Water Resources Research

RESEARCH ARTICLE

10.1029/2018WR024072

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

Correspondence to:

J. Groh,
j.groh@fz-juelich.de

Citation:

Groh, J., Pütz, T., Gerke, H. H., Vanderborght, J., & Vereecken, H. (2019). Quantification and prediction of nighttime evapotranspiration for two distinct grassland ecosystems. *Water Resources Research*, 55. <https://doi.org/10.1029/2018WR024072>

Received 31 OCT 2017

Accepted 16 MAR 2019

Accepted article online 21 MAR 2019

Quantification and Prediction of Nighttime Evapotranspiration for Two Distinct Grassland Ecosystems

J. Groh^{1,2} , T. Pütz¹ , H. H. Gerke² , J. Vanderborght¹ , and H. Vereecken¹

¹Institute of Bio- and Geoscience IBG-3: Agrosphere, Forschungszentrum Jülich GmbH, Jülich, Germany, ²Research Area 1 “Landscape Functioning”, Working Group “Hydropedology”, Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany

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 (Pattay 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

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 ($\sim 1.6 \text{ L/m}^2$) 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 $\approx 0.01 \text{ mm}$. 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 Sezzano, 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_{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_{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_{noc}) between nautical dusk and nautical dawn.
4. Nighttime evapotranspiration (ET_N) between sunset and sunrise.
5. Daytime evapotranspiration (ET_D) between sunrise and sunset.
6. Daily evapotranspiration (ET) from 00:00 until 24:00

The functions *sunrise* 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_{dawn} , ET_{dusk} , ET_{noc} , ET_N , and ET_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:

$$\lambda ET_{PM} = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\left(\Delta + \gamma \left(1 + \frac{r_s}{r_a}\right)\right) \rho_w}, \quad (1)$$

where ET_{PM} is the evapotranspirative flux expressed as depth per unit time, Δ is the slope of the saturation vapor pressure temperature relationship (Pa/K), R_n the net radiation at the grass surface (W/m^2), G the soil heat flux density at the soil surface (W/m^2), ρ_a the air density (kg/m^3), c_p the specific heat of moist air at constant pressure ($\text{J}\cdot\text{K}^{-1}\cdot\text{kg}^{-1}$), e_s the saturation vapor pressure at air temperature (Pa), e_a the actual vapor pressure (Pa), r_a the aerodynamic resistance (s/m), γ the psychrometric constant (Pa/K), r_s the bulk surface resistance (s/m), ρ_w is the density of liquid water (kg/m^3), and λ 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 (Evelt 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} :

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

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

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 ; $^{\circ}\text{C}$), soil temperature (T_s ; $^{\circ}\text{C}$), 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).

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 sensor). 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 Average ET_N (mm/year)	Rollesbroich Average ET_N (mm/year)	Wüstebach Average ET_{Nwet} (mm/year)	Rollesbroich Average ET_{Nwet} (mm/year)	Wüstebach Average ET_{Ndry} (mm/year)	Rollesbroich Average ET_{Ndry} (mm/year)	Wüstebach Average dew formation (mm/year)	Rollesbroich 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 abies* 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

the lack of sensed near-surface G at Wüstebach site and relative similar average annual cumulative ET_{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_N , the difference in dew formation between both stations was much smaller. The dew formation was larger than ET_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_a and r_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_N , average daily duration of nighttime period, and average ET_N and ET_{PMN} rates for lysimeters of the two grassland ecosystems. Monthly ET_N showed a clear seasonal tendency with generally larger monthly cumulative ET_N values during November until March for both sites. The standard deviation shows the spatial variability of ET_N between the corresponding lysimeters. Between November and March, the variability between ET_N was in comparison to the other months somehow larger at Rollesbroich. The seasonal tendency was also visible from average ET_N rates and showed that larger ET_N during the nonvegetation season was not only related to the seasonal duration of the nighttime period. Comparing the monthly cumulative ET_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 (Wilcoxon-rank-sum test). The test showed no significant differences between consecutive monthly ET_N at Rollesbroich from November until March. For Wüstebach, however, changes in monthly ET_N were also significant during winter months. Thus, ET_N followed a distinct seasonal pattern over the year with significant changes between consecutive months. ET_{PMN} rates, obtained from approach PM_{r0} , agreed well with measured ET_N rates at Rollesbroich. For Wüstebach, however, the approach PM_{r0} underestimated ET_{PMN} rates from May until December.

