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**Key Points:**
- Nighttime evapotranspiration as determined with precision weighing lysimeters contributes annually up to 10% of daytime evapotranspiration
- Nighttime evapotranspiration can be predicted based on a modified parameterized Penman-Monteith model
- Wind was the most significant environmental driver for nighttime evapotranspiration

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# Quantification and Prediction of Nighttime Evapotranspiration for Two Distinct Grassland Ecosystems

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**Abstract** Evapotranspiration (*ET*) is, after precipitation, the second largest flux at the land surface in the water cycle and occurs mainly during daytime. Less attention has been given to water fluxes from the land surface into the atmosphere during nighttime (i.e., between sunset and sunrise). The nighttime *ET* ($ET_N$) may be estimated based on models that use meteorological data; however, due to missing experimental long-term data, the verification of $ET_N$ estimates is limited. In this paper, the amount of $ET_N$ for two grassland ecosystems was determined from highly temporally resolved and precise weighing lysimeter data. We found that annual $ET_N$ ranged between 3.5% and 9.5% of daytime annual *ET* ($ET_D$) and occurred mainly during wet soil and canopy surface conditions, which suggests that $ET_N$ is largely related to evaporation. $ET_N$ was positively correlated with wind speed. Dew formation, ranging from 4.8% to 6.4% of annual precipitation, was in absolute terms larger than $ET_N$. The prediction of $ET_N$ with the Penman-Monteith model improved if the aerodynamic and surface resistance parameters were based on vegetation height observations and the nighttime stomatal resistance parameter was assumed to be zero. The occurrence of hot days during the observation period showed to increase average $ET_N$ rates. Our results suggest that $ET_N$ can be observed with precision weighing lysimeters, was a not negligible component in the water balance of the grassland ecosystems, and thus needs more attention when simulating land surface hydrological processes.

## 1. Introduction

In the past, models often assumed that nighttime transpiration is negligible as the widespread stomatal optimization theory suggested that plants try to maximize their carbon gain while minimizing the water loss (Cowan & Farquhar, 1977). Traditionally, at the leaf level, stomata are assumed to be closed during nonphotosynthetic periods to prevent water loss through transpiration. Various observations showed an incomplete stomatal closure or sap flow during the night for a range of *C3* and *C4* species (Caird et al., 2007; Coupel-Ledru et al., 2016; Forster, 2014; O'Keefe, 2016; Rogiers et al., 2009), which involves a loss of water at night without carbon assimilation. Investigations reported that nighttime ecosystem transpiration could account in arid to semihumid conditions for 10–55% of the daytime transpiration, and hence, it contributes substantially to the total evapotranspiration (*ET*; Caird et al., 2007; Resco de Dios et al., 2015; Schoppach et al., 2014; Skaggs & Irmak, 2011; Tolk et al., 2006; K Wang & Dickinson, 2012). A recent simulation study with a global land-surface model (*CLM4.5SP*) considering updated nighttime stomatal conductance values showed that such an extension increased the transpiration by up to 5% globally and reduced soil moisture (Lombardozzi et al., 2017). This overnight increase in water use can result in a major reduction of water use efficiency (*WUE*) at the single plant and landscape level (Chaves et al., 2016), which can be determined by the ratio of yield and the seasonal *ET*. Moreover, extreme weather conditions like hot days or heat waves, which frequency is expected to increase due to climate change (Fischer & Schar, 2010), could affect nighttime transpiration and *WUE*. This increasing evidence suggests that nighttime transpiration significantly contributes to the water cycle. Resco de Dios et al. (2015) pointed out that nighttime water loss could have a higher impact on the global *ET* than current changes of *ET* by global warming.

Nighttime stomatal conductance or sap-flow measurements have been reported for a wide range of climate conditions (arid and humid), species, and ecosystem, but the environmental factors that regulate such nighttime water losses are still poorly understood (Zeppel et al., 2014). Eddy-covariance observations for three distinct ecosystems showed that the ratios of nighttime $ET$ ($ET_N$) to daytime $ET$ ($ET_D$) were dependent not only on the vegetation type but also on the seasonal environmental conditions (Novick et al., 2009). Leaf gas exchange, nocturnal stomatal conductance, or sap flow, which are associated with $ET_N$, was found to respond to exogenous atmospheric drivers like wind speed (Karpul & West, 2016), air temperature (Fisher et al., 2007), and vapor pressure deficit (Doronila & Forster, 2015; Fisher et al., 2007; Novick et al., 2009) and to depend on soil water (Howard & Donovan, 2007) and nutrient availability (Eller et al., 2017). But counteracting effects of different drivers prevented some authors from observing clear effects from single drivers (Fisher et al., 2007; Howard & Donovan, 2007). Models that are used to predict $ET_D$ from meteorological variables and a surface energy balance have not been tested yet for $ET_N$ predictions. Therefore, a better understanding and quantification of nighttime water flux in different ecosystems and for different environmental conditions is needed when trying to improve land surface hydrology.

The reported estimates of $ET_N$ were mostly based on measurements over a relatively short period, on a single plant, or under partially controlled atmospheric and soil conditions (e.g., Coupel-Ledru et al., 2016; Liu et al., 2015; Resco de Dios et al., 2015) and with different, often indirect methods. For instance, sap flow in trees during night may also be a result of recharge of depleted stem internal water storage (Dawson et al., 2007), so additional measurements, for example, leaf gas exchange and correction methods (e.g., Karpul & West, 2016) are necessary to estimate nighttime transpiration from sap flow. Sap-flow measurements are not necessarily related to transpiration (H. Wang et al., 2012), and observations can differ according to the technology used to measure sap flow (Forster, 2014). The disadvantage of using gas exchange measurements to estimate nighttime transpiration is that the measurements disturb the leaf surrounding environment and are limited in time, and samples represent only a relative small area of the ecosystem specific canopy (Ewers, 2013). The eddy-covariance method is often unsuitable to estimate $ET_N$, because of stable atmospheric and low wind conditions paired with relative small $ET$ fluxes during night (Pattey et al., 2002).

High-precision weighing lysimeters offer an alternative to obtain estimates of $ET_N$ over a long time period, under natural outdoor conditions, for nonwoody plants and a representative number of plants. Recent developments in lysimeter technology improved the precision of measurements, the temporal resolution of measurements, and the control of the lower boundary (Unold & Fank, 2008). The use of a dynamic tension controlled lower boundary condition based on field tension measurements enables water influx at the bottom during upward water flow conditions in the lysimeter soil. This can more realistically represent $ET$ processes in lysimeters under conditions of upward-directed water fluxes from shallow groundwater tables or deeper soil layers (Groh et al., 2016; Karimov et al., 2014; Schwaerzel & Bohl, 2003). In addition to technological improvements that enable measuring mass changes with high accuracy and temporal resolution, the data analysis has made substantial progress by developing quality checks and algorithms to reduce the impact of noise on lysimeter balance data (Küpper et al., 2017; Marek et al., 2014; Peters et al., 2014, 2017; Pütz et al., 2016). Hence, we used state of the art weighable lysimeter systems with a high temporal resolution and precision to quantify $ET_N$ and to investigate the following points:

1. What is the contribution of $ET_N$ to the total $ET$ on the seasonal and annual time scale in two low mountain range grassland ecosystems under a humid and temperate climate?
2. Which atmospheric- and soil-related drivers control nighttime and daytime $ET$?
3. Can approaches that are used to predict $ET$ based on meteorological variables and that are based on the land surface energy balance predict $ET_N$ and its contribution to the total $ET$?
4. To what extent is $ET_N$ increased during hot days and can this increase be predicted?

