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Actual evapotranspiration and precipitation measured by lysimeters: a comparison with eddy covariance and tipping bucket

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Abstract

This study compares actual evapotranspiration (ET_a) measurements by a set of six weighable lysimeters, ET_a estimates obtained with the eddy covariance (EC) method, and potential crop evapotranspiration according to FAO (ET_c-FAO) for the Rollesbroich site in the Eifel (Western Germany). The comparison of ET_a measured by EC (including correction of the energy balance deficit) and by lysimeters is rarely reported in literature and allows more insight into the performance of both methods. An evaluation of ET_a for the two methods for the year 2012 shows a good agreement with a total difference of 3.8 % (19 mm) between the ET_a estimates. The highest agreement and smallest relative differences (< 8 %) on monthly basis between both methods are found in summer. ET_a was close to ET_c-FAO, indicating that ET was energy limited and not limited by water availability. ET_a differences between lysimeter, ET_c-FAO, and EC were mainly related to differences in grass height caused by harvesting management and the EC footprint. The lysimeter data were also used to estimate precipitation amounts in combination with a filter algorithm for high precision lysimeters recently introduced by Peters et al. (2014). The estimated precipitation amounts from the lysimeter data show significant differences compared to the precipitation amounts recorded with a standard rain gauge at the Rollesbroich test site. For the complete year 2012 the lysimeter records show a 16 % higher precipitation amount than the tipping bucket. With the help of an on-site camera the precipitation measurements of the lysimeters were analyzed in more detail. It was found that the lysimeters record more precipitation than the tipping bucket in part related to the detection of rime and dew, which contributes 17 % to the yearly difference between both methods. In addition, fog and drizzle explain an additional 5.5 % of the total difference. Larger differences are also recorded for snow and sleet situations. During snowfall, the tipping bucket device underestimated precipitation severely and these situations contributed also 7.9 % to the total difference. However, 36 % of the total yearly difference was associated to snow cover without apparent snowfall and under these conditions snow bridges and snow drift seem to explain the

strong underestimation of precipitation by the lysimeter. The remaining precipitation difference (about 33 %) could not be explained, and did not show a clear relation with wind speed. The variations of the individual lysimeters devices compared to the lysimeter mean of 2012 are small showing variations up to 3 % for precipitation and 8 % for evapotranspiration.

1 Introduction

Precipitation and actual evapotranspiration measurements have a quite long tradition. First devices for modern scientific purposes were developed in Europe during the 17th century (Kohnke et al., 1940; Strangeways, 2010). However, the accurate estimation of precipitation (P) and actual evapotranspiration (ET_a) is still a challenge. Common precipitation measurement methods exhibit systematic and random errors depending on the device locations and climatic conditions. Legates and DeLiberty (1993) concluded from their long-term study of precipitation biases in the United States that Hellman type gauges (US standard) undercatch precipitation amounts. Undercatch is larger in case of snowfall and larger wind speeds. Wind-induced loss is seen as the main source of error (Sevruk, 1981, 1996; Yang et al., 1998; Chvíla et al., 2005; Brutsaert, 2010). Precipitation gauges are commonly installed above ground to avoid negative impact on the measurements by splash water, hail, and snow drift. However, this common gauge setup causes wind distortion and promotes the development of eddies around the device. Wind tunnel experiments with Hellman type gauges (Nešpor and Sevruk, 1999) have shown precipitation losses of 2–10 % for rain and 20–50 % for snow compared to the preset precipitation amount. In general, wind-induced loss increases with installation height of the device and wind speed and decreases with precipitation intensity (Sevruk, 1989). Further precipitation losses, which affect the rain gauge measurement, are evaporation of water from the gauge surface and recording mechanisms (Sevruk, 1981; Michelson, 2004). Moreover, rime, fog and dew, which contribute up to 5 % to

the annual precipitation at a humid grassland site (Jacobs et al., 2006; Meissner et al., 2007), are usually not captured by a standard precipitation gauge.

As an alternative, state-of-the-art high precision weighing lysimeters are able to capture the fluxes at the interface of soil, vegetation and atmosphere (Unold and Fank, 2008). A high weighing accuracy and a controlled lower boundary condition permit high temporal resolution precipitation measurements at ground level, including dew, fog, rime, and snow. Additionally, ET_a can be estimated with the help of the lysimeter water balance. However, the high acquisition and operational costs are a disadvantage of lysimeters. Moreover, the accuracy of lysimeter measurements is affected by several error sources. Differences in the thermal, wind and radiation regime between a lysimeter device and its surroundings (oasis effect) (Zenker, 2003) as well as lysimeter management (e.g. inaccuracies in biomass determination) can affect the measurements. Wind or animal induced mechanical vibrations can influence the weighing system but can be handled by accurate data processing using filtering and smoothing algorithms (Schrader et al., 2013; Peters et al., 2014). Vaughan and Ayars (2009) examined lysimeter measurement noise for minutely resolved data caused by wind loading. They presented noise reduction techniques that rely on Savitzky–Golay (Savitzky and Golay, 1964) smoothing. Schrader et al. (2013) evaluated the different filter and smoothing strategies for lysimeter data processing on the basis of synthetic and real measurement data. They pointed out, that the adequate filter method for lysimeter measurements is still a challenge, especially at high temporal resolution, due the fact that noise of lysimeter measurements varies strongly with weather conditions and mass balance dynamics. Peters et al. (2014) recently introduced a filter algorithm for high precision lysimeters, which combines a variable smoothing time window with a noise dependent threshold filter that accounts for the factors mentioned above. They showed that their "Adaptive Window and Adaptive Threshold Filter" (AWAT) improves actual evapotranspiration and precipitation estimates from noisy lysimeter measurements compared to smoothing methods for lysimeter data using the Savitzky–Golay filter or simple moving