Seasonal patterns for average ET_N rates were also visible for single nighttime periods: dusk, nocturnal, and dawn (Figure 4). For both test sites, average ET_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_N was higher during dusk than during nocturnal or dawn periods. The magnitude and seasonal and nighttime dynamics of ET_N , with larger ET_{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_{PMN} rates, respectively, during the three different nighttime periods in comparison to observed average ET_N rates for Rollesbroich and Wüstebach.

The observed higher average ET_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

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 (ρ). 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 ρ 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 ρ 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)

Variable	Spearman rank correlation coefficient (ρ) Rollesbroich				Spearman rank correlation coefficient (ρ) Wüstebach			
	Evapotranspiration rates				Evapotranspiration rates			
	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 (ρ) 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.

Acknowledgments

We acknowledge the support of TERENO and SOILCan, which were funded by the Helmholtz Association (HGF) and the Federal Ministry of Education and Research (BMBF). We want to thank Werner Küpper, Ferdinand Engels, Leander Fürst, and Phillip Meulendick for the ongoing maintenance of the experimental setup. Thanks to Alexander Graf for helpful discussions and constructive comments. All data for the specific lysimeter and weather station (raw data) can be freely obtained from the TERENO data portal (<https://teodoor.icg.kfa-juelich.de/ibg3searchportal2/index.jsp>; lysimeter station Rollesbroich RO_Y_01 and Wüstebach WU_Y_01), and processed data necessary to reproduce the reported findings are also available from TERENO data portal (<https://hdl.handle.net/20.500.11952/et.nighttime>).