## 2. Materials and Methods

### 2.1. Site Description

The study was carried out at the grassland stations in Rollesbroich (50°37′12″N, 6°18′15″E, 515 m a.s.l.) and Wüstebach (50°30′10 ″N, 6°19′41″E, 625 m a.s.l.). Both are located in the TERENO Eifel/Lower Rhine Valley observatory in Germany and belong to the German wide lysimeter network *SOILCan* (Pütz et al., 2016). The vegetation on and around the lysimeters in Wüstebach, which is located in the Eifel National Park, corresponds to a natural forest meadow with no active land use. Main species are *Agrostis capillaris* and *Galium saxatile*. Beneath the grass and shrub canopy, a 5–10-cm-thick moss layer (*Rhytidiadelphus squarosus*) covers the lysimeter surfaces. The grassland vegetation on the lysimeters and

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the surrounding field at Rollesbroich is extensively managed with three to four cuts per growing season during the observation period from 1 January 2013 until 31 December 2016. In accordance to the local agricultural management of the surrounding grassland, liquid manure was applied (~1.6 L/m$^2$) two to three times per growing season. The plant canopy management (cutting and fertilizer) on the lysimeter in Rollesbroich was carefully adapted to their surrounding and regular measurements of grass height confirmed the representative height. The plant community consists mainly of *Lolium perenne* and *Trifolium repens*. Both sites have a humid temperate climate with a mean annual precipitation of 1,150 and 1,200 mm/year and a mean annual temperature of 8 and 7.5 °C for Rollesbroich and Wüstebach, respectively (Pütz et al., 2016).

Since December 2010, stations composed of six weighable, cylindrical, high-precision lysimeters (METER, Munich) each with a surface of 1 m$^2$ and a depth of 1.5 m were installed at both sites (see Figure 1). Each lysimeter was placed on three load cells with a 10-g resolution, which corresponds to water depth of ≈0.01 mm. The lysimeters have controlled bottom boundaries, which permit downward- and upward-directed water fluxes. The water flux across the bottom boundary is controlled by field measurements of soil water potentials at the corresponding depth (1.4 m) and hence contributes to a better representation of land surface fluxes (Groh et al., 2016). At both sites, the lysimeters contain undisturbed soil monoliths of a Stagnic Cambisol. The lysimeters were equipped with time-domain reflectometry probes (sensor: CS610 connected to a TDR100, both Campbell Scientific, North Logan, UT, USA) to measure soil moisture at 0.1-, 0.3-, and 0.5-m depth and heat fluxes plates (HFP-01, Hukseflux Thermal Sensors B.V., Delft, the Netherlands) to measure heat flux at 0.1-m depth. At each station, a net radiation sensor (LP Net07, Delta OHM S.r.L., Caselle di Sevazzano, Italy) was installed above one lysimeter. Beside the lysimeter stations, a weather station (WXT510, Vaisala Oyj, Helsinki, Finland) provides standard meteorological parameters on wind speed, air temperature, relative humidity, air pressure, and precipitation.

### 2.2. Lysimeter Data

We analyzed the land surface flux data, obtained from lysimeter mass data, for both sites and for four consecutive years (1 January 2013 until 31 December 2016) to quantify the $ET_N$. Lysimeter mass measurements are in general prone to external disturbances like animals, management operations, and wind. These can have a significant impact on land surface water flux rates derived from lysimeter mass data (Marek et al., 2014). The separation of precipitation, dew formation, and *ET* from lysimeter mass changes requires an appropriate data preprocessing and post-processing scheme to minimize the effect that external errors and noise have on the determination of land surface water fluxes. The 1-minutely recorded lysimeter raw data (mean value of six measurements per minute) first underwent an extensive manual and automated plausibility check (more details, see Groh et al., 2015; Küpper et al., 2017; Pütz et al., 2016). In the next step, we used the “adaptive window and threshold” filter (*AWAT*; Peters et al., 2017) to further reduce the impact of noisy lysimeter mass changes on the determination of land surface water fluxes. In order to separate precipitation from dew formation, increases of lysimeter mass that were not concurrent with tipping bucket measurements of rainfall were classified as dew formation (Fank & Unold, 2007; Meissner et al., 2007). The parameters of the *AWAT* filter were set to 31 min for the maximum window width, 0.2 mm for the maximum threshold, and 0.75 for the quantiles of the snap routine (see Peters et al., 2014, and Peters et al., 2017, for the definition of these parameters). The minimal resolution parameter in *AWAT* was set to 0.02 mm to account for lower lysimeter measurement accuracy than lysimeter precision (0.01 mm). A recent study by Peters et al. (2017) showed that a combined use of the *AWAT* filter and the implemented snap routine can quantify low water fluxes (e.g., 0.008 mm/hr) and can be used to quantify dew formation at both sites in Wüstebach and Rollesbroich (Groh, Slawitsch, et al., 2018; Groh, Stumpp, et al., 2018).

### 2.3. Definition of Evapotranspiration Fluxes

Evapotranspiration is generally defined as the water flux from the land surface to the atmosphere. Since an instantaneous measurement of this flux is not possible, the measured flux always represents a temporal average of the flux. Evapotranspiration is associated with a flux of water vapor from the land surface to the atmosphere. Under certain conditions, this water vapor flux might be directed from the atmosphere to the land surface and lead to dew formation. Jacobs et al. (2006) showed for a grassland site, located in the center of the Netherlands that dew formation occurred at nearly 70% of the nights per year. Since “averaged” fluxes may be defined in different ways and in order to avoid confusion about the interpretation of fluxes that

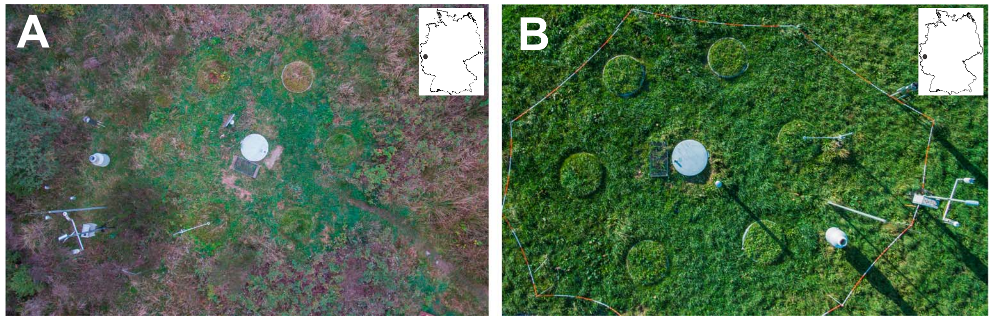


**Figure 1.** Lysimeter station at Wüstebach (a) and Rollesbroich (b). The map shows the location of the stations in Germany.

were defined at different time scales, we used one definition that we applied consistently for the different time scales. First, we split up the lysimeter data set of fluxes at the 1-min time scale in one subset with only positive and one subset with only negative fluxes. Based on this data set, time-averaged fluxes over 10 min (including the zero values) were calculated for upward-directed (evapotranspiration) and downward-directed water fluxes (precipitation and dew formation).