averages used in other lysimeter studies (e.g. Vaughan and Ayars, 2009; Huang et al., 2012; Nolz et al., 2013; Schrader et al., 2013).

The eddy covariance (EC) method is one of the most established techniques to determine the exchange of water, energy and trace gases between the land surface and the atmosphere. On the basis of the covariance between vertical wind speed and water vapor density, the EC method calculates the vertical moisture flux (and therefore ET) in high spatial and temporal resolution with relatively low operational costs. The size and shape of the measurement area (EC footprint) varies strongly with time (Finnigan, 2004). Under conditions of limited mechanical and thermal turbulence the EC method tends to underestimate fluxes (Wilson et al., 2001; Li et al., 2008). Energy balance deficits are on average found to be between 20 and 25 % (Wilson et al., 2001; Hendricks Franssen et al., 2010) and therefore latent heat flux or actual evapotranspiration estimated from EC data shows potentially a strong underestimation. The energy balance closure problem can be corrected by closure procedures using the Bowen ratio. However, this is controversially discussed, especially because not only the underestimation of the land surface fluxes, but also other factors like the underestimation of energy storage in the canopy might play a role (Twine et al., 2000; Foken et al., 2011).

In the literature we find several comparisons between lysimeter measurements and standard ET calculations. López-Urrea et al. (2006) found a good agreement of FAO-56 Penman–Monteith with lysimeter data on an hourly basis. Vaughan et al. (2007) also reported a good accordance of hourly lysimeter measurements with a Penman–Monteith approach of the California Irrigation Management Information System. Wegehenkel and Gerke (2013) compared lysimeter ET with reference ET and ET estimated by a numerical plant growth model. They found that lysimeter ET overestimated actual ET, the cause being an oasis effect. On the other hand, also ET estimated by EC measurements and water budget calculations are compared in literature. Scott (2010) found that the EC-method underestimated evapotranspiration for a grassland site related to the energy balance deficit. However, only a few comparisons between ET estimated by EC and lysimeter data were found in literature. Chavez et al. (2009)

evaluated actual evapotranspiration determined by lysimeters and EC in the growing season for a cotton field site. They found a good agreement of both methods after correcting the energy balance deficit and they suggested to consider also the footprint area for EC calculations. Ding et al. (2010) found a lack of energy balance closure and underestimation of ET_a by the EC-method for maize fields. An energy balance closure based on the Bowen ratio method was able to reduce the ET-underestimation. Alfieri et al. (2012) provided two possible explanations for a strong underestimation of EC-ET_a compared to lysimeter ET_a. First, the energy balance deficit of the EC data, especially for those cases where EC-measurements are affected by strong advection. Second, deviations between the vegetation status of the lysimeter and the surrounding field. Evett et al. (2012) found an 18 % underestimation of corrected EC-ET_a compared to ET_a estimated by lysimeter and attributed the difference to differences in vegetation growth.

The Terrestrial Environmental Observatories (TERENO) offer the possibility of detailed long-term investigations of the water cycle components at a high spatio-temporal resolution (Zacharias et al., 2011). This study compares precipitation and evapotranspiration estimates calculated with a set of six weighing lysimeters (LYS) with nearby eddy covariance and precipitation measurements for the TERENO grassland site Rollesbroich. Additional soil moisture, soil temperature and meteorological measurements at this TERENO test site enable a detailed analysis of differences between the different measurement techniques. The lysimeter data (ET_a-LYS) are processed with the AWAT filter (Peters et al., 2014) and the comparison is carried out with energy balance corrected EC data (ET_a-EC). Actual ET estimates are additionally compared to FAO standard grass reference evapotranspiration (ET_0-FAO) and potential crop evapotranspiration (ET_c-FAO) calculated according to the FAO crop approach for grassland (Allen, 2000). Precipitation measurements by a classical Hellmann type tipping bucket were compared with lysimeter data for one year (2012).

For our study, we (1) compared precipitation measurements by lysimeters and a standard tipping bucket device and interpreted the differences. For example, the

vegetated high precision lysimeters potentially allow better estimates of precipitation accounting for dew, rime and fog; (2) compared eddy covariance and lysimeter ET estimates and tried to explain differences in estimated values; (3) tested whether a correction of the energy balance deficit for the EC-method results in an ET_a estimate which is close to the lysimeter method; (4) analysed the variability of the measurements by the six lysimeters with identical configuration and management.

