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Measurement and estimation of evapotranspiration in semi-arid grassland during the summer season in southwest Siberia

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Abstract

This study quantifies actual evapotranspiration (ET_a) for a period from June to September 2016 measured by two weighable gravitation lysimeters in a semi-arid grassland in southwest Siberia. As part of a crop rotation system, the first lysimeter was fallow but covered with ruderal vegetation. The second lysimeter is permanently characterized by pristine steppe vegetation. In addition to ET_a measurements, the reference evapotranspiration (ET_0) is computed by a Penman-Monteith model. The estimates are related to the ET_a records and the model is evaluated with regard to its performance in a semi-arid environment. The results indicated an ET_a driven by energy but limited by water. Within 115 days the total amounts of ET_a ranged from 205 mm to 374.1 mm, and daily values varied from 0.1 to 6.9 mm day^{-1}. The large differences are caused by the different vegetation cover of the lysimeters. Due to the high and dense canopy of the pristine steppe vegetation, the transpiration term was considerably higher compared to the ruderal vegetation where soil evaporation took the major part. The daily ET_a records differed on average by -91.1% to the ET_0 estimates. The statistical analyses yielded a low correlation between ET_a of the ruderal vegetation and ET_0 but an acceptable model performance for the pristine steppe. However, it was observed that ET_a occasionally exceeds ET_0, particularly after precipitation. Due to the high water availability and the subsequent rise of ET_a, ET_0 was underestimated, whereas it was overestimated during dry periods. Finally, the quality of the Penman-Monteith model varied substantially with the water supply at the study site.

Keywords: Actual evapotranspiration, Penman-Monteith FAO-56, semi-arid, Siberia, weighable gravitation lysimeter.

Article Info

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Introduction

In semi-arid areas, the availability of water is of particular importance. These environments are characterized by low precipitation and water is a limited resource, which influences vegetation density, cover, and biomass. Knowledge of soil-atmosphere exchange of energy and moisture, as well as crop water requirement, is important for the management of regional water resources. For this purpose, processes have to be identified that exhibit influence on the hydrological cycle. Actual evapotranspiration (ET_a) is often used to determine the water loss from the soil surface (evaporation) and from the growth and temperature regulation process of plants (transpiration). However, measurement of ET_a is a challenge (Wohlfahrt et al., 2010; Allen et al., 2011; Amatya et al., 2016). There are different possibilities for obtaining accurate estimates of ET_a; indirect methods such as residual energy balance, Bowen ratio energy balance, soil water balance (Shi et al., 2008; Wegehenkel et al., 2008; Meissner et al., 2016a; Martel et al., 2018), and those that

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include lysimetry and eddy covariance methods for direct measurements (Wohlfahrt et al., 2010; Fleischer et al., 2015; Gebler et al., 2015). Weighable lysimeters are widely used for ET_a measurements (Von Unold and Fank, 2008; Schrader et al., 2013; Wegehenkel and Gerke, 2013; Mauder et al., 2017; Oberholzer et al., 2017). Though, for lysimeter measurements a lot of requirements have to be considered (Allen et al., 2011). In summary, soil properties and vegetation cover of the lysimeter must be very similar to the surrounding area. It is usually difficult to reconstruct the original soil profile and to maintain the field conditions of soil and vegetation. Eventually, lysimeter measurements represent only point measurements that will be transferred to large areas. Nevertheless, they remain effective due to the weighing system that enables the derivation of evapotranspiration (ET) from mass records with the highest accuracy compared to the methods mentioned above (Allen et al., 2011).

Furthermore, lysimeter measurements will also be used for calibration and validation of ET models (Makkink, 1957; DehghaniSanij et al., 2004; López-Urrea et al., 2006; Wegehenkel and Gerke, 2013). As water stress become more and more to an important issue, baseline information is required for water resource planning, particularly in arid and semi-arid regions. Therefore, the estimation of ET by deterministic models has exponentially increased in recent years. These models built around climate and land surface data, provide reliable ET rates for a reference crop. From the several existing models, the Penman-Monteith FAO-56 (PM FAO) equation is the most used for estimating reference evapotranspiration (ET_0). Due to the high demand of data, the PM FAO model proved to be highly accurate (DehghaniSanij et al., 2004; López-Urrea et al., 2006; Sabziparvar and Tabari, 2010; Martel et al., 2018). Nevertheless, the data demand is also a major drawback of the model. For calculation of ET_0 high-resolution, the data that is required is limited in many regions. Large parts of Siberia, for instance, are not covered by meteorological measurement stations. Yet, water resources and ET estimations are relevant for these large areas; especially with regard to climate change, which has a direct impact on the regional hydrological cycle and agriculture (Fraser et al., 2013; Degefie et al., 2014). Moreover, they belong to the region which has the potential to become the "*bread basket*" of the world due to the large land and yield reserves (Bagley et al., 2012; Swinnen et al., 2017).