References

- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration—Guidelines for computing crop water requirements in FAO irrigation and drainage papers (Vol. 56, pp. XXVI, 300 S). FAO, Rome: Food and Agriculture Organization of the United States.
- Allen, R. G., Pruitt, W. O., Wright, J. L., Howell, T. A., Ventura, F., Snyder, R., et al. (2006). A recommendation on standardized surface resistance for hourly calculation of reference ET_o by the FAO56 Penman-Monteith method. *Agricultural Water Management*, 81(1–2), 1–22. <https://doi.org/10.1016/j.agwat.2005.03.007>
- Bivand, R., & Lewin-Koch, N. (2016). maptools: Tools for reading and handling spatial objects. R package version 0.8–39. Retrieved from <https://CRAN.R-project.org/package=maptools>
- Bucci, S. J., Goldstein, G., Meinzer, F. C., Franco, A. C., Campanello, P., & Scholz, F. G. (2005). Mechanisms contributing to seasonal homeostasis of minimum leaf water potential and predawn disequilibrium between soil and plant water potential in Neotropical savanna trees. *Trees*, 19(3), 296–304. <https://doi.org/10.1007/s00468-004-0391-2>
- Caird, M. A., Richards, J. H., & Donovan, L. A. (2007). Nighttime stomatal conductance and transpiration in C3 and C4 plants. *Plant Physiology*, 143(1), 4–10. <https://doi.org/10.1104/pp.106.092940>
- Chaves, M. M., Costa, J. M., Zarrouk, O., Pinheiro, C., Lopes, C. M., & Pereira, J. S. (2016). Controlling stomatal aperture in semi-arid regions—The dilemma of saving water or being cool? *Plant Science*, 251, 54–64. <https://doi.org/10.1016/j.plantsci.2016.06.015>
- Claverie, E., Meunier, F., Javaux, M., & Sadok, W. (2017). Increased contribution of wheat nocturnal transpiration to daily water use under drought. *Physiologia Plantarum*, 162(3), 290–300. <https://doi.org/10.1111/ppl.12623>
- CoupeL-Ledru, A., Lebon, E., Christophe, A., Gallo, A., Gago, P., Pantin, F., et al. (2016). Reduced nighttime transpiration is a relevant breeding target for high water-use efficiency in grapevine. *Proceedings of the National Academy of Sciences of the United States of America*, 113(32), 8963–8968. <https://doi.org/10.1073/pnas.1600826113>
- Cowan, I. R., & Farquhar, G. D. (1977). Stomatal function in relation to leaf metabolism and environment: Stomatal function in the regulation of gas exchange, Paper presented at Symposia of the Society for Experimental Biology, February 1977.
- Dawson, T. E., Burgess, S. S. O., Tu, K. P., Oliveira, R. S., Santiago, L. S., Fisher, J. B., et al. (2007). Nighttime transpiration in woody plants from contrasting ecosystems. *Tree Physiology*, 27(4), 561–575. <https://doi.org/10.1093/treephys/27.4.561>
- De Boeck, H. J., Bassin, S., Verlinden, M., Zeiter, M., & Hiltbrunner, E. (2016). Simulated heat waves affected alpine grassland only in combination with drought. *New Phytologist*, 209(2), 531–541. <https://doi.org/10.1111/nph.13601>
- De Boeck, H. J., Dreesen, F. E., Janssens, I. A., & Nijs, I. (2010). Climatic characteristics of heat waves and their simulation in plant experiments. *Global Change Biology*, 16(7), 1992–2000. <https://doi.org/10.1111/j.1365-2486.2009.02049.x>