Since the photoperiod length and the intensity of light might affect the degree and velocity to which plants close their stomata during the night (Caird et al., 2007; Schwabe, 1952) and impact *ET*, average fluxes were calculated for the following periods:

1. Dawn evapotranspiration ($ET_{\mathrm{dawn}}$) during the period from nautical dawn (when the geometric center of the sun is 12° below the horizon) and sunrise (when the geometric center of the sun is at 0° relative to the horizon),
2. Dusk evapotranspiration ($ET_{\mathrm{dusk}}$) during the period between sunset (0° relative to the horizon) and nautical dusk (geometric center of the sun is 12° below the horizon),
3. Nocturnal evapotranspiration ($ET_{\mathrm{noc}}$) between nautical dusk and nautical dawn.
4. Nighttime evapotranspiration ($ET_{\mathrm{N}}$) between sunset and sunrise.
5. Daytime evapotranspiration ($ET_{\mathrm{D}}$) between sunrise and sunset.
6. Daily evapotranspiration (*ET*) from 00:00 until 24:00

The functions *sunriset* and *crepuscule* of the R software package *maptools* V0.9-2 (Bivand & Lewin-Koch, 2016), which are based on astronomical algorithms of Meeus (1991), were used to obtain the time of nautical dawn, sunrise, sunset, and nautical dusk for every day. Subsequently, hourly averages of $ET_{\mathrm{dawn}}$, $ET_{\mathrm{dusk}}$, $ET_{\mathrm{noc}}$, $ET_{\mathrm{N}}$, and $ET_{\mathrm{D}}$ were calculated for each day as well as monthly and annual cumulative fluxes.

### 2.4. Grass Reference Evapotranspiration

*ET* fluxes and dew formation measured by the lysimeters were compared with calculated *ET* and dew water fluxes from the "full-form" Penman-Monteith model (*PM*). The full-form *PM* model can be expressed according to the following equation:

$$\lambda ET_{\mathrm{PM}} = \frac{\Delta(R_{\mathrm{n}} - G) + \rho_{\mathrm{a}} c_{\mathrm{p}} \frac{(e_{\mathrm{s}} - e_{\mathrm{a}})}{r_{\mathrm{a}}}}{\left(\Delta + \gamma\left(1 + \frac{r_{\mathrm{s}}}{r_{a}}\right)\right)\rho_{\mathrm{w}}}, \quad (1)$$

where $ET_{\mathrm{PM}}$ is the evapotranspirative flux expressed as depth per unit time, $\Delta$ is the slope of the saturation vapor pressure temperature relationship (Pa/K), $R_{\mathrm{n}}$ the net radiation at the grass surface (W/m$^2$), $G$ the soil heat flux density at the soil surface (W/m$^2$), $\rho_{\mathrm{a}}$ the air density (kg/m$^3$), $c_{\mathrm{p}}$ the specific heat of moist air at constant pressure (J·K$^{-1}$·kg$^{-1}$), $e_{\mathrm{s}}$ the saturation vapor pressure at air temperature (Pa), $e_{\mathrm{a}}$ the actual vapor pressure (Pa), $r_a$ the aerodynamic resistance (s/m), $\gamma$ the psychrometric constant (Pa/K), $r_{\mathrm{s}}$ the bulk surface resistance (s/m), $\rho_{\mathrm{w}}$ is the density of liquid water (kg/m$^3$), and $\lambda$ the latent heat of vaporization (J/kg).

The advantage of the full-form *PM* model is that it can be applied to estimate the *ET* flux at locations with nonreference vegetation conditions, with varying vegetation and ground coverage during the different crop development stages. The required meteorological input parameters were obtained at each site from the lysimeter climate station to calculate reference $ET$ ($ET_{PM}$) on a temporal resolution of 10 min. Time series of sensed net radiation and soil heat flux (sensed at 0.1-m depth) were used in the model to estimate $ET_{PM}$. The term $G$ in the $PM$ model describes the diffusive heat flux at the soil surface, but $G$ is often determined with a sensor installed below the soil surface. Even though $G$ can be considered to be a relatively small term in the surface energy balance, various methods exist to correct measured fluxes for heat storage above the sensor plate, for example, by the calorimetric method (Evett et al., 2012). Data from a nearby TERENO Eddy-covariance station at Rollesbroich were used to exemplarily test the effect of $G$ on the calculation of $ET$ by the use of the $PM$ model with (i) near-surface measured heat fluxes (0.02 m, HFP-01, Hukseflux Thermal Sensors B.V., Delft, the Netherlands) and (ii) a correction of heat flux values sensed at 0.08-m depth (HFP-01, Hukseflux Thermal Sensors B.V., Delft, the Netherlands) to surface heat flux values based on the calorimetric method. The required data on soil temperature (TCAV, Campbell Scientific, North Logan, UT, USA) and soil moisture (CS616, Campbell Scientific, North Logan, UT, USA) were sensed in the layer between the surface and the sensor depth of 0.08 m to correct measured fluxes for heat storage above the sensor plate with the calorimetric method.

For the estimation of $r_a$ and $r_s$ variables, we used three distinct settings in the $PM$ model. First, we used the reference grass height of 0.12 m and a bulk stomatal resistance $r_1$ of 100 s/m to compute $r_a$ and $r_s$ according to Allen et al. (1998) from equations (2) and (3) and results from this approach are consequently called $PM_{FAO}$:

$$r_a = \frac{\ln\left[\frac{z_m - \frac{2}{3}h_{plant}}{0.123 h_{plant}}\right] \ln\left[\frac{z_h - \frac{2}{3}h_{plant}}{0.1\left(0.123 h_{plant}\right)}\right]}{k^2 u_2}, \tag{2}$$

$$r_s = \frac{r_1}{0.5\left(24\ h_{plant}\right)}, \tag{3}$$

where $z_m$ is the height of the wind measurement (m), $h_{plant}$ the grass height (m), $z_h$ the height of humidity measurements (m), $k$ the von Karman constant (−), $u_2$ the wind speed at 2-m height (m/s), and $r_1$ is a bulk stomatal resistance (s/m). In a second attempt ($PM_{r288}$), we calculated with the help of measured grass heights the variable $r_a$ and $r_s$. The additional values of $r_1$ for the estimation of $r_s$ from equation (3) was set according to Allen et al. (2006) to 72 s/m when the net radiation $R_n > 0$ and to 288 s/m when $R_n < 0$. The larger $r_1$ for nighttime calculations represents the effect of stomatal closure at night. In a third approach, we consider a value of zero for $r_1$ ($PM_{r0}$), when $R_n < 0$.

### 2.5. Statistical Analysis and Comparison Between *PM* and Lysimeter Derived *ET*

The measured annual cumulative $ET_N$, calculated from annual cumulative $ET_{dusk}$, $ET_{dawn}$, and $ET_{noc}$, was compared with calculated data using the full-form $PM$ model, to clarify how well the widely used approach could account for water losses and dew formation during nighttime. In a next step, monthly cumulative $ET_N$ and monthly average $ET_N$ rates were compared with $PM$ calculated values to investigate their intra-annual variability. The Wilcoxon rank-sum test between consecutive months of each test site was used to determine the significant differences between changes of $ET$ at night. The function *wilcox.test* of the R software package "stats" (R-Core-Team, 2016) was used for the statistical analysis.

Correlations between measured average (six lysimeters) and $PM$ calculated daily $ET$ rates were evaluated using the nonparametric Spearman correlation test function *cor.test* of the R software package "stats" (R-Core-Team, 2016). Spearman correlations were also calculated between measured dawn, dusk, nocturnal, and daytime $ET$ rates and the corresponding environmental conditions: soil moisture ($SWC$; $cm^3/cm^3$), soil heat flux ($G$; $MJ/m^2$), air temperature at 2 m ($T_a$; °C), soil temperature ($T_s$; °C), air pressure ($p$; hPa), relative humidity ($RH$, %), wind speed at 2 m ($u_2$; m/s), vapor pressure deficit ($VPD$; kPa), and net radiation ($R_n$; $MJ/m^2$). A nonparametric statistical test was chosen, because the residuals of the variables were not normally distributed. In all cases, the 95% confidence interval was considered as statistical significance level ($\rho < 0.05$). Spearman's rank correlation coefficients were classified from very strong to very weak according to the correlation strength scale of Overholser and Sowinski (2008).