Previous studies conducted in Siberia (Yamazaki et al., 2004; Park et al., 2008; Fleischer et al., 2015), have used land surface models to investigate water and energy exchanges at forests and transition zones. The estimation of ET refers solely to the Bowen ratio method, eddy covariance, and models based on Penman formulations. However, there is an absence of studies based on ET estimation by weighable lysimeter measurements.

In the framework of the research project KULUNDA (Balikyn et al., 2016) an established monitoring network enabled the estimation of ET_a by weighable gravitation lysimeters in the Kulunda grass steppe of southwest Siberia. On this basis, the study quantifies ET_a of two lysimeters with different vegetation cover under semi-arid conditions. In addition, ET_0 is calculated by using the PM FAO equation (Allen et al., 1998), which was selected due to the crop reference of grass and the independence to the climate type.

The objectives of the study are:

i. to assess ET_a as a function of vegetation cover and climatic conditions,
ii. to compare ET_0 estimates with ET_a records,
iii. to assess the PM FAO model for a semi-arid environment.

Material and Methods

The study site and monitoring network

The study site is part of the semi-arid Kulunda steppe, southwest Siberia, and located between the Central Asian steppe and the North Asian forest-steppe (Balikyn et al., 2016). The site is 100-140 m a.s.l.; its mean annual temperature is about 0 °C with a maximum in July (up to +40 °C) and a minimum in January (down to -47 °C). The annual precipitation is about 250-450 mm, where the major part of 200 mm occurs from April to October. The global radiation is 2-3 times higher than the energy that is required to evaporate precipitation. The surrounding area is plain and dominated by natural steppe vegetation.

In the framework of the research project KULUNDA a monitoring network was established, which has consisted of a weather station and a weighable gravitation lysimeter station. The set-up of the weather station was in September 2012. Meteorological parameters such as rainfall, air temperature, wind speed and direction, air humidity and barometric pressure are measured by a multisensor at a height of 2.3 m. A pyranometer recorded the solar radiation at a height of 2 m, and a pluviometer mounting in a tipping bucket rain gauge collected precipitation at the standard height of 1 meter.

The containerized lysimeter station with two weighable soil monoliths (manufacturer “UGT-Muencheberg”, Germany and Helmholtz Centre for Environmental Research – UFZ, Germany) was installed at the test farm of the project in Poluyamki (N52° 03.959’ E79° 42.786’; approximately 700 km southwest of Novosibirsk) between June and August 2013 (Balikyn et al., 2016). The soil monoliths were monolithically extracted from an arable land (lysimeter 1 - LYS 1- ruderal vegetation) and a fallow site (lysimeter 2 - LYS 2 – pristine steppe), which was covered with pristine steppe vegetation since the 1950s. The different cultivation allowed comparative analyses between arable land and unconverted grassland. Thus, there was an ascertained crop rotation at LYS 1: wheat (2013), peas (2014), wheat (2015), and fallow (2016). In contrast, LYS 2 was dominated by natural feather grass (*Stípa pennáta*) between 2013 and 2016.

Each lysimeter had a surface area of 1 m^2, a depth of 2 m and was monolithically filled with a soil, which was identified as Calcic Chernozems according to the guidelines of the Food and Agriculture Organization of the United Nations (FAO). A detailed description of the lysimeters is given by Meissner et al. (2016b). The total mass of each lysimeter vessel was approximately 4000 kg and the mass changed with water input (precipitation, dew, rime, and the water equivalent of snow) and water output (ET_a). The vessels were positioned into the lysimeter station on load cells that measure the mass with high precision of ± 20 g (Xiao et al., 2009). The data were consolidated and stored in a data logger with a recording interval of one hour. Due to their geometry, a change of mass is equal to a water storage change in millimeters (1 kg ≈ 1 L/m^2 = 1 mm). Therefore, all changes of mass are given in millimeters in the following.

