer (0–5 cm depth) expressed in m³ m⁻³. Soil moisture was analysed both as absolute values and as anomalies calculated relative to the long-term mean for each day of year (DOY), month, and year.

Assessment of agreement over datasets

The datasets were compared using indicators of relative difference, systematic difference, and linear association. Model discrepancy were quantified using the weighted absolute percentage error (WAPE) and mean bias. Model similarity and linear association were assessed using Pearson's correlation coefficient (R).
The weighted absolute percentage error (WAPE) was used to quantify absolute relative differences between the examined models and the reference data, and it was calculated as follows:

$$WAPE=\frac{1}{n}\frac{\sum_{i=1}^{n}|O_i\text{-}M_i|}{\sum_{i=1}^{n}|O_i|}\times 100\%, \quad (4)$$

where n is the number of measurements; O_i is the reference value and M_i is the modelled value.
The weighted absolute percentage error (WAPE) expresses the average magnitude of absolute differences between simulated and observed values relative to

the observations, reported as a percentage. In this study, WAPE is interpreted as an indicator of discrepancy between potential crop evapotranspiration and actual evapotranspiration, rather than as a direct measure of model error. Mean bias quantifies the systematic differences between modeled and observed values by averaging their differences. This metric reveals whether ET_c tends to exceed or fall below lysimeter-measured ET_a under specific seasonal and moisture conditions.

$$BIAS = \frac{\sum(M_i - O_i)}{n}, \quad (5)$$

The Pearson correlation coefficient (R) quantifies the strength and direction of the linear relationship between the observed and modeled datasets and is defined as follows:

$$R = \frac{\sum(M_i - \overline{M})(O_i - \overline{O})}{\sqrt{\sum(M_i - \overline{M})^2 \sum(O_i - \overline{O})^2}}, \quad (6)$$

where $\overline{O}$ is mean of reference values and $\overline{M}$ is mean of modelled values. Slope of trend in parameter values we determinate by nonparametric Sen's slope estimator.

Results and discussion

Seasonal agreement and differences between FAO-56 ETc and lysimeter measurements at Borovce

Lysimeter measurements from station Borovce was analyzed for period 4/2014-11/2023. Fig. 2 shown daily time series of lysimeter measurements of ET_a, FAO56 P-M reference evapotranspiration values ET_0 (Eq. 1) and coresponding ET_c values (Eq. 2). The figure shown, that differences between values are most signifficant in summer months, while in early spring and late autumn the differences are smaller.

The comparison of daily crop evapotranspiration against lysimeter measurements showed a mean WAPE (Eq. 4) of 38.1% and a mean daily BIAS (Eq. 5) of 0.29 mm. Aggregation of daily values to the monthly scale reduced WAPE to 31.6%, with a mean monthly BIAS of 11.9 mm. On the annual scale, ET_c exceeded lysimeter-