2 Material and methods

2.1 Study site and measurement setup

The Rollesbroich study site (50°37′27″ N, 6°18′17″ E) is located in the TERENO Eifel low mountains range/Lower Rhine Valley Observatory (Germany). This sub-catchment of the river Rur has an area of 31 ha with an altitude ranging from 474 to 518 m a.s.l. The vegetation of the extensively managed grassland site is dominated by ryegrass and smooth meadow grass. The annual mean precipitation is 1033 mm and the annual mean temperature 7.7 °C (period 1981–2001); these data are obtained from a meteorological station operated by the North Rhine-Westphalian State Environment Agency (LUA NRW) at a distance of 4 km from the study site. Figure 1 shows a map of the study site and gives an overview of the installed measurement devices.

In 2010 a set of six lysimeters (TERENO-SoilCan project, UMS GmbH, Munich, Germany) was arranged in a hexagonal design around the centrally placed service unit, which hosts the measurement equipment and data recording devices. Each lysimeter contains silty-clay soil profiles from the Rollesbroich site and is covered with grass. The conditions at the lysimeters therefore closely resemble the ones in the direct surroundings (Fig. 2). Additionally, the spatial gap between lysimeter and surrounding soil was minimized to prevent thermal regimes which differ between the lysimeter and the surrounding field (oasis effect). Every lysimeter device has a surface of 1 m², a depth of 1.5 m and is equipped with a 50 L weighted leachate tank connected via a bidirectional

pump to a suction rake in the bottom of each lysimeter. To reproduce the field soil water regime, the lower boundary conditions are controlled by tensiometers (TS1, UMS GmbH, Munich, Germany) monitoring the soil matric potential inside the lysimeter bottom and the surrounding field. Matric potential differences between field and lysimeter are compensated by suction rakes (SIC 40, UMS GmbH, Munich, Germany) injecting leachate tank water into the lysimeter monolith during capillary rise or removing water during drainage conditions. The weighing precision is 100 g for the soil monolith and 10 g for the leachate tank accounting for long-term temperature variations and load alternation hysteresis effects. For short term signal processing the relative accuracy for accumulated mass changes of soil monolith and leachate is 10 g. For the year 2012 measurements were made each 5 s and averaged to get minute values. In the winter season a connection between the snow lying on the lysimeter and the surrounding snow layer potentially disturbs the weighing system. A snow separation system is engaged at all lysimeter devices to prevent this situation by a mechanical vibration plate, which is activated once in 5 s between two measurements. The lysimeters are also equipped with soil moisture, matric potential and temperature sensors at different depths (10, 30, 50 and 140 cm). Amongst others, soil temperature is determined in 10, 30 and 50 cm depth with PT-100 sensors integrated in TS1-tensiometers (UMS GmbH, Munich, Germany). A schematic overview of the lysimeter device (Fig. 3) shows the installing locations and the different sensor types. The lysimeter site was kept under video surveillance by a camera taking a photo of the lysimeter status every hour. Further technical specifications can be found in Unold and Fank (2008).

Latent and sensible heat fluxes were measured by an eddy covariance station at a distance of approximately 30 m from the lysimeters. The EC-station (50°37′19″ N, 6°18′15″ E, 514 m a.s.l.) is equipped with a sonic anemometer (CSAT3, Campbell Scientific, Inc., Logan, USA) at 2.6 m height to measure wind components. The open path device of the gas analyzer (LI7500, LI-COR Inc., Lincoln, NE, USA) is mounted along with the anemometer at 2.6 m above the ground surface and measures H_2O content of the air. Air pressure is measured at the processing unit of the gas analyser in a height

of 0.57 m. Air humidity and temperature were measured by HMP45C, Vaisala Inc., Helsinki, Finland (at 2.58 m above the ground surface). Radiation was determined by a four-component net radiometer (NR01, Hukseflux Thermal Sensors, Delft, Netherlands). Soil heat flux was determined at 0.08 m depth by a pair of two HFP01 (Hukseflux Thermal Sensors, Delft, Netherlands).

Precipitation measurements are made by a standard Hellmann type tipping bucket balance (TB) rain gauge (ecoTech GmbH, Bonn, Germany) with a resolution of 0.1 mm and a measurement interval of 10 min. The measurement altitude of 1 m above ground is in accordance with recommendations of the German weather service (DWD, 1993) for areas with an elevation > 500 m a.s.l. and occasional heavy snowfall (WMO standard is 0.5 m). The gauge was temporary heated during winter time to avoid freezing of the instrument.

Additional soil moisture and soil temperature measurements were carried out with a wireless sensor network (SoilNet) installed at the study site (Bogena et al., 2010). The 179 sensor locations at the Rollesbroich site contain six SPADE sensors (model 3.04, sceme.de GmbH i.G., Horn-Bad Meinberg, Germany) with two redundant sensors at 5, 20 and 50 cm depth. Further technical details can be found in Qu et al. (2013). Soil water content and temperature were also measured by two sensor devices installed nearby the lysimeter site.

2.2 Data processing