Data preparation and calculation of ET_a

The lysimeter measurements started in August 2013. However, reliable measurements have turned out to be a challenge at this study site. Currently, data was only available from August 2013 to September 2016, but the time series was not continuous. Due to the malfunction of the lysimeters during winter induced by sub-zero temperatures and snow, all data between October and May were nonapplicable for data analysis. Furthermore, direct access to the data was not possible. The release of the data was hindered by the Russian administration and created a time delay between measurement and receipt of data. For these reasons, data analysis took place only with a data set from June 08, 2016 to September 30, 2016.

The processing of lysimeter data was executed in several steps according to the principle of the adaptive window and adaptive threshold filter (AWAT) developed by Peters et al. (2014). First, the raw data were manually filtered, and all data during system error or noticeable outliers were removed. If the resulting gaps did not exceed a period of four hours, values were estimated by linear interpolation. In step two, the data were smoothed by using an adapted window width. The *Savitzky-Golay* filter (Savitzky and Golay, 1964) was proven as an eligible smoothing routine for the data set. The window width (ω) was set at 5 hours and a polynomial of 3rd order was used. The window width was adapted to increasing noises. Third, an adaptive threshold (δ) was applied to obtain ET_a out of mass data. The setting of threshold was optimized for lysimeter separately. For LYS 1 the lower limit for threshold (δ_{min}) was set to 0.04 mm, whereas the upper limit (δ_{max}) was set to 0.7 mm. The threshold values of LYS 2 were increased with δ_{min} = 0.05 mm and δ_{max} = 0.8 mm. At last, inconsistent values of the filter output were corrected manually.

Information about water fluxes at the pedosphere-atmosphere interface can be derived from mass changes of a lysimeter. The total mass of the system (M) is the sum of lysimeter mass (M_{lys}) and of drainage (M_{drain}). It is assumed that a mass increase is precipitation (P) and a mass decrease is ET_a. With this assumption that either ET_a or P occurs, but not both at the same time, P is equal to zero when ET_a is active, and vice versa (Schrader et al., 2013):

$$M = M_{lys} + M_{drain} \quad (1)$$

$$P = \begin{cases} \Delta M & \text{for} \quad \Delta M > 0 \\ 0 & \text{for} \quad \Delta M \leq 0 \end{cases}$$

$$ET_a = \begin{cases} \Delta M & \text{for} \quad \Delta M < 0 \\ 0 & \text{for} \quad \Delta M \geq 0 \end{cases}$$

where M_{lys} is the mass of lysimeter vessel [kg], M_{drain} is the amount of seepage water [kg], and ΔM is the total mass change of lysimeter vessel in the according time interval [kg].

Depending on the aims of data use, ET_a can be expressed at different time scales. Where daily values are required, hourly values are summed-up for one day, starting from 12:00 and follows to 24 hours. Furthermore, for lysimeter readings of ET_a, LYS 2 was considered as a reference since the canopy of the lysimeter corresponded to the surrounding field.

Estimation of ET_0 by using the PM FAO model

The measurements of ET_a by lysimeters were compared with ET_0 calculated by the PM FAO equation according to Allen et al. (1998). The Penman-based models are widely used in virtually any climate type. The recommended FAO version has proven as a highly accurate model for calculating ET_0 if the required meteorological input parameters are available. The approach assumes a surface of a uniform and actively growing grass vegetation without water stress, an approximate height of 0.12 m, a daily surface resistance of 70 s m^{-1}, and an albedo of 0.23. In connection with the original Penman-Monteith equation (Monteith, 1965) the final form is as follows:

$$ET_0 = \frac{408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\, u_2)} \qquad (2)$$

where ET_0 is the reference evapotranspiration [mm d^{-1}], R_n the net radiation [MJ m^{-2} d^{-1}], G the soil heat flux density [MJ m^{-2} d^{-1}], T the mean daily air temperature [°C], u_2 the mean daily wind speed at 2 m height [m s^{-1}], e_s the saturation vapor pressure [kPa], e_a the actual vapor pressure [kPa], Δ the slope vapor pressure curve [kPa $°C^{-1}$], and γ the psychrometric constant [kPa $°C^{-1}$] (Allen et al., 1998).