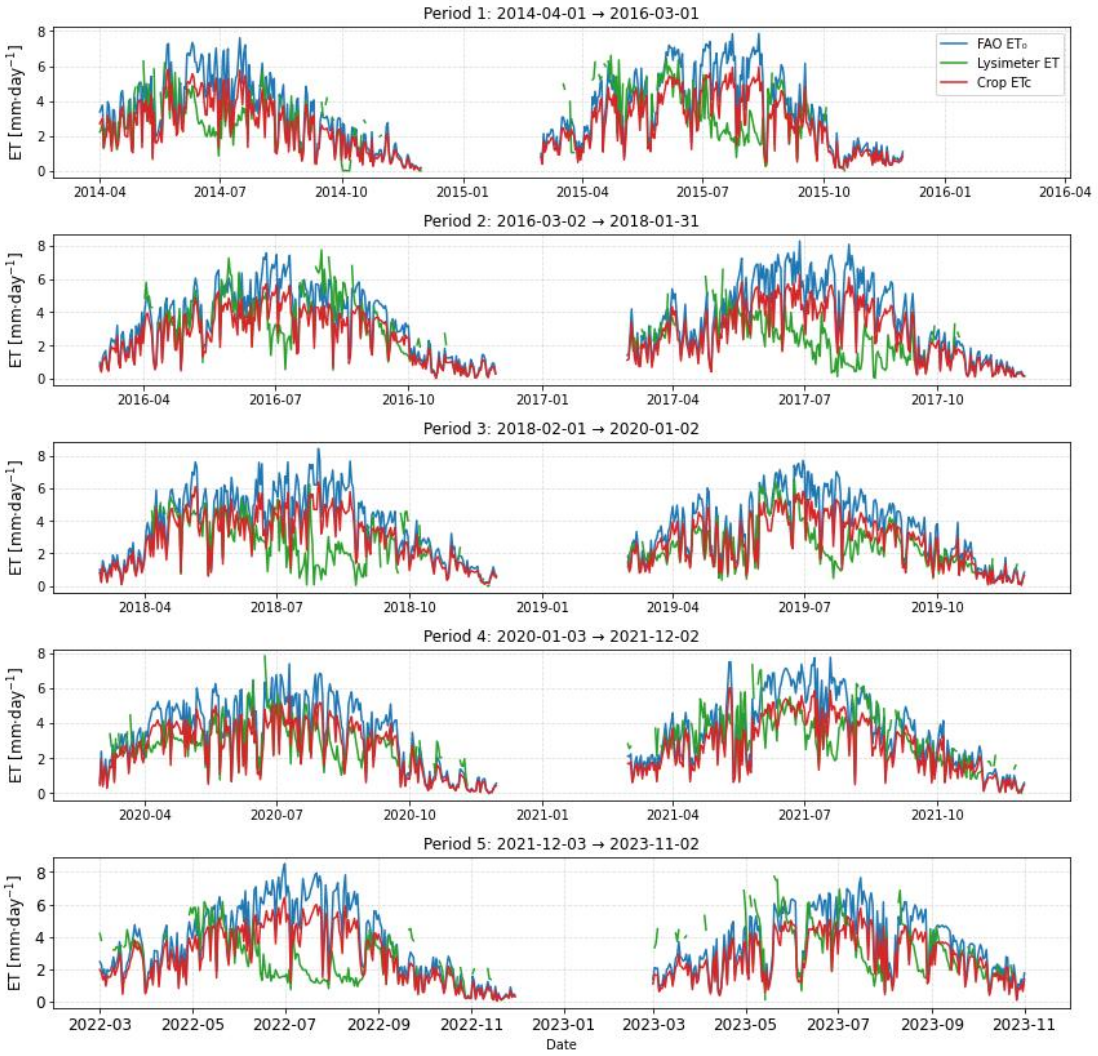


Fig. 2. Comparison of daily FAO-56 reference evapotranspiration (ET_0), crop evapotranspiration (ET_c), and lysimeter-measured actual evapotranspiration (ET_a) for five consecutive periods (2014–2023).

measured evapotranspiration by 138.1 mm, with a corresponding WAPE of 23.8%. The monthly WAPE of reference evapotranspiration (ET_0) reached 46.27%, with a mean BIAS of 6.5 mm month^{-1}.

The agreement between daily ET_c and ET_a markedly throughout the year, closest agreement observed in May and September, which also exhibited the lowest variability of *ET*. In May, the mean WAPE of daily values was 17.5% (minimum 0.91%, maximum 36.8%), with ET_c tending to be lower than ET_a, as indicated by a mean BIAS of −0.73 mm. The largest differences were detected in the summer months, July and August, with mean daily WAPE values of 66.1% and 62.2%, respectively. In July, FAO-56 ET_c showed a strong tendency to exceed daily lysimeter-measured ET_a, with a mean BIAS of 1.44 mm, ranging from 0.14 to 2.80 mm. Seasonally, the largest differences across all indicators were detected in summer (Fig. 3), when daily WAPE reached 50.1%, the mean daily BIAS was 0.98 mm, and Pearson's *R* (Eq.5) was only 0.23. The results further show a clear seasonal pattern, with ET_c tending to exceed ET_a in summer, while being lower than ET_a during spring. The closest agreement between ET_c and ET_a was observed in spring months (March–May), with a daily WAPE of 26.4%, a mean daily BIAS of −0.44 mm, and Pearson's *R* of 0.66, indicating a strong positive correlation. In autumn, a WAPE of 30.9%, Pearson's *R* of 0.74, and a mean daily BIAS of 0.011 mm were detected, also reflecting relatively good agreement. Similar seasonal differences were identified for reference evapotranspiration (ET_0), for which summer WAPE reached as high in July.