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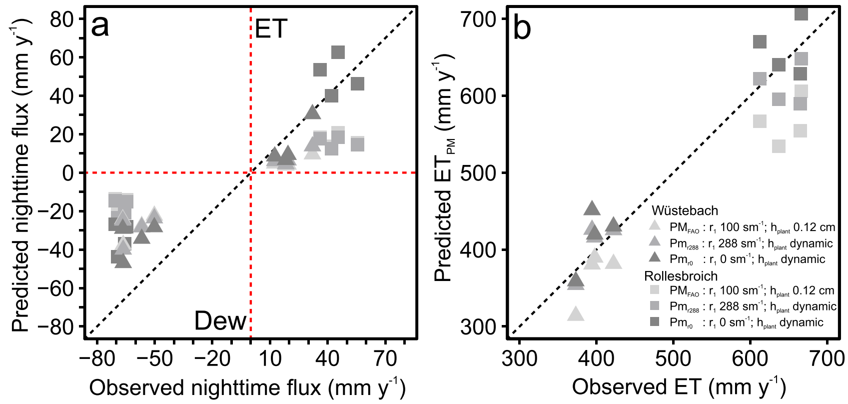


**Figure 2.** Scatterplot of calculated annual cumulative $ET_{PMN}$ (negative values represent dew) using different parameterizations ($PM_{FAO}$, $PM_{r288}$, and $PM_{r0}$) versus measured ones (a) entire nighttime (sunset to sunrise) and (b) day and night in Rollesbroich (square) and Wüstebach (triangle) for a period from 2013 to 2016.

## 3. Results and Discussion

### 3.1. Observation and Prediction of Nighttime Evapotranspiration at the Annual Scale

The total annual amounts of precipitation, obtained from six weighable lysimeters, for four consecutive years at the two low mountain range grassland locations ranged between 1,048 and 1,239 mm/year for Wüstebach and between 1,024 and 1,133 mm/year for Rollesbroich. Differences in cumulative annual land surface fluxes between both grassland ecosystems were notably larger for $ET$ than for precipitation. Annual cumulative $ET$ ranged between 373 and 422 mm/year for Wüstebach and 612 and 666 mm/year for Rollesbroich (see Figure 2b). Also cumulative $ET_N$ was on average 44.7 mm/year in Rollesbroich which was larger than the 20.5 mm/year in Wüstebach (see Table 1). The cumulative $ET_N$ ranged in Rollesbroich annually between 36.2 and 55.4 mm/year and in Wüstebach between 12.5 and 32.1 mm/year (Figure 2a). Average annual cumulative $ET_N$ was 7.5% and 5.5% of the $ET_D$ at Rollesbroich and Wüstebach, respectively.

Pearce et al. (1980) showed for an evergreen-mixed forest canopy that nighttime evaporation was mainly related to wet canopy surface conditions. Thus, we further separated nighttime water losses into $ET_N$ during wet or dry soil and canopy surface conditions. No data on surface wetness conditions were available to assess surface wetness of the canopy or soil (e.g., leaf wetness senor). Precipitation (1 hr before sunset) and dew formation data were used as a reasonable assumption to define if soil and canopy surface was wet or dry during nighttime. $ET_N$ during wet surface canopy conditions ($ET_{Nwet}$) was on average 16.95 and 42.03 mm/year at Wüstebach and Rollesbroich (Table 1), which accounts on average 83% and 94% of $ET_N$ at the corresponding test site. The $ET_N$ during dry canopy conditions ($ET_{Ndry}$) was on average with 3.56 and 2.68 mm/year clearly smaller than $ET_{Nwet}$ (Table 1). The higher $ET_N$ during wet surface conditions may indicate that $ET_N$ is largely evaporation of water from the surface canopy.

**Table 1**
*Average Observed and Predicted Cumulative Nighttime Evapotranspiration, Nighttime Evapotranspiration During Wet ($ET_{Nwet}$) and Dry ($ET_{Ndry}$) Soil and Canopy Surface Conditions, and Dew Formation (2013–2016) at Rollesbroich and Wüstebach*

| | Wüstebach | Rollesbroich | Wüstebach | Rollesbroich | Wüstebach | Rollesbroich | Wüstebach | Rollesbroich |
|---|---|---|---|---|---|---|---|---|
| | Average $ET_N$ (mm/year) | | Average $ET_{Nwet}$ (mm/year) | | Average $ET_{Ndry}$ (mm/year) | | Average dew formation (mm/year) | |
| Observation | 20.51 (±2.40) | 44.71 (±4.50) | 16.95 (±1.85) | 42.03 (±4.21) | 3.56 (±0.67) | 2.68 (±1.11) | 60.00 (±2.81) | 67.53 (±4.06) |
| $PM_{FAO}$ | 5.59 | 17.05 | 4.46 | 16.07 | 1.13 | 0.98 | 27.90 | 17.04 |
| $PM_{r288}$ | 7.69 | 15.77 | 6.22 | 14.83 | 1.47 | 0.94 | 29.22 | 18.50 |
| $PM_{r0}$ | 13.75 | 50.64 | 10.32 | 47.65 | 3.43 | 2.99 | 34.66 | 33.86 |

*Note.* Predictions of nighttime land surface water fluxes were done with Penman-Monteith model and three different parameterizations. The standard deviations between the lysimeters are given in parentheses.

Both annual $ET$ and $ET_N$ were much smaller in Wüstebach than in Rollesbroich. Previous investigations at the test site Rollesbroich showed that daytime ET measured by weighable lysimeters agreed well with $ET_D$ data obtained with the eddy-covariance method (Gebler et al., 2015), which demonstrated that lysimeter observations are representative for the surrounding area. The lysimeter station in Wüstebach is located on a clearing with natural forest meadow, and the surrounding area is covered by Norway Spruce (*Picea abis* L.). Thus, the station exposure and surrounding land use type in Wüstebach might reduce the $ET$. Our findings on $ET_N$ are in line with previous observations from Novick et al. (2009), which showed for a grassland ecosystem in Durham (North-Carolina, USA) that average cumulative $ET_N$ at the annual scale were 8% of the $ET_D$. Tolk et al. (2006) showed that measured $ET_N$ as percentage of $ET_D$ for one season was 3.1% for cotton crop and 7.8% for irrigated alfalfa. O'Keefe and Nippert (2018) showed that $ET_N$ expressed as percentage of $ET_D$ can be up to 35.5% at the daily scale in grasslands. Without any increase of biomass, this additional loss of water during night will reduce the *WUE* of ecosystems, which was exemplarily shown for grapevines in Medrano et al. (2015).