The calculation of daily ET_0 values was conducted by using R software. The R software package "*Evapotranspiration*" included different models to estimate ET_a, ET_0 and potential evapotranspiration (ET_p) (Guo et al., 2016). For the modeling, PM FAO required information about daily minimum and maximum temperature, incoming solar radiation, and wind speed as well as minimum and maximum relative humidity. The data were taken from the weather station of the monitoring network. Hourly data were manually calculated according to Eq. 2. In order to assess the model results related to the ET_a records the correlation of Pearson (r), the root mean square error (RMSE, Eq. 3), and the mean absolute error (MAE, Eq. 4) was used.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \qquad (3)$$

$$MAE = \frac{\sum_{i=1}^{n}|X_i - Y_i|}{n} \qquad (4)$$

The variables X_i and Y_i are the i*th* observed reference and estimated values, respectively; n is the total number of data.

In addition, the ratio of ET_a to ET_0 delivers information about the water supply of the soil for a grass vegetation with an height of 0.12 m. The daily ET_a record divided by ET_0 estimate resulted in an index varying between 0 and 1. The water availability is high (moist) by an index of 1, i.e. there is no climatic risk of non-water supply (Louzada et al., 2018). Optimal water availability goes along with an index between 0.8 and 1. An index of <0.8 indicates a water deficit where only <80% of ET_0 will be satisfied (Roth et al., 2005).

Results and Discussion

Within the measuring period of 115 days, the total sum of ET_0 was considerably higher than ET_a of the lysimeters, +157.8% for ruderal vegetation and +41.3% for pristine steppe. The minimum of ET_a was 205 mm measured by LYS 1, which was 45.2% less than ET_a measured by LYS 2 (374.1 mm). A maximum of ET_0 was calculated by 528.6 mm. As the theoretical maximum estimate by ET_0 was not reached, it is assumed that ET_a was limited by water and not by energy. Table 1 lists the monthly ET_a and ET_0 records of June – September 2016. The maximum ET_a was achieved in July as well as the slightest deviation (-31%) between both lysimeters. The largest deviation was in June with -66.4%. ET_0 differs on average +235.5% (ruderal vegetation) and +163% (pristine steppe) per month, respectively.

Table 1. Monthly ET_a records of the lysimeters and ET_0 estimates calculated by PM FAO model; the data are based on daily mean values.

Month	ET_a LYS 1 ruderal vegetation	LYS 2 pristine steppe	ET_0 PM FAO
	mm month^{-1}		
Jun[a]	34.8	103.7	125.8
Jul	88.5	128.3	145.2
Aug	56.4	100.2	142.4
Sep	25.3	41.8	115.4

[a]No data from June 01 to June 07, 2016

The daily ET_a values were within the range of 0.1 to 6.9 mm day^{-1}, whereas ET_0 calculated by PM FAO model varied from 2 to 8.3 mm day^{-1} (Figure 1). The medians lay between 1.4 and 4.5 mm day^{-1}. The difference between mean ET_a of the lysimeters and ET_0 is -91.1%. The ET_a of the ruderal vegetation had the smallest median and yielded the lowest values as well as variation. The median of the ET_a of the pristine steppe was at 3.3 mm day^{-1} and it covered the widest range of values. The minimum and maximum values of ET_a of the lysimeters were very similar. ET_0 had a maximum value of 8.3 mm day^{-1} with a maximum difference of +24.5% (to ET_a of the ruderal vegetation), and a mean difference of +20.7% (to maximum ET_a of both lysimeters). The absolute deviation was greatest with 7 mm day^{-1} between ET_a of the ruderal vegetation and ET_0, which corresponds to a difference of -556.3%.