Seasonal ET_a/ET_c ratios showed clear seasonal differences between actual evapotranspiration and FAO-56 crop evapotranspiration (Fig. 4). The lowest ratios were observed during summer, indicating strong water limitation of actual evapotranspiration under dry conditions. In contrast, autumn ratios were generally close to 1, reflecting relatively good agreement between lysimeter-measured ET_a and FAO-56 ET_c under wetter conditions. Spring showed higher interannual variability, with ET_a occasionally exceeding ET_c.

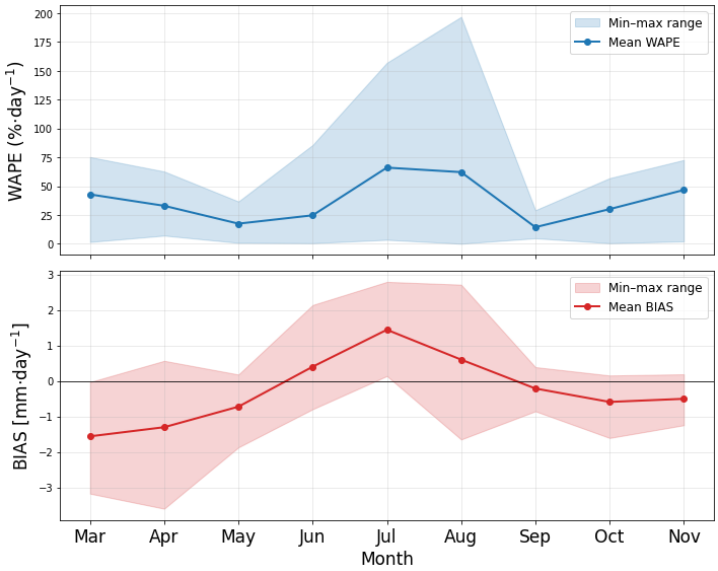


Fig. 3. Monthly mean weighted absolute percentage difference (WAPE) and BIAS between daily ET_c and lysimeter-measured ET_a with corresponding minimum-maximum ranges.

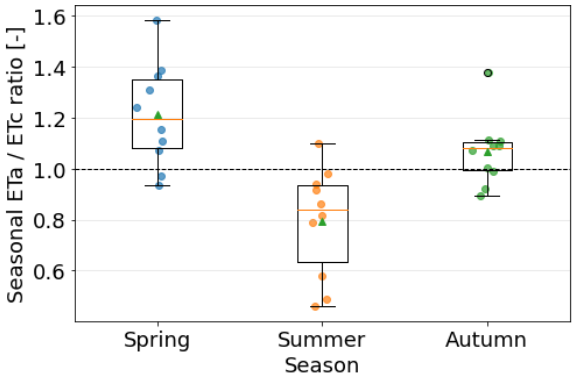


Fig. 4. Seasonal differences between lysimeter-measured ETa and FAO-56 ET_c expressed as ET_a/ET_c ratios.

We further analyzed the effect of water availability on the differences between ET_c and ET_a by evaluating the BIAS over 1–10-day dry periods following rainfall events (Fig. 5). The rolling BIAS analysis was interrupted whenever a new rainfall event occurred (P>0.2 mm). The results show that daily BIAS systematically increased with increasing time since the last rainfall event. One day after rainfall, the mean daily BIAS was 0.27 mm; from the 4-day to the 9-day lag it ranged from 1.10 to 1.13 mm, followed by a slight decrease to approximately 0.8 mm at the 10-day lag. During the summer season, the evolution of BIAS across the different lag periods was similar, with the mean daily BIAS increasing from 0.8 mm at a 1-day lag to 1.97 mm at a 4-day lag, followed by a gradual decrease to 1.58 mm at the 6-day lag and a further reduction by the 10-day lag. These results indicate increasing discrepancy between potential crop evapotranspiration and actual evapotranspiration during rain-free periods.

Analyses of monthly ET_c values showed pronounced seasonal variability in the agreement between ET_c and lysimeter-measured ET_a. In summer months, monthly WAPE reached 16.8% in June, 31.5% in July, and 26.1% in August. In all three summer months, the BIAS values were positive, indicating that calculated ET_c exceeded lysimeter-measured ET_a. This pattern suggests that actual evapotranspiration in this locality was water-limited during summer months. The extremely high WAPE observed in March was primarily driven by very low lysimeter-measured evapotranspiration, which causes even small absolute differences to appear proportionally large. WAPE then decreased steadily through April and May as actual evapotranspiration increased and the agreement between ET_c and ET_a improved, reaching 15.45% month^{-1} in April and only 8.0% month^{-1} in May. Correspondingly, the mean monthly BIAS decreased from 13.8 mm month^{-1} in March to 6.3 mm month^{-1} in April, while in May ET_c showed a slight tendency to underestimate monthly ET_a values.