Compared to $ET$ values derived from lysimeter observations, the calculated $ET_{PM}$ during nighttime using the reference *FAO* parameterization (Food and Agriculture Organization, $PM_{FAO}$) were on average much smaller than the measured ones (see Table 1). Using the proposed method by Allen et al. (2006) to parametrize $r_a$ and $r_s$ in the *PM* model ($PM_{r288}$) for nonreference vegetation conditions led for Wüstebach in comparison to the $PM_{FAO}$ approach to a slightly larger average predicted annual $ET_{PMN}$ value (2.1 mm/year; see Table 1). However, for Rollesbroich, the parameterization of approach $PM_{r288}$ reduced the predicted $ET_{PMN}$ in comparison to $PM_{FAO}$ approach by 1.3 mm/year. Grass heights during autumn and winter were in general less than the reference value of 0.12 m in the $PM_{FAO}$ approach. Reducing vegetation height increased the value of $r_a$ and reduced at the same time the estimates of $ET$. Both *PM* model approaches largely underestimated $ET_N$ during wet surface conditions (see Table 1).

However, the best agreement between measured and estimated $ET_N$ was obtained using the full-form *PM* model, which accounts for nonreference vegetation conditions ($r_a$ and $r_s$) and a stomatal resistance of 0 s/m at night. The approach $PM_{r0}$ predicted on average annual cumulative $ET_{PMN}$ of 13.75 and 50.64 mm/year at Wüstebach and Rollesbroich, respectively. The modified *PM* model captured in comparison to the previous approaches also the observed average annual amount of $ET_N$ during wet and dry surface conditions relatively well. This demonstrates that a zero canopy bulk resistance value at night was a reasonable assumption to calculate evaporation processes for a vapor saturated canopy (Gavin & Agnew, 2000), caused by surface wetting events such as precipitation or dew formation. Dry surface conditions were rare at our site. Thus, the assumption of using zero bulk surface resistance value cannot be generalized for sites where dew formation is less frequent and dry surface conditions more prevalent.

This is in line with recent field studies for grassland sites, which indicate that both soil evaporation and plant transpiration contributed to $ET$ at night (Eichelmann et al., 2018; O'Keefe & Nippert, 2018). The differences in annual $ET$ measurements between the two sites were well reproduced by the *PM* model ($PM_{r0}$; see Figure 2b) and indicate that these differences were mainly due to different meteorological conditions at the two sites. No clear answer can be given on how much transpiration and evaporation contributed to $ET_N$ because lysimeter observations provide combined information on evaporation and transpiration. Thus, despite the large evidence of nighttime transpiration (Caird et al., 2007; Forster, 2014), we cannot exclude that nighttime water fluxes stems partially from evaporation processes from the soil or plant surface (dew rise, guttation, and canopy intercept) or the plant itself (stomata and cuticula). However, the analysis of $ET_N$ and surface conditions (wet or dry) might indicate that the majority of the annual $ET_N$ is related to evaporation from the wet soil and canopy surface (intercept).

So far, we used measured soil heat fluxes at 0.1 m below the surface as a proxy for soil heat fluxes at the surface. In a next step, we used measured $G$ at 0.02-m soil depth as proxy for soil heat fluxes at the surface in the $PM_{r0}$ approach exemplarily for the Rollesbroich site. Using near-surface measured heat flux in the *PM* model improved the prediction of $ET$ during nighttime slightly and achieved an average annual cumulative $ET_{PMN}$ of 49.9 mm/year (measured $ET_N$ = 44.71 mm/year and $ET_{PMN}$ using 0.1-m depth $G$ measurements = 50.64 mm/year). Correcting $G$ that is measured at 0.08 m by the calorimetric method increased the overestimation of $ET_{PMN}$ to an average annual value of 54.6 mm/year at Rollesbroich. Consequently, due to

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the lack of sensed near-surface $G$ at Wüstebach site and relative similar average annual cumulative $ET_{\mathrm{PM}}$ value, $G$ that was measured at 0.1 m in the lysimeters was used without correction in the $PM_{r0}$ to predict $ET$ at night.

In the absence of precipitation, the formation of dew at the soil and plant surface is the complementary process to $ET$ at night. To account for dew formation in our investigation, lysimeter data were also used to determine the formation of dew during different nighttimes. Annual cumulative dew formation at nighttime is depicted in Figure 2a. The average annual cumulative dew formation was 60.0 and 67.5 mm/year at Wüstebach and Rollesbroich, respectively. Compared to $ET$ and $ET_{\mathrm{N}}$, the difference in dew formation between both stations was much smaller. The dew formation was larger than $ET_{\mathrm{N}}$. The annual cumulative dew formation during night ranged between 50.2 and 66.6 mm/year in Wüstebach. The dew formation at Rollesbroich was larger than in Wüstebach and ranged annually between 64.7 and 70.7 mm/year. The analysis shows that dew corresponds on average to 5.1% and 6.2% of the total annual amount of precipitation at Wüstebach and Rollesbroich, respectively. This is in line with previous investigations at Rollesbroich (Groh, Slawitsch, et al., 2018), Wüstebach (Groh, Stumpp, et al., 2018), and other grasslands sites under humid climate conditions, which showed that dew contributes between 4.5% and 6.9% of the total annual precipitation (Heusinger & Weber, 2015; Jacobs et al., 2006; Xiao et al., 2009). The different parameterized $PM$ models were also used to predict dew formation. Also here the best agreement between measured and estimated dew formation was obtained using the full-form $PM$ model, which was parameterized ($PM_{r0}$) for nonreference vegetation conditions ($r_{\mathrm{a}}$ and $r_{\mathrm{s}}$) and a stomatal resistance of 0 s/m at night. The average annual dew formation predicted with $PM_{r0}$ was 34.66 and 33.86 mm/year for Wüstebach and Rollesbroich, respectively, and thus underestimated dew formation in comparison to observations at both sites.

### 3.2. Seasonal Patterns of Nighttime Evapotranspiration

Figure 3 depicts average monthly cumulative $ET_{\mathrm{N}}$, average daily duration of nighttime period, and average $ET_{\mathrm{N}}$ and $ET_{\mathrm{PMN}}$ rates for lysimeters of the two grassland ecosystems. Monthly $ET_{\mathrm{N}}$ showed a clear seasonal tendency with generally larger monthly cumulative $ET_{\mathrm{N}}$ values during November until March for both sites. The standard deviation shows the spatial variability of $ET_{\mathrm{N}}$ between the corresponding lysimeters. Between November and March, the variability between $ET_{\mathrm{N}}$ was in comparison to the other months somehow larger at Rollesbroich. The seasonal tendency was also visible from average $ET_{\mathrm{N}}$ rates and showed that larger $ET_{\mathrm{N}}$ during the nonvegetation season was not only related to the seasonal duration of the nighttime period. Comparing the monthly cumulative $ET_{\mathrm{N}}$ between consecutive months at each station showed significant differences between consecutive months during the season, for example, March to April and September to November (Wilcox-rank-sum test). The test showed no significant differences between consecutive monthly $ET_{\mathrm{N}}$ at Rollesbroich from November until March. For Wüstebach, however, changes in monthly $ET_{\mathrm{N}}$ were also significant during winter months. Thus, $ET_{\mathrm{N}}$ followed a distinct seasonal pattern over the year with significant changes between consecutive months. $ET_{\mathrm{PMN}}$ rates, obtained from approach $PM_{r0}$, agreed well with measured $ET_{\mathrm{N}}$ rates at Rollesbroich. For Wüstebach, however, the approach $PM_{r0}$ underestimated $ET_{\mathrm{PMN}}$ rates from May until December.