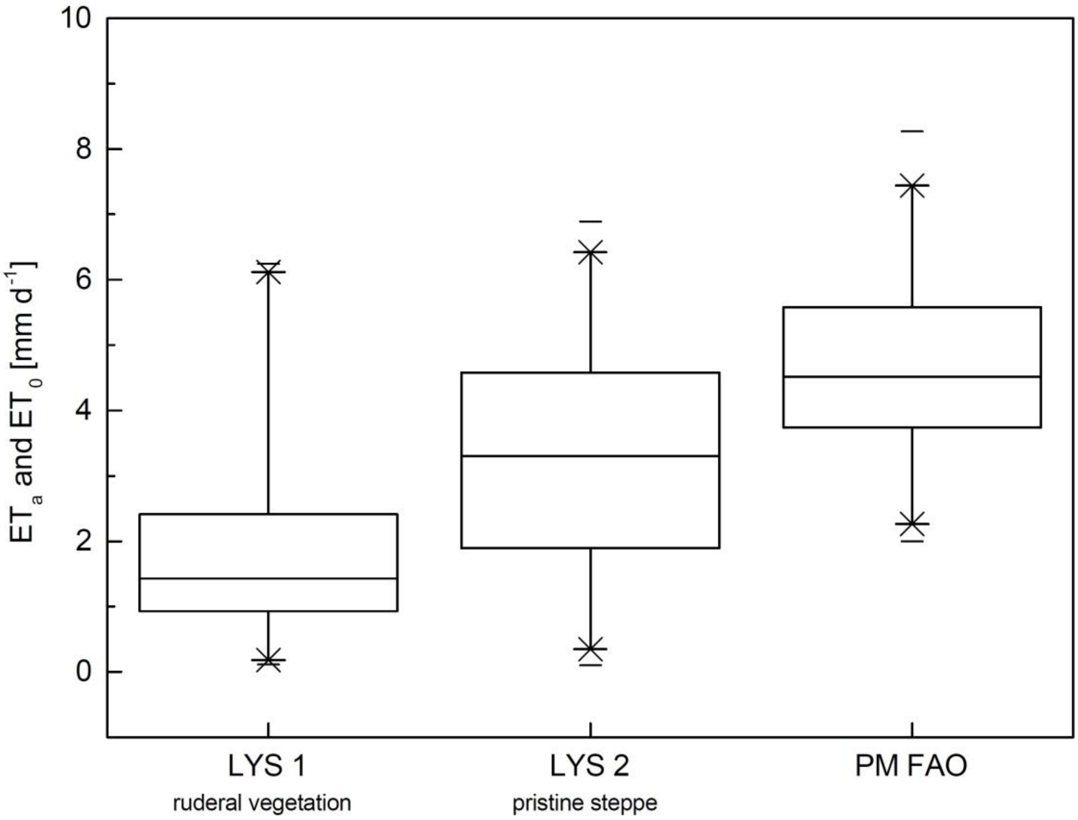

Figure 1. Comparison of ET_a measured by lysimeters and ET_0 computed by the PM FAO model. The box plots are based on daily data. The box boundaries represent the 25th and 75th percentiles, the inner lines indicate the medians, the whiskers extend to 1.5 times the interquartile range, the crosses mark the 1st and 99th percentiles, and the strokes show the minimum and maximum values.

In general, daily ET_a and daily values of solar radiation and air temperature were positive correlated (Table 2). Therefore, the energy was the leading factor for ET_a at the study site. In contrast to observations of other studies in which factors such as relative humidity and wind speed removed water vapor from the vegetation surface (Priestley and Taylor, 1972; Shi et al., 2008; Yang et al., 2014) their low correlation indicated no relationship. The negative correlation with wind speed was noticeable, but similar results were found in previous studies with arid and semi-arid site conditions (El Bably, 2003; Martel et al., 2018).

Table 2. Pearson correlation coefficients (r) between ET_a of the lysimeters and meteorological parameters

Lysimeter	Meteorological parameter			
	Solar radiation	Air temperature	Relative humidity	Wind speed
LYS 1 - ruderal vegetation	0.41**	0.45**	0.46**	-0.17
LYS 2 - pristine steppe	0.80**	0.69**	0.18*	-0.13

*P< 0.05; **P< 0.01

Daily ET_a rates between lysimeters and ET_0 illustrated largely negative differences (Figure 2). Lysimeter 1 recorded up to 5.2 mm day^{-1} (06/14/2016) less than LYS 2 (cf. Figure 2a). The fluctuations were high in June and became lower from August. This may be caused by the diversity of vegetation. LYS 2 exhibited a high and dense layer of grass, which has induced ET_a and interception. On the other hand, LYS 1 was fallow in June. Hence, evaporation was the exclusive process at LYS 1, as a result of the lack of vegetation. From July a convergence of ET_a of LYS 1 to ET_a of LYS 2 was observed based on the development of ruderal vegetation and the additional transpiration term at LYS 1. The conditions of LYS 1 were also reflected in the high fluctuation between ET_a of the ruderal vegetation and ET_0 during the whole period (cf. Figure 2b). The discrepancies between observed and calculated data were high with an average of -3.2 mm day^{-1}, except for July where the deviations became lower with a mean of -1.8 mm day^{-1}. ET_a of the pristine steppe demonstrated minor deviations to ET_0 between June and August, and account several days where $ET_a = ET_0$ (cf. Figure 2c). It was found that ET_a repeatedly exceeded ET_0 with amounts up to +0.8 mm day^{-1} (07/13/2016), in which ET_a of the pristine steppe tended more frequently to exceed ET_0.