The relationship between monthly precipitation totals and the weighted absolute percentage error (WAPE) of daily ET_c estimates shows a seasonally contrasting pattern, though statistically significant associations are limited to specific months (Fig. 6). In April, a positive but marginally non-significant trend was observed (R=0.65, p=0.060), suggesting that wetter spring conditions tend to be associated with larger relative differences between ET_c and lysimeter ET. This may reflect the transitional nature of early spring, when vegetation is incompletely developed and lysimeter ET responds directly to increases in soil water availability, while ET_c driven by modelled crop coefficients and atmospheric demand may not yet capture the actual state of the surface. In July, the only statistically significant relationship was identified (R=−0.64, p=0.044), with higher precipitation associated with lower WAPE. This is consistent with a water-limited environment: during dry summers, soil moisture deficits lead to stronger discrepancy between ET_c assumptions and actual lysimeter-measured ET, whereas higher precipitation alleviates soil moisture constraints and brings lysimeter ET closer to modelled ET_c. Although August showed a similar negative tendency (R=−0.57, p=0.084), it did not reach statistical significance at the 0.05 level. No significant relationships were found in the remaining months. Together, these results suggest that the direction and strength of the WAPE–precipitation relationship shifts from a positive, energy- and phenology-limited regime in early spring to a negative, water-limited regime in summer, with July representing the month where precipitation most clearly controls the agreement between FAO-56 ET_c and lysimeter measurements.

To further examine the role of soil water availability in controlling the discrepancy between ET_c and lysimeter-measured ET_a, we incorporated daily soil moisture data from the ESA Climate Change Initiative Combined Soil Moisture product (ESA CCI SM v8.1) extracted for the Borovce station (nearest grid point: 48.625°N, 17.625°E). ESA CCI soil moisture exhibited the strongest bivariate relationship with daily BIAS among all predictors examined (Pearson R=-0.556, p<0.001), explaining 30.9% of its daily variance in simple linear regression. The OLS regression yielded BIAS=−32.75×SM+8.59, with a zero-crossing at SM*=0.262 m³ m⁻³ (Table 2), below this threshold,

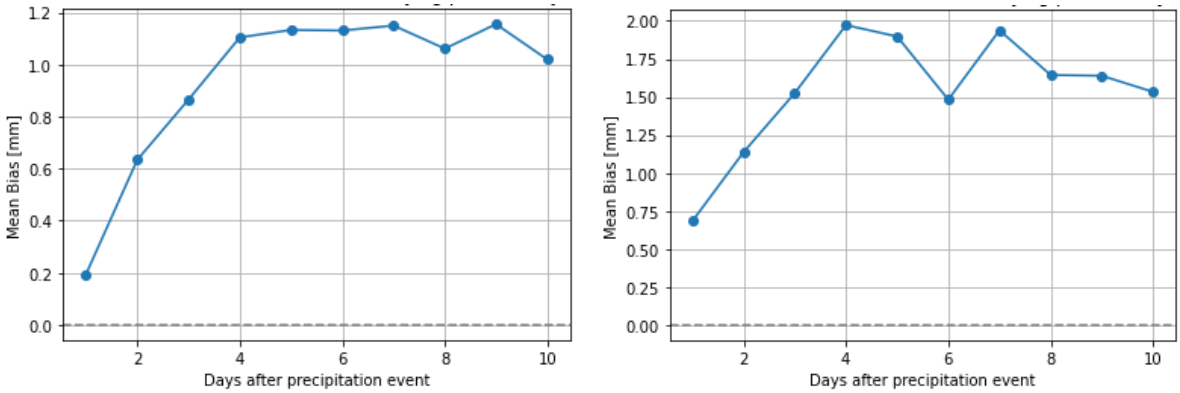


Fig. 5. Change in the mean BIAS between daily ET_c and lysimeter-measured ET_a for 1-10-day lags after precipitation events: three-season period (left) and summer months only (right).