- Dodd, A. N., Salathia, N., Hall, A., Kévei, E., Tóth, R., Nagy, F., et al. (2005). Plant circadian clocks increase photosynthesis, growth, survival, and competitive advantage. *Science*, 309(5734), 630–633. <https://doi.org/10.1126/science.1115581>
- Doronila, A. I., & Forster, M. A. (2015). Performance measurement via sap flow monitoring of three eucalyptus species for mine site and dryland salinity phytoremediation. *International Journal of Phytoremediation*, 17(2), 101–108. <https://doi.org/10.1080/15226514.2013.850466>
- Duarte, A. G., Katata, G., Hoshika, Y., Hossain, M., Kreuzwieser, J., Arneth, A., & Ruehr, N. K. (2016). Immediate and potential long-term effects of consecutive heat waves on the photosynthetic performance and water balance in Douglas-fir. *Journal of Plant Physiology*, 205, 57–66. <https://doi.org/10.1016/j.jplph.2016.08.012>
- Easlon, H. M., & Richards, J. H. (2009). Photosynthesis affects following night leaf conductance in Vicia faba. *Plant, Cell & Environment*, 32(1), 58–63. <https://doi.org/10.1111/j.1365-3040.2008.01895.x>
- Eichelmann, E., Hemes, K. S., Knox, S. H., Oikawa, P. Y., Chamberlain, S. D., Sturtevant, C., et al. (2018). The effect of land cover type and structure on evapotranspiration from agricultural and wetland sites in the Sacramento–San Joaquin River Delta, California. *Agricultural and Forest Meteorology*, 256–257, 179–195. <https://doi.org/10.1016/j.agrformet.2018.03.007>
- Eller, F., Jensen, K., & Reisdorff, C. (2017). Nighttime stomatal conductance differs with nutrient availability in two temperate floodplain tree species. *Tree Physiology*, 37(4), 428–440. <https://doi.org/10.1093/treephys/tpw113>
- Evet, S. R., Agam, N., Kustas, W. P., Colaizzi, P. D., & Schwartz, R. C. (2012). Soil profile method for soil thermal diffusivity, conductivity and heat flux: Comparison to soil heat flux plates. *Advances in Water Resources*, 50(Supplement C), 41–54. <https://doi.org/10.1016/j.advwatres.2012.04.012>
- Ewers, B. E. (2013). Understanding stomatal conductance responses to long-term environmental changes: A Bayesian framework that combines patterns and processes. *Tree Physiology*, 33(2), 119–122. <https://doi.org/10.1093/treephys/tpi008>
- Fank, J., & Unold, G. (2007). High-precision weighable field Lysimeter—A tool to measure water and solute balance parameters. *International Water and Irrigation*, 27(3), 28–32.
- Fischer, E. M., & Schar, C. (2010). Consistent geographical patterns of changes in high-impact European heatwaves. *Nature Geoscience*, 3(6), 398–403. <https://doi.org/10.1038/ngeo866>
- Fisher, J. B., Baldocchi, D. D., Misson, L., Dawson, T., & Goldstein, A. H. (2007). What the towers don't see at night: Nocturnal sap flow in trees and shrubs at two AmeriFlux sites in California. *Tree Physiology*, 27(4), 597–610. <https://doi.org/10.1093/treephys/27.4.597>
- Forster, M. A. (2014). How significant is nocturnal sap flow? *Tree Physiology*, 34(7), 757–765. <https://doi.org/10.1093/treephys/tpu051>
- Fuentes, S., Mahadevan, M., Bonada, M., Skewes, M. A., & Cox, J. W. (2013). Night-time sap flow is parabolically linked to midday water potential for field-grown almond trees. *Irrigation Science*, 31(6), 1265–1276. <https://doi.org/10.1007/s00271-013-0403-3>