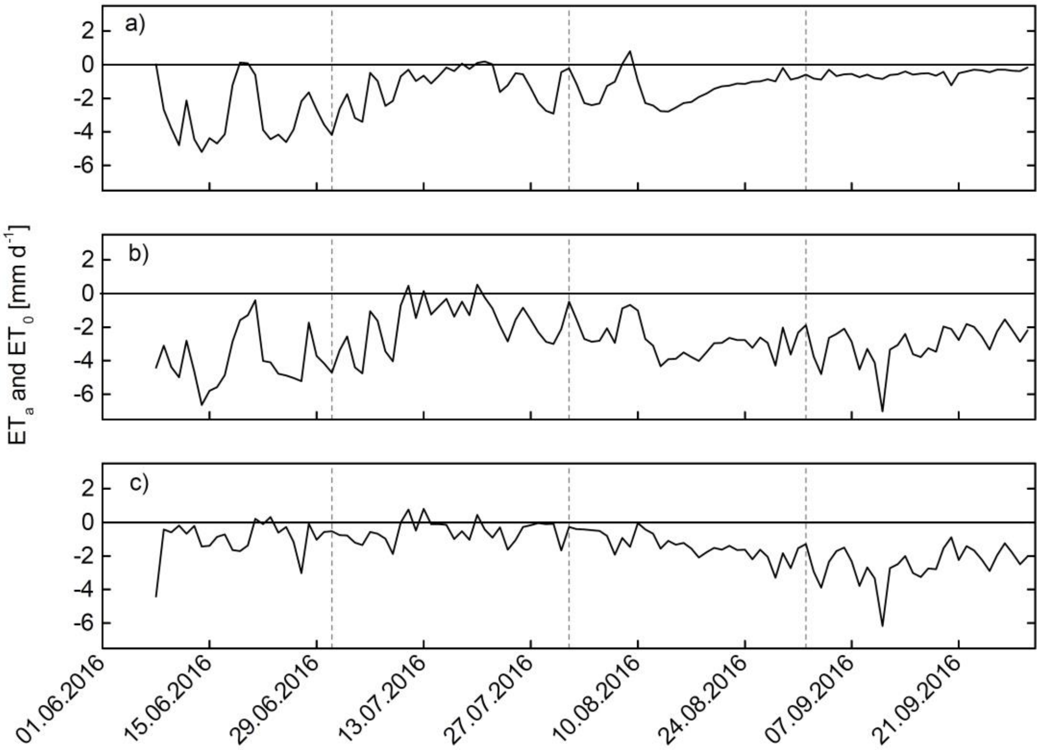

Figure 2. Daily differences of ET between June 08 and September 30, 2016; a) ET_a of ruderal vegetation – ET_a of pristine steppe, b) ET_a of ruderal vegetation – ET_0, c) ET_a of pristine steppe - ET_0.

The results of the statistical analyses showed a low correlation between ET_a of the ruderal vegetation and ET_0 (Figure 3). In addition to the high values of RMSE and MAE, the model can be assessed with poor quality for LYS 1. The PM FAO assumes an extensive surface canopy that completely covers the ground. However, the ruderal vegetation at LYS 1 did not comply with these conditions over the investigated period. ET_a of the pristine steppe and ET_0 were strongly correlated. The RMSE with 1.7 mm and MAE with 1.4 mm presented a significant performance, with a tendency to overestimation. Nevertheless, due to the dense and high steppe grass at LYS 2, the transpiration term may be larger as the model assumed. This assumption is justified by Roth et al. (2005) who pointed that the water consumption of a full developed vegetation cover may lead to an underestimation of ET_0. Similar results were also found by other studies (Wegehenkel and Gerke, 2013; Gebler et al., 2015). Indeed, a further and more widespread explanation for $ET_a > ET_0$ is the “oasis effect”. It occurs if conditions of vegetation and atmosphere of the lysimeters differ to those of the surrounding area. Actually, LYS 2 had to be preventing the oasis effect by reason of the same vegetation cover. Yet, LYS 1 was fallow; therefore, different soil water availability between the surrounding area and LYS 1 has to be considered. On the other hand, there is also the possibility that ET_a was overestimated by the pristine steppe vegetation. If the canopy of the lysimeter exceeds the rim, the effective area of the lysimeter can be larger than the original lysimeter extent. This "bloom effect" leads to higher radiation absorption of the vegetation, which eventually results in increased ET_a (Allen et al., 2011). The bloom condition can be excluded at LYS 1 because the vegetation is not tall and dense enough to exceed the lysimeter. There is a low likelihood that the oasis effect, as well as the bloom effect, occurs at both lysimeters at the same time. Thus, they cannot be responsible for $ET_a > ET_0$ in this case.