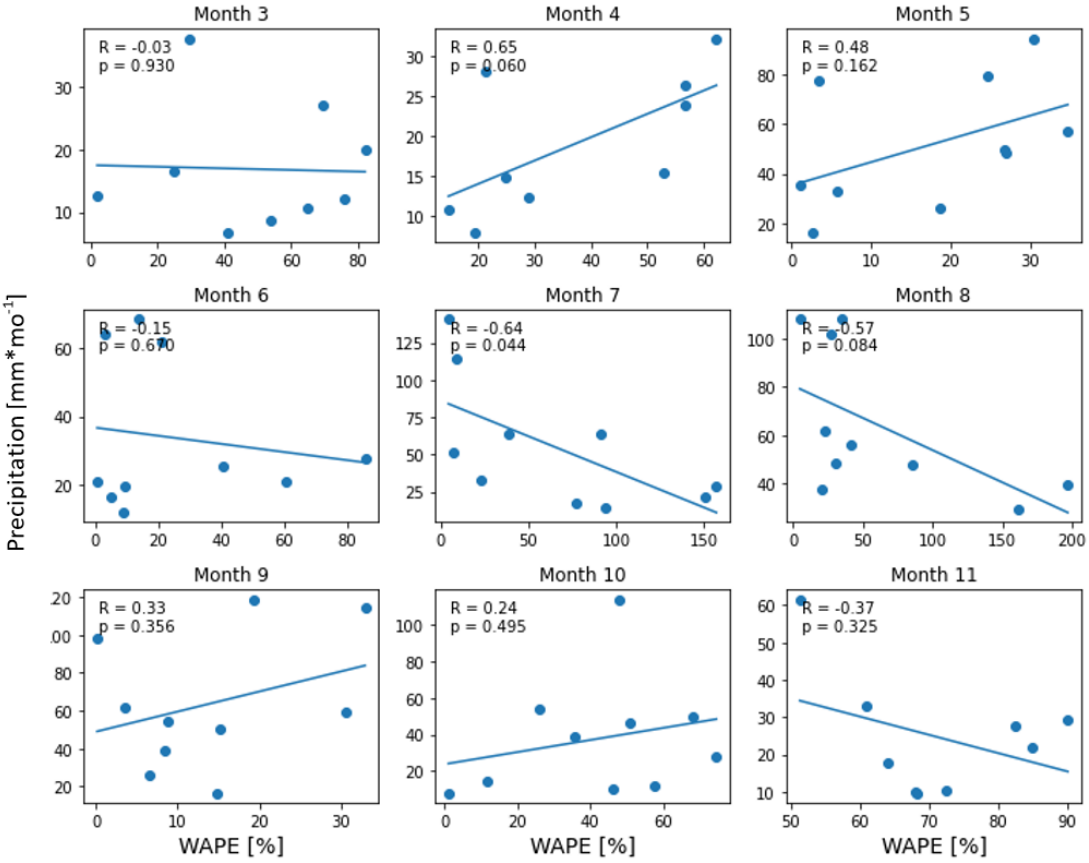


Fig. 6. Monthly relationship between precipitation totals and WAPE of daily ET_c estimates for the period March-November, including Pearson's correlation coefficient (R) and significance level (p).

FAO-56 ET_c systematically overestimates lysimeter ET_a, while above it the two estimates approach agreement. To test whether this threshold reflects a genuine within-season response rather than the seasonal co-occurrence of summer dryness and large BIAS, the analysis was repeated using soil moisture anomalies relative to the long-term daily, monthly, and annual climatology. In all three cases the zero-crossing converged near zero (0.005–0.008 $m^3\ m^{-3}$), indicating that any departure below the prevailing soil moisture normal, regardless of the reference period, is sufficient to produce a positive ET_c–ET_a bias (Fig. 7).

Seasonal agreement and differences between FAO-56 ET_c and lysimeter measurements at Petrovce nad Laborcom

Data from the lysimeter station in Petrovce nad Laborcom were available only for a limited period, from February to the end of November 2019. Therefore, the comparison between FAO-56 ET_c and lysimeter-measured ET_a was evaluated only at daily and monthly temporal scales for this nine-month period. Fig. 8 shows pronounced seasonal variability in the agreement between ET_c and lysimeter ET_a, reflected by substantial differences in both WAPE and BIAS values throughout the year.