- Gavin, H., & Agnew, C. T. (2000). Estimating evaporation and surface resistance from a wet grassland. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 25(7-8), 599–603. [https://doi.org/10.1016/S1464-1909\(00\)00071-X](https://doi.org/10.1016/S1464-1909(00)00071-X)
- Gebler, S., Hendricks Franssen, H. J., Pütz, T., Post, H., Schmidt, M., & Vereecken, H. (2015). Actual evapotranspiration and precipitation measured by lysimeters: A comparison with eddy covariance and tipping bucket. *Hydrology and Earth System Sciences*, 19(5), 2145–2161. <https://doi.org/10.5194/hess-19-2145-2015>
- Groh, J., Slawitsch, V., Herndl, M., Graf, A., Vereecken, H., & Pütz, T. (2018). Determining dew and hoar frost formation for a low mountain range and alpine grassland site by weighable lysimeter. *Journal of Hydrology*, 563, 372–381. <https://doi.org/10.1016/j.jhydrol.2018.06.009>
- Groh, J., Stumpp, C., Lücke, A., Pütz, T., Vanderborght, J., & Vereecken, H. (2018). Inverse estimation of soil hydraulic and transport parameters of layered soils from water stable isotope and lysimeter data. *Vadose Zone Journal*, 17(1). <https://doi.org/10.2136/vzj2017.09.0168>
- Groh, J., Vanderborght, J., Pütz, T., & Vereecken, H. (2015). Estimation of evapotranspiration and crop coefficient of an intensively managed grassland ecosystem with lysimeter measurements. (In English with German abstract.). Paper presented at 16. Gumpensteiner Lysimetertagung, Raumberg-Gumpenstein.
- Groh, J., Vanderborght, J., Pütz, T., & Vereecken, H. (2016). How to control the lysimeter bottom boundary to investigate the effect of climate change on soil processes? *Vadose Zone Journal*, 15(7). <https://doi.org/10.2136/vzj2015.08.0113>
- Heusinger, J., & Weber, S. (2015). Comparative microclimate and dewfall measurements at an urban green roof versus bitumen roof. *Building and Environment*, 92, 713–723. <https://doi.org/10.1016/j.buildenv.2015.06.002>
- Howard, A. R., & Donovan, L. A. (2007). Helianthus nighttime conductance and transpiration respond to soil water but not nutrient availability. *Plant Physiology*, 143(1), 145–155. <https://doi.org/10.1104/pp.106.089383>
- Irmak, S. (2011). Dynamics of nocturnal, daytime, and sum-of-hourly evapotranspiration and other surface energy fluxes over nonstressed maize canopy. *Journal of Irrigation and Drainage Engineering*, 137(8), 475–490. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000360](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000360)
- Jacobs, A. F. G., Heusinkveld, B. G., Wichink Kruit, R. J., & Berkowicz, S. M. (2006). Contribution of dew to the water budget of a grassland area in the Netherlands. *Water Resources Research*, 42, W03415. <https://doi.org/10.1029/2005WR004055>
- Karimov, A. K., Šimůnek, J., Hanjra, M. A., Avliyakulov, M., & Forkutsa, I. (2014). Effects of the shallow water table on water use of winter wheat and ecosystem health: Implications for unlocking the potential of groundwater in the Fergana Valley (Central Asia). *Agricultural Water Management*, 131, 57–69. <https://doi.org/10.1016/j.agwat.2013.09.010>
- Karpul, R. H., & West, A. G. (2016). Wind drives nocturnal, but not diurnal, transpiration in *Leucospermum conocarpodendron* trees: Implications for stilling on the Cape Peninsula. *Tree Physiology*, 36(8), 954–966. <https://doi.org/10.1093/treephys/tpw033>
- Küpper, W., Groh, J., Fürst, L., Meulendick, P., Vereecken, H., & Pütz, T. (2017). TERENO-SOILCan-Management eines deutschland-weiten Lysimeternetzwerkes. (In German.) Paper presented at 17. Gumpensteiner Lysimetertagung, Raumberg-Gumpenstein.
- Liu, X., Li, Y., Chen, X., Zhou, G., Cheng, J., Zhang, D., et al. (2015). Partitioning evapotranspiration in an intact forested watershed in southern China. *Ecohydrology*, 8(6), 1037–1047. <https://doi.org/10.1002/eco.1561>