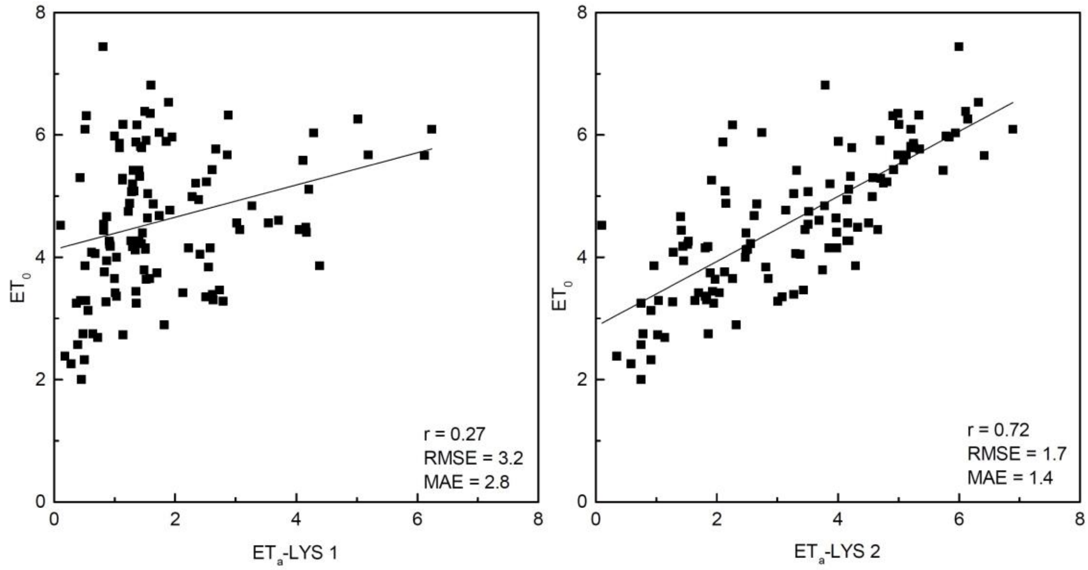

Figure 3. The relationship between ET_a and ET_0 on a daily basis (n=115), and the respective error values.

Figure 4 illustrates the daily water availability for the lysimeters. In June, the mean soil water availability index was at 0.3 for LYS 1 and at 0.8 for LYS 2. Thus, the pristine steppe showed an optimal water supply, whereas only 30% of the potential water demand was available for soil and the ruderal vegetation. However, the values for the ruderal vegetation should be treated with caution since it has already been demonstrated that the model quality for LYS 1 was poor. Thus, the lower index of the ruderal vegetation in June was less related to the soil water availability. Frequent precipitation caused a rise in water availability in July; consequently, ET_a is increased (Wever et al., 2002; Armstrong et al., 2008). On some days the water availability crossed the 100% threshold ($ET_a/ET_0 = 1$), which follows from $ET_a > ET_0$ (cf. Figure 2b, 2c). A connection was found between $ET_a > ET_0$ and precipitation events with cumulative amounts of >20 mm occurring a few days before. Between July 09 and July 11, for instance, a total rainfall of 30.9 mm was measured by the tipping bucket rain gauge. Within two days the water availability indices rose from 0.3 (ruderal vegetation) and 0.7 (pristine steppe) to 1.1, respectively. However, the virtual absence of precipitation led to a decrease of ET_a from August to September. During this period only 30 to 50% of ET_0 could be covered by ET_a. Due to the water stress, the deviations from observed data have increased. Hence, the PM FAO model overestimated ET_0 and indicated that the quality is strongly influenced by water availability. The PM FAO model is more suitable for short vegetation with permanent high water supply. As the growth stage constitutes an essential part within the ET_a process, the crop evapotranspiration may be a more appropriate approach because the crop canopy and aerodynamic resistance will be adapted to the reference crop. Though, the response to water stress cannot be reproduced since the method does not process information about soil water content. The issue of $ET_a > ET_0$ suggests that the calculated ET_0 reflects insufficiently the real water consumption of the vegetation (Roth et al., 2005). In such a case, plant-specific correction factors are necessary to derive ET_a from ET_0. This circumstance is again a proof that lysimeter measurements are qualified to improve model estimations (irrespective of model assumptions) because they provide reliable field data.