The monthly analysis showed the closest agreement during April, May, and September, when WAPE reached 5.0%, 7.9%, and 6.2%, respectively. During these months, BIAS values were also relatively small, indicating relatively good agreement between ET_c and lysimeter-measured ET_a. In contrast, the largest relative differences were observed in March (WAPE of 41.6%), November (22.5%), and during summer months, particularly in August (20.3%) and June (18.6%). The high WAPE values detected in March and November are mainly related to the low magnitude of actual evapotranspiration during transitional periods, when even small absolute differences produce large relative deviations.

During summer months, lysimeter-measured ET_a systematically exceeded calculated ET_c, resulting in strongly negative BIAS values of −26.3 mm $month^{-1}$ in June and −23.5 mm $month^{-1}$ in August. These results indicate substantial difference between potential crop evapotranspiration and actual evapotranspiration under dry summer conditions, when lysimeter ET_a was likely limited by reduced soil-water availability, while FAO-56 ET_c continued to represent evapotranspiration under non-stressed conditions.

Babaee et al. (2019) reported that the FAO Penman-Monteith method tends to overestimate crop evapotranspiration when compared with lysimeter

Table 2. **Regression statistics and zero-crossing of the OLS regression line (SM*) for the relationship between daily ET_c–ET_a bias and ESA CCI soil moisture, using four definitions of the soil moisture predictor. SM* is the value of soil moisture at which BIAS=0 (ET_c=ET_a). All correlations significant at p<0.001, DOY=day of year**

Variant	*n*	Pearson *R*	R^2	Slope	Intercept	SM* [m³ m⁻³]
Absolute SM	1652	-0.556	0.309	-32.748	8.588	0.2623
Anomaly vs DOY normal	1652	-0.472	0.223	-33.967	0.168	0.005
Anomaly vs monthly mean	1652	-0.474	0.225	-34.169	0.171	0.005
Anomaly vs annual mean	1652	-0.516	0.267	-31.309	0.262	0.0084

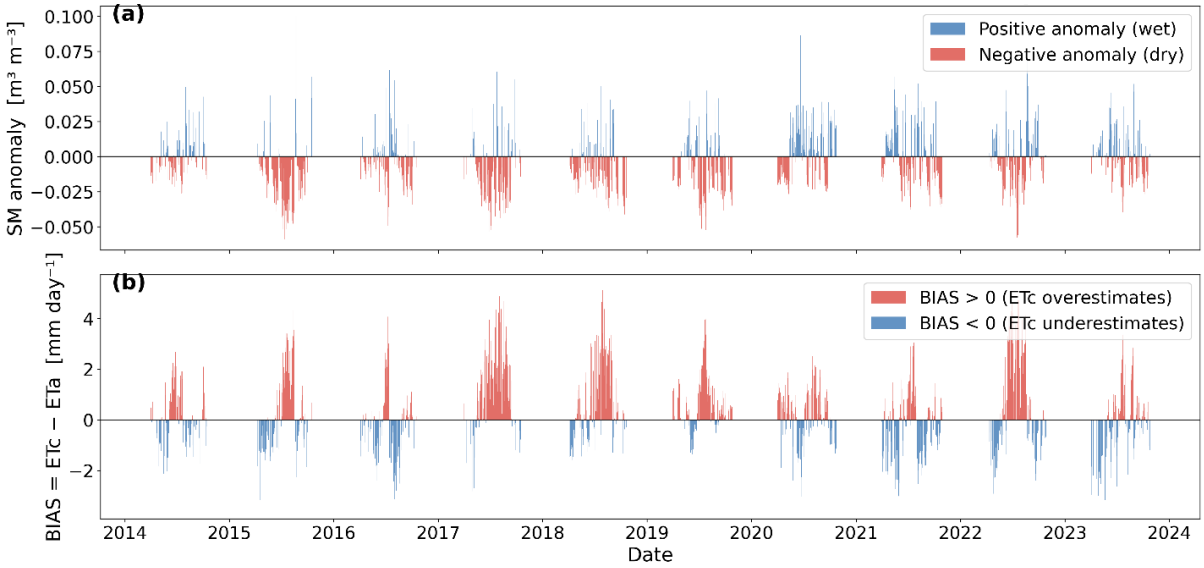


Fig. 7. Daily ESA CCI soil moisture anomalies (a) and ET_c–ET_a bias (b) at the Borovce station for the growing season (April–October, 2014–2023). Anomalies are computed as deviations from the long-term daily climatology derived from the full ESA CCI record.