Seasonal patterns for average $ET_{\mathrm{N}}$ rates were also visible for single nighttime periods: dusk, nocturnal, and dawn (Figure 4). For both test sites, average $ET_{\mathrm{N}}$ rates in the nongrowing season (November–March) were larger than during the growing season and were generally fairly constant over the night period. Only at Rollesbroich during the growing season, the average $ET_{\mathrm{N}}$ was higher during dusk than during nocturnal or dawn periods. The magnitude and seasonal and nighttime dynamics of $ET_{\mathrm{N}}$, with larger $ET_{\mathrm{PMN}}$ rates during the nongrowing season at both sites and almost no systematic variations in $ET$ rates from dusk until dawn, were captured well by the $PM_{r0}$ approach. However, Figures 4a and 4b showed also that the modified $PM$ model ($PM_{r0}$) slightly overpredicted or underpredicted average $ET_{\mathrm{PMN}}$ rates, respectively, during the three different nighttime periods in comparison to observed average $ET_{\mathrm{N}}$ rates for Rollesbroich and Wüstebach.

The observed higher average $ET_{\mathrm{N}}$ rates during the nongrowing season are opposite to the seasonal tendency of daytime $ET$ rates, which were larger during the growing period. These observations are at first sight contradictory to the influence of daytime plant physiological processes on stomatal conductance at night

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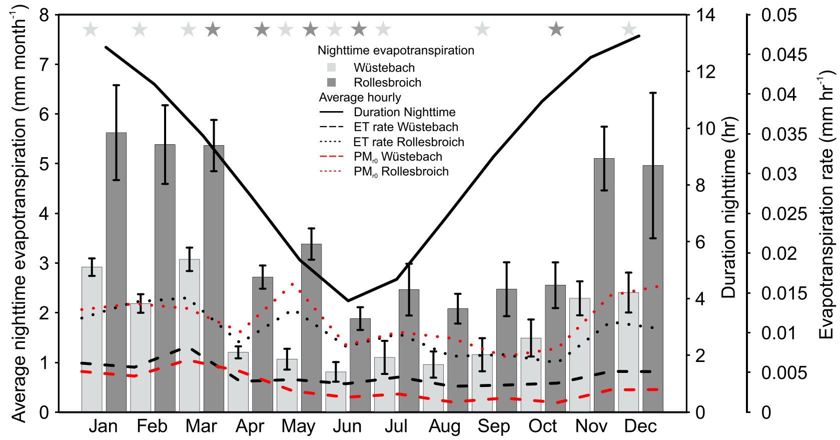


**Figure 3.** Average monthly cumulative evapotranspiration during nighttime for two different grassland ecosystems at Wüstebach and Rollesbroich. The observation period comprised observation from four consecutive years (2013–2016). The second *y* axis depicts the seasonal course of the nighttime duration (hr), the average rate of evapotranspiration, and reference evapotranspiration (mm/hr) per month. Significant differences (Wilcoxon rank-sum test) between the adjacent months of each site are indicated by a star.

(O'Keefe & Nippert, 2018). Recent investigations showed that carbohydrate supply regulates stomatal conductance at night and thus suggest that photosynthetic rates influence $ET_N$ of the following night (Easlon & Richards, 2009; Resco de Dios et al., 2015). Various studies also reported an increased endogenous stomatal opening during twilight hours (e.g., Bucci et al., 2005; Caird et al., 2007; Dodd et al., 2005; Resco de Dios et al., 2016) and would therefore suggest a higher $ET_N$ during dusk and dawn than during the nocturnal period. Again, our observations do not indicate that this process has an important influence on the nighttime *ET* at two grassland test sites. Moreover, our analysis indicates that observed $ET_N$ is largely evaporation of water from the soil or canopy surface (plant intercept). Thus, seasonal patterns of $ET_N$ might be stimulated by evaporation of water from wetter surface conditions during the nongrowing season (precipitation and especially dew formation). The good representation of the seasonal and nighttime dynamics of *ET* rates by the *PM* model reveals that meteorological conditions regulate the

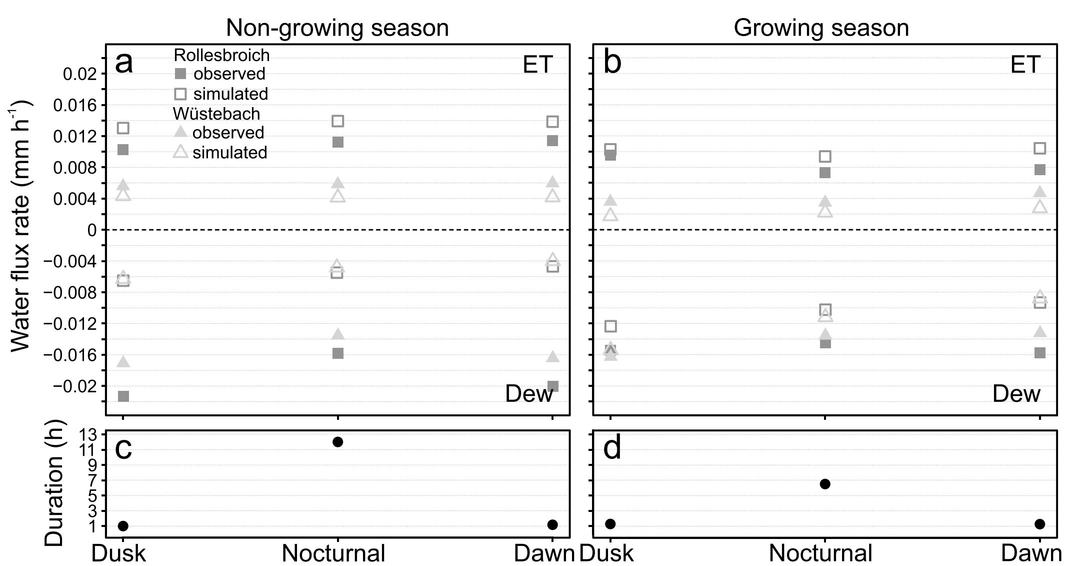


**Figure 4.** Average observed and predicted evapotranspiration rates at different nighttimes (dusk; nocturnal; and dawn) for two different grassland ecosystems at Wüstebach and Rollesbroich during the nongrowing (a) and growing season (b). (c) and (d) depicts the corresponding average daily duration of dusk, nocturnal, and dawn period during the non-growing and growing season.

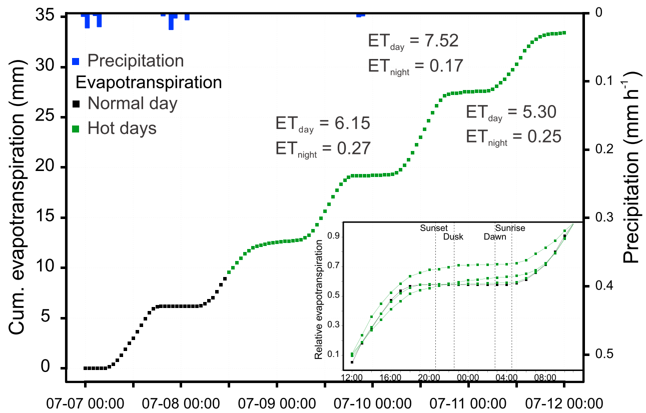


**Figure 5.** Cumulative evapotranspiration and precipitation rate for hot days (green marks) in July 2016 in Rollesbroich. The subplot depicts the relative cumulative evapotranspiration from 12 am until 11 am of the following day to show the continuous evapotranspiration for each night from 7 July 2016 until 11 July 2016. The vertical lines in the subplot represents the starting time of sunset, dusk, dawn, and sunrise (Central European Time Berlin).

seasonal and nighttime dynamics of $ET_N$ at our grassland sites. The fact that the best agreement between observed and *PM*-estimated $ET_N$ was obtained for a stomatal resistance of zero is a further indication that endogenous stomatal regulation did not control $ET_N$ at our grassland sites. Furthermore, the *PM* model ($PM_{r0}$) showed that $ET_{PMN}$ occurred largely after surfaces wetting events such as precipitation or dew formation, which generate soil and canopy surface conditions where nighttime surface resistance can be assumed as zero.