- Lombardozzi, D. L., Zeppel, M. J. B., Fisher, R. A., & Tawfik, A. (2017). Representing nighttime and minimum conductance in CLM4.5: Global hydrology and carbon sensitivity analysis using observational constraints. *Geoscientific Model Development*, 10(1), 321–331. <https://doi.org/10.5194/gmd-10-321-2017>
- Malek, E. (1992). Night-time evapotranspiration vs. daytime and 24h evapotranspiration. *Journal of Hydrology*, 138(1-2), 119–129. [https://doi.org/10.1016/0022-1694\(92\)90159-S](https://doi.org/10.1016/0022-1694(92)90159-S)
- Marek, W. G., Evett, R. S., Gowda, H. P., Howell, A. T., Copeland, S. K., & Baumhardt, R. L. (2014). Post-processing techniques for reducing errors in weighing Lysimeter evapotranspiration (ET) datasets. *Transactions of the ASABE*, 57(2), 499–515. <https://doi.org/10.13031/trans.57.10433>
- Medrano, H., Tomás, M., Martorell, S., Flexas, J., Hernández, E., Rosselló, J., et al. (2015). From leaf to whole-plant water use efficiency (WUE) in complex canopies: Limitations of leaf WUE as a selection target. *The Crop Journal*, 3(3), 220–228. <https://doi.org/10.1016/j.cj.2015.04.002>
- Meeus, J. (1991). *Astronomical algorithms*. Richmond, VA: Willmann-Bell.
- Meinzer, F. C., Goldstein, G., Jackson, P., Holbrook, N. M., Gutiérrez, M. V., & Cavelier, J. (1995). Environmental and physiological regulation of transpiration in tropical forest gap species: The influence of boundary layer and hydraulic properties. *Oecologia*, 101(4), 514–522. <https://doi.org/10.1007/bf00329432>
- Meissner, R., Seeger, J., Rupp, H., Seyfarth, M., & Borg, H. (2007). Measurement of dew, fog, and rime with a high-precision gravitation lysimeter. *Journal of Plant Nutrition and Soil Science*, 170(3), 335–344. <https://doi.org/10.1002/jpln.200625002>
- Moene, A. F., & van Dam, J. C. (2014). *Transport in the atmosphere-vegetation-soil continuum* (Vol. 11, p. 436). New York: Cambridge University Press.
- Novick, K. A., Oren, R., Stoy, P. C., Siqueira, M. B. S., & Katul, G. G. (2009). Nocturnal evapotranspiration in eddy-covariance records from three co-located ecosystems in the Southeastern U.S.: Implications for annual fluxes. *Agricultural and Forest Meteorology*, 149(9), 1491–1504. <https://doi.org/10.1016/j.agrformet.2009.04.005>
- O’Keefe, K. (2016). Patterns and ecological consequences of water uptake, redistribution, and loss in tallgrass prairie (Doctoral dissertation). Retrieved from K-REx. (<http://hdl.handle.net/2097/34514>). Division of Biology College of Arts and Sciences Kansas State University, Manhattan, Kansas.
- O’Keefe, K., & Nippert, J. B. (2018). Drivers of nocturnal water flux in a tallgrass prairie. *Functional Ecology*, 32(5), 1155–1167. <https://doi.org/10.1111/1365-2435.13072>
- Overholser, B. R., & Sowinski, K. M. (2008). Biostatistics primer: Part 2. *Nutrition in Clinical Practice*, 23(1), 76–84. <https://doi.org/10.1177/011542650802300176>
- Pattey, E., Strachan, I. B., Desjardins, R. L., & Massheder, J. (2002). Measuring nighttime CO₂ flux over terrestrial ecosystems using eddy covariance and nocturnal boundary layer methods. *Agricultural and Forest Meteorology*, 113(1-4), 145–158. [https://doi.org/10.1016/S0168-1923\(02\)00106-5](https://doi.org/10.1016/S0168-1923(02)00106-5)
- Pearce, A. J., Rowe, L. K., & Stewart, J. B. (1980). Nighttime, wet canopy evaporation rates and the water balance of an evergreen mixed forest. *Water Resources Research*, 16(5), 955–959. <https://doi.org/10.1029/WR016i005p00955>
- Pereira, A. B., Villa Nova, N. A., Pires, L. F., Angelocci, L. R., & Beruski, G. C. (2014). Estimation method of grass net radiation on the determination of potential evapotranspiration. *Meteorological Applications*, 21(2), 369–375. <https://doi.org/10.1002/met.1346>
- Peters, A., Groh, J., Schrader, F., Durner, W., Vereecken, H., & Pütz, T. (2017). Towards an unbiased filter routine to determine precipitation and evapotranspiration from high precision lysimeter measurements. *Journal of Hydrology*, 549, 731–740. <https://doi.org/10.1016/j.jhydrol.2017.04.015>