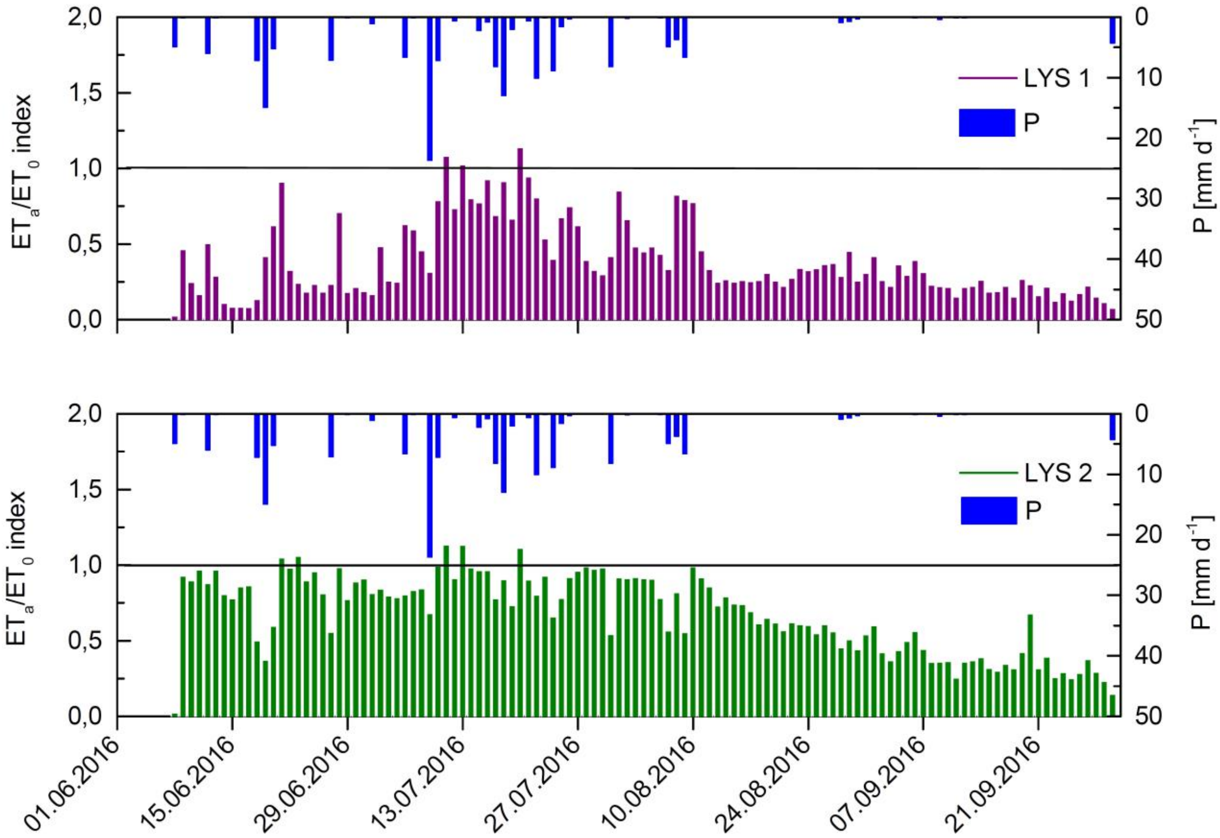

Figure 4. Illustration of the daily water availability between June and September 2016. The ET_a/ET_0 indices are related to the left axis; the upper bars are related to the right axis and show the daily sum of P measured by a tipping bucket rain gauge.

Although the study led to first scientific findings of ET_a for this site, further investigations are necessary. The major challenge is to get long-term data as measurements could not be executed so far over winter. Finally, a long-term study can enable to determine the local soil water balance and to evaluate the contribution of ET_a.

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