The average rates of dew formation showed a different dynamic during night than the *ET* rates with in general lowest average dew rates during nocturnal periods and an increase during dusk and dawn (Figures 4a and 4b). In contrast to the larger differences in $ET_N$ rates between grassland ecosystem in Wüstebach and Rollesbroich, the magnitude of dew rates was rather similar in both grassland ecosystems (Figures 4a and 4b). Comparing predicted with observed average dew rates demonstrated that the *PM* model could not reproduce the seasonal tendency of dew rates well and clearly underestimated the magnitude of dew rates, especially during the nongrowing season at both test sites (Figures 4a and 4b).

### 3.3. Impact of Hot Days on Nighttime Evapotranspiration

We followed the recommendations of De Boeck et al. (2010) and defined warm days as a marked unusual hot weather, when daily maximum air temperature ($T_{max}$) exceed the 90th percentile of $T_{max}$ of the time of the year. The analysis was only conducted for the summer period (1 June to 31 August). We relied on air temperature time series (1983–2016) from the nearby located meteorological station Simmerath (Data license Germany-Land NRW-Version 2.0) to obtain $T_{max}$ percentiles. In order to account for the impact of daily $T_{max}$ on the following night, the first day after a hot day was included additionally into our analysis. The analysis showed that 14% (53 days) and 12% (45 days) of the days between June and August from 2013 until 2016 were marked as hot days in Wüstebach and Rollesbroich, respectively. The higher percentages (higher than 10%) were consistent with observations from the meteorological station in Simmerath, which showed in comparison to the reference period (1983–2016) also an elevated amount of hot days during summer of the observation period (44 days; 2013–2016).

Figure 5 depicts exemplarily the cumulative *ET* and hourly precipitation rate from the 7 until 12 July 2016 and demonstrates the influence of hot days on $ET_N$ at Rollesbroich. The subplot from Figure 5 shows the relative hourly *ET* from 12 am until 11 am of the following day. Hot days with enhanced *ET* during nighttime periods are marked in green. During this time, the total daily *ET* was relatively large and reached on the 10 July 2016 a maximum value of 7.7 mm/day which was nearly 13% larger than the calculated $ET_{PM}$ value of 6.7 mm/day. The large observed daily *ET* might be related to an enhanced air entrainment in the atmospheric boundary layer (Moene & van Dam, 2014; van Heerwaarden et al., 2009). The *PM* model reproduced the observed *ET* ($ET_N$: 0.17 mm) at night well ($ET_{PMN}$: 0.15 mm) but underestimated *ET* processes at daytime by 1 mm.

The average $ET_N$ rates during hot and normal days in the summer are depicted for both stations in Figure 6. Average rates of $ET_N$ influenced by hot days were for both stations larger than during normal days. Larger average $ET_N$ rate after intense climate extremes (i.e., hot days) might be related to higher entrainment rates, which lead to a drying and warming of the boundary layer and thus higher *ET* rates (Moene & van Dam, 2014), than during normal days. Consistent with the results for annual (Figure 2 and Table 1) and monthly $ET_N$ (Figure 3), the $ET_N$ rates at normal and hot days were underestimated by the *PM* for Wüstebach and overestimated for Rollesbroich. During hot days, $ET_N$ reached values up to 0.31 and 0.38 mm/day per night for Wüstebach and Rollesbroich, respectively. Our results are in line with earlier findings from De Boeck et al. (2016) who showed for a single event that $ET_N$ ranged between 0.12 and 0.32 mm/day for grassland influenced by several hot days (heat wave). Duarte et al. (2016) showed for Douglas-fir that daytime and nighttime stomatal conductance was markedly affected during and after heat waves. Over all the

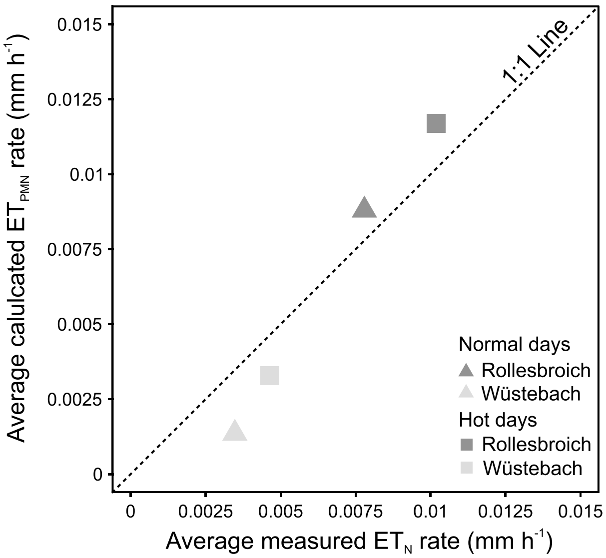


**Figure 6.** Average-measured and *PM*-calculated *ET* rates ($ET_{PM}$, $r_1 = 0$ s/m) for periods which were under the influence of hot days (squared) and normal days (triangle) from June to August (2013–2016) at Wüstebach and Rollesbroich.

considered summer periods, the $ET_N$ during hot days was 5.8 mm in Rollesbroich and 3 mm in Wüstebach which corresponds to 23% and 26% of the total summer $ET_N$ in, respectively, Rollesbroich and Wüstebach. Largest values were reaching in August 2015 at both sites, when $ET_N$ during hot days correspond to 55% and 59% of the total monthly $ET_N$. The relatively large contribution of $ET_N$ during hot days to the overall $ET_N$ during summer demonstrates the importance of hot days and of their expected increase due to climate change for the water balance and *WUE* of ecosystems. The good agreement between measured and predicted $ET_N$ rates with the *PM* model suggests that meteorological conditions are the main reason for large $ET_N$ rates during hot days at both sites. Therefore, our data could not confirm the effect of plant physiological changes due to higher temperatures on transpiration during night that were reported in other studies such as increased cuticular transpiration and incomplete stomatal closure (e.g. Claverie et al., 2017). $ET_N$ rates during dusk, nocturnal, and dawn also differed between hot and normal days, but no consistent change in the dynamics of the nighttime *ET* that could be linked to plant physiological reactions was observed.