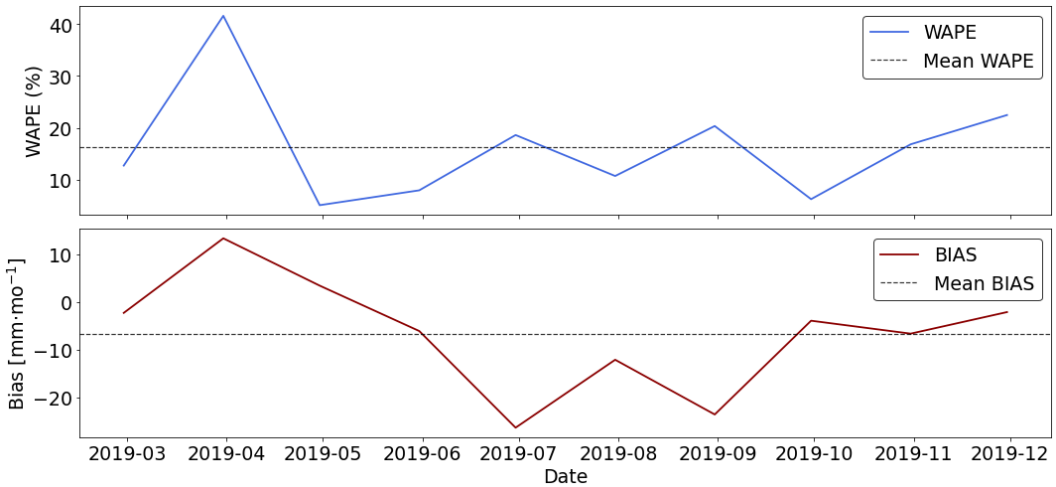


Fig. 8. Monthly crop evapotranspiration (ET_c), monthly BIAS, and monthly weighted absolute percentage error (WAPE) of ET_c at Petrovce nad Laborcom station.

observations. Our results show that the magnitude and direction of the ET_c–ET_a differences are strongly linked to seasonal water availability. In periods with reduced soil moisture availability, lysimeter-measured ET_a decreases due to stomatal regulation and limited transpiration, while the FAO-56 method estimates ET_c under standard, non-stressed conditions, increasing the positive BIAS. A number of authors have evaluated the agreement between ET_0 or ET_c calculated from FAO-56 Penman-Monteith and lysimeter measurements across different climatic zones. Gebler et al. (2015) reported a relative absolute error below 20% and a coefficient of determination (R^2) greater than 0.9 for a lysimeter site in Spain, indicating strong agreement between ET_0 and lysimeter *ET* under humid conditions. Dai et al. (2022), using 373 days of lysimeter data, found a mean daily error of -0.26 mm day^{-1}, corresponding to an 11.0% deviation, which again suggests good performance of the PM method when water stress is minimal. Benli et al. (2006) compared crop evapotranspiration (ET_c) derived from FAO-56 with lysimeter measurements and reported a standard difference of 1.74 mm day^{-1}, demonstrating that ET_c-ET_a agreement is more variable and crop-dependent. Similarly, Hunsaker et al. (2002) found that daily ET_c for alfalfa was highly correlated with lysimeter ET_c (R^2=0.98), with a mean daily bias of only 0.03 mm. The low bias in their study can be attributed to irrigation management, which minimized soil-water stress and thereby reduced differences between modeled and measured ET_c. Djaman and Irmak (2013) also demonstrated that water availability plays a critical role. For maize, the difference between modeled ET_c and lysimeter-measured actual *ET* (ET_a) reached 38% under rainfed conditions, but decreased to 18% under full irrigation. In a wetter year, the discrepancy ranged from 21% under full irrigation to 12% under rainfed conditions, highlighting the sensitivity of ET_c/ET_a differences to seasonal precipitation. These findings are consistent with our results from the Borovce lysimeter station, where the mean daily WAPE was 38.1%, and the largest deviations occurred during summer months, when soil moisture limitations were most pronounced. Our analysis confirms that precipitation and soil-water availability are key factors controlling discrepancies between calculated ET_c and lysimeter-measured ET_a. Under water-limited conditions, Penman-Monteith ET_c systematically exceeds actual evapotranspiration, whereas in well-watered or irrigated conditions, the agreement between ET_c and ET_a improves substantially.