- Peters, A., Nehls, T., Schonsky, H., & Wessolek, G. (2014). Separating precipitation and evapotranspiration from noise—A new filter routine for high resolution lysimeter data. *Hydrology and Earth System Sciences Discussions*, 18(3), 1189–1198. <https://doi.org/10.5194/hess-18-1189-2014>
- Phillips, N. G., Lewis, J. D., Logan, B. A., & Tissue, D. T. (2010). Inter- and intra-specific variation in nocturnal water transport in Eucalyptus. *Tree Physiology*, 30(5), 586–596. <https://doi.org/10.1093/treephys/tpq009>
- Pütz, T., Kiese, R., Wollschläger, U., Groh, J., Rupp, H., Zacharias, S., et al. (2016). TERENO-SOILCan: A lysimeter-network in Germany observing soil processes and plant diversity influenced by climate change. *Environmental Earth Sciences*, 75(18), 1–14. <https://doi.org/10.1007/s12665-016-6031-5>
- R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from <http://www.R-project.org/>
- Resco de Dios, V., Loik, M. E., Smith, R., Aspinwall, M. J., & Tissue, D. T. (2016). Genetic variation in circadian regulation of nocturnal stomatal conductance enhances carbon assimilation and growth. *Plant, Cell & Environment*, 39(1), 3–11. <https://doi.org/10.1111/pce.12598>
- Resco de Dios, V., Roy, J., Ferrio, J. P., Alday, J. G., Landais, D., Milcu, A., & Gessler, A. (2015). Processes driving nocturnal transpiration and implications for estimating land evapotranspiration. *Scientific Reports*, 5(1). <https://doi.org/10.1038/srep10975>
- Rogiers, S. Y., Greer, D. H., Hutton, R. J., & Landsberg, J. J. (2009). Does night-time transpiration contribute to anisohydric behaviour in a Vitis vinifera cultivar? *Journal of Experimental Botany*, 60(13), 3751–3763. <https://doi.org/10.1093/jxb/erp217>
- Schoppach, R., Claverie, E., & Sadok, W. (2014). Genotype-dependent influence of night-time vapour pressure deficit on night-time transpiration and daytime gas exchange in wheat. *Functional Plant Biology*, 41(9), 963–971. <https://doi.org/10.1071/FP14067>
- Schwabe, W. W. (1952). Effects of photoperiodic treatment on stomatal movement. *Nature*, 169(4312), 1053–1054. <https://doi.org/10.1038/1691053a0>
- Schwaerzel, K., & Bohl, H. P. (2003). An easily installable groundwater lysimeter to determine waterbalance components and hydraulic properties of peat soils. *Hydrology and Earth System Sciences*, 7(1), 23–32. <https://doi.org/10.5194/hess-7-23-2003>
- Skaggs, K. E., & Irmak, S. (2011). Characterization of nighttime evapotranspiration and other surface energy fluxes and interactions with microclimatic variables in subsurface drip and center-pivot irrigated soybean fields. *Transactions of the ASABE*, 54(3), 941–952. <https://doi.org/10.13031/2013.37119>
- Tolk, J. A., Howell, A. T., & Evett, R. S. (2006). Nighttime evapotranspiration from alfalfa and cotton in a semiarid climate. *Agronomy Journal*, 98(3), 730–736. <https://doi.org/10.2134/agronj2005.0276>
- Unold, G., & Fank, J. (2008). Modular design of field lysimeters for specific application needs. *Water, Air, & Soil Pollution: Focus*, 8(2), 233–242. <https://doi.org/10.1007/s11267-007-9172-4>
- van Heerwaarden, C. C., Vilà-Guerau de Arellano, J., Moene, A. F., & Holtslag, A. A. M. (2009). Interactions between dry-air entrainment, surface evaporation and convective boundary-layer development. *Quarterly Journal of the Royal Meteorological Society*, 135(642), 1277–1291. <https://doi.org/10.1002/qj.431>
- Wang, H., Zhao, P., Hölscher, D., Wang, Q., Lu, P., Cai, X. A., & Zeng, X. P. (2012). Nighttime sap flow of Acacia mangium and its implications for nighttime transpiration and stem water storage. *Journal of Plant Ecology*, 5(3), 294–304. <https://doi.org/10.1093/jpe/rtr025>
- Wang, K., & Dickinson, R. E. (2012). A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability. *Reviews of Geophysics*, 50, RG2005. <https://doi.org/10.1029/2011RG000373>
- Xiao, H., Meissner, R., Seeger, J., Rupp, H., & Borg, H. (2009). Effect of vegetation type and growth stage on dewfall, determined with high precision weighing lysimeters at a site in northern Germany. *Journal of Hydrology*, 377(1–2), 43–49. <https://doi.org/10.1016/j.jhydrol.2009.08.006>
- Zeppel, M. J. B., Lewis, J. D., Phillips, N. G., & Tissue, D. T. (2014). Consequences of nocturnal water loss: A synthesis of regulating factors and implications for capacitance, embolism and use in models. *Tree Physiology*, 34(10), 1047–1055. <https://doi.org/10.1093/treephys/tpu089>