### 3.4. Relationship Between Rates of Nighttime Evapotranspiration and Environmental Variables

The closeness of the relationship between dawn, dusk, nocturnal, and daytime *ET* rates, obtained from six lysimeters, and environmental drivers was expressed by the Spearman rank correlation coefficient ($\rho$). Results of the relationship between *ET* rates during dawn, dusk, and nocturnal period and environmental variables in Table 2 show similar patterns at Wüstebach and Rollesbroich. The variable wind speed ($u_2$) achieved with values of $\rho$ between 0.32 and 0.38 (positive weak) and 0.47 and 0.50 (positive moderate) the highest correlation with *ET* rates during different nighttimes at Wüstebach and Rollesbroich, respectively. These results agreed well with previous studies which showed that water losses during night were significantly related to $u_2$ (Irmak, 2011; Malek, 1992; Novick et al., 2009; Phillips et al., 2010; Skaggs & Irmak, 2011). Other variables typically affecting *ET*, like $R_n$, *RH*, and $T_a$, show little variation during the night. The variable $u_2$, in contrast, can still show high variability. Larger wind speeds and wet soil and surface conditions at night provide a higher exchange between air close to the grassland canopy and the lower atmosphere. Negative correlations between *RH* and nighttime *ET* rates at Rollesbroich suggest a removal of evaporated or transpired water vapor and immediate replacement with drier air from the free atmosphere (Meinzer et al., 1995), because the boundary layer is in reality not a closed system (Moene & van Dam, 2014). Dry air entrainment represents a loss of humidity from the boundary layer and enhances surface evaporation (van Heerwaarden et al., 2009). But analysis for at least Rollesbroich showed only a weak negative correlation between *RH* and *ET* rates at night. This might be related to the measurement height of *RH*, as nocturnal air humidity changes steeply between the vegetation canopy and the observation height of *RH* at 2 m. The *SWC* showed for both stations a weak positive correlation with *ET* rates at night. Higher availability of water in the soil enhances plant water uptake (Fuentes et al., 2013; Howard & Donovan, 2007) and evaporation at night. The variables $R_n$, *p*, *G*, and *VPD* showed partially also weak relationships with *ET* rates at different nighttimes at both sites. Predicted *ET* rates at dawn, dusk, and nocturnal agreed in general well with the observed average *ET* rates. The correlations coefficients $\rho$ were positive and ranged for Rollesbroich between moderate and strong and in Wüstebach between weak and moderate.

During the day, average $ET_D$ rates were mainly governed by the environmental variables $R_n$ and *VPD* (both very strong correlations) which agrees well with previous studies (Liu et al., 2015; Pereira et al., 2014; H. Wang et al., 2012). Variables like *RH*, $T_a$, and $T_s$ showed a strong correlation with average $ET_D$ rates. Predicted daytime *ET* rates showed for both stations a very strong correlation with observed daytime *ET* rates. The result suggests that the modified *PM* model can be used to predict *ET* processes not only at daytimes but also at different nighttimes. The good agreement between measured and predicted *ET* rates

**Table 2**
*Relationship Between Dawn, Dusk, Nocturnal, and Daytime ET Rates, Environmental Variables, and Predicted Reference Evapotranspiration ($ET_{PM}$, Penman-Monteith Model)*

| | Spearman rank correlation coefficient ($\rho$) Rollesbroich | | | | Spearman rank correlation coefficient ($\rho$) Wüstebach | | | |
|---|---|---|---|---|---|---|---|---|
| | Evapotranspiration rates | | | | Evapotranspiration rates | | | |
| Variable | Nocturnal | Dawn | Daytime | Dusk | Nocturnal | Dawn | Daytime | Dusk |
| $VPD$ | 0.13 | 0.25 | 0.88 | 0.10 | −0.03* | 0.04* | 0.90 | −0.05* |
| $G$ | 0.15 | 0.27 | 0.63 | −0.01* | −0.12 | 0.08 | 0.64 | −0.20 |
| $R_n$ | 0.14 | 0.30 | 0.88 | 0.11 | 0.17 | 0.35 | 0.90 | 0.16 |
| $RH$ | −0.27 | −0.36 | −0.75 | −0.18 | −0.03* | −0.09 | −0.81 | −0.00* |
| $u_2$ | 0.48 | 0.50 | −0.33 | 0.47 | 0.37 | 0.38 | −0.27 | 0.32 |
| $T_a$ | −0.06 | −0.00* | 0.72 | −0.03* | −0.11 | −0.06* | 0.77 | −0.12 |
| $p$ | −0.24 | −0.29 | 0.18 | −0.15 | −0.17 | −0.22 | 0.26 | −0.13 |
| $SWC$ | 0.27 | 0.24 | −0.59 | 0.11 | 0.23 | 0.20 | −0.57 | 0.20 |
| $T_s$ | −0.16 | −0.19 | 0.72 | −0.07* | −0.08 | −0.09 | 0.72 | −0.13 |
| $ET_{PM}$ | 0.56 | 0.65 | 0.91 | 0.62 | 0.35 | 0.50 | 0.92 | 0.32 |

*Note*. Environmental variables are the following: vapor pressure deficit ($VPD$), soil heat flux ($G$), net radiation ($R_n$), relative humidity ($RH$), wind speed ($u_2$), air temperature ($T_a$), air pressure ($p$), soil water content 0.1 m ($SWC$), and soil temperature 0.1 m ($T_s$). The relationship is expressed by Spearman's rank correlation coefficient ($\rho$) on a significance level of 0.05.
*No significance.

suggests in addition that soil water did not limit *ET* at these sites. Our study thus suggests that *ET* rates of two low grassland ecosystems are controlled by distinct environmental variables during day and night.

## 4. Conclusions

We determined nighttime evapotranspiration ($ET_N$) for two grassland ecosystems by the use of highly temporally resolved precision weighing lysimeter data. $ET_N$ ranged on a yearly basis between 12.5 and 32.1 mm/year at Wüstebach and between 36.2 and 55.4 mm/year at Rollesbroich, which corresponds with 3.5–8.9% and 6.3–9.5% of the daytime *ET* at Wüstebach and Rollesbroich grassland sites, respectively. The seasonality of $ET_N$ was closely related to meteorological conditions and was in general larger during the nongrowing season. About 83% and 94% of the average annual $ET_N$ occurred during wet surface conditions at Wüstebach and Rollesbroich and suggest that nighttime *ET* is largely evaporation. Lysimeter data were also used to quantify dew formation, which can be considered to be an opposite water flux to nighttime *ET*. The analysis showed that annual dew formation (60 and 68 mm/year at Wüstebach and Rollesbroich, respectively) was at both sites larger in absolute terms than $ET_N$. Also annual dew formation is a relevant component of the water balance in Wüstebach and Rollesbroich (5.1% and 6.2% of precipitation). These results indicate that nighttime *ET* and dew formation need to be considered in ecosystem water balance and *WUE* calculations.

Our investigation suggested that the *PM* model to calculate $ET_{PM}$ on a 10-min basis could be used to estimate $ET_N$ if the stomatal resistance parameter was set to zero at night and the actual vegetation height was considered. The zero stomatal resistivity implies that nighttime evapotranspiration at our sites took place from a vapor saturated canopy and was not restricted by stomatal closure or other plant physiological controls on transpiration. This may also explain why we did not observe a general response of nighttime *ET* to stomatal opening during twilight or to changes of stomatal opening, stomatal controls, or other plant physiological changes in response to extreme weather conditions (e.g., high temperatures). But we anticipate that for drier sites, the parameterization of the *PM* model might have to be adapted to account for plant physiological controls on transpiration. The modified parametrization of the *PM* model also improved the prediction of dew in comparison to the traditional *FAO* parametrization; however, predictions for the nongrowing season require further improvements.

The correlation analysis between *ET* rate and environmental variables at different times of the day revealed that wind was the most significant driver for *ET* at night. *ET* rates during daytime were mainly controlled by the available energy and gradient in vapor pressure between plant and atmosphere. Despite the fact that air temperature did not show a correlation with $ET_N$, measured and *PM* calculated $ET_N$ after hot days in summer were considerably larger than during other days in summer. Here again, a modified parameterization of the *PM* model using $r_s = 0$ gave the best results and plant responses to high temperatures were not observed in the $ET_N$ data. But, at drier sites, plant controls on $ET_N$ may become important. Future studies about the impact of climate change, which generally corresponds with an increased occurrence of hot days, on ecosystem water balances and water use efficiencies should consider the increase in $ET_N$. High-precision weighing lysimeter stations at drier locations could in this perspective provide relevant information for unraveling the impact of increased temperature and reduced water availability on daytime and nighttime *ET* and dew formation.

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