Conclusion

Although the FAO-56 Penman-Monteith model is widely used as a benchmark for evapotranspiration estimation in Central Europe, direct comparisons with lysimeter observations remain limited due to the scarcity of long-term lysimeter measurements covering entire growing seasons. Rather than validating the FAO-56 approach, this study aimed to quantify the seasonal differences between crop evapotranspiration estimated by the FAO-56 Penman-Monteith method (ET_c) and lysimeter-measured actual evapotranspiration (ET_a) at theBorovce lysimeter station, with ET_a data from lysimetric station at Petrovce nad Laborcom. In Borovce, lysimeter records were used to evapotranspiration estimates for the first time since the installation of the monitoring system. Unlike many *ET*c studies focusing on agricultural crops, the present analysis used crop coefficients representing cool-season grass vegetation similar to the lysimeter surface cover. Therefore, the observed differences between ET_c and ET_a cannot be attributed solely to vegetation type and are more likely associated with differences in water availability and soil moisture conditions.

The results demonstrated that the agreement between ET_c and ET_a depends strongly on seasonal conditions, and soil moisture dynamics. At the Borovce station, the mean daily weighted absolute percentage difference reached 38.1% and decreased to 31.6% at the monthly scale, confirming closer agreement with temporal aggregation. Despite differences in climate, soil, and data availability, the seasonal pattern of ET_c-ET_a difference observed at Petrovce nad Laborcom was consistent with Borovce, the largest differences occurred in summer, BIAS was positive during dry periods, and spring and autumn showed smaller or negative differences. This agreement between the two stations confirms that the differences of the seasonal cycle of ET_c-ET_a difference identified at Borovce is not site-specific but reflects a common response to seasonal water availability under Slovak climatic conditions.

The comparison of lysimeter ET_a with Penman-Monteith ET_c revealed that the ET_c-ET_a relationship strongly depends on season and local site conditions. The largest relative differences occurred in spring and autumn, when lysimeter ET_a is naturally low and the land surface undergoes rapid transitions in vegetation activity, soil moisture regime, and surface energy balance. During these periods, even moderate absolute differences produced large percentage differences.

The direction and magnitude of summer BIAS varied between years, showing that the relationship between lysimeter evapotranspiration and crop evapotranspiration is strongly controlled by local water availability. During periods with sufficient soil moisture, lysimeter-measured ET_a occasionally exceeded ET_c, resulting in negative BIAS. In contrast, during dry summer periods, evapotranspiration was clearly limited by water availability, often leading to positive BIAS values and larger differences between ET_c and ET_a. The post-rainfall analysis further demonstrated that daily ET_c-ET_a BIAS increased consistently with the number of consecutive rain-free days, confirming the growing impact of soil moisture depletion on model measurement differences. Analysis of ESA CCI soil moisture data revealed that near-surface soil moisture was the strongest predictor of daily ET_c-ET_a differences (Pearson R=−0.556, p<0.001, R^2=0.309), and identified a threshold of SM*=0.262 m^3 m^{-3} below which FAO-56 ET_c systematically overestimates lysimeter ET_a. An analysis showed that

the dry periods differences ET_c-ET_a increase through soil moisture depletion.

Taken together, the results show that:

- Spring and autumn differences ET_c-ET_a are mainly driven by low ET_a values and rapid changes in atmospheric and vegetation conditions, which amplify relative differences.
- Summer differences are primarily controlled by limited water availability, leading to systematic exceedance of ET_c over ET_a during dry summer periods.
- The seasonal pattern of ET_c-ET_a is common across both lysimetric stations.
- ESA CCI soil moisture is the dominant predictor of daily ET_c-ET_a differences with a clearly identifiable threshold below which FAO-56 overestimation becomes systematic.
- These findings highlight the need for soil-moisture-based adjustments when applying FAO-56 *ETc* under water-limited conditions.

Overall, the study demonstrates that while the FAO-56 Penman-Monteith method remains a robust reference approach under well-watered conditions, its direct application as an approximation of actual evapotranspiration under soil moisture deficit can lead to substantial systematic overestimation. Integrating soil moisture information, stress coefficients, or locally calibrated crop parameters is therefore essential for reliable estimation of actual evapotranspiration in Central European environments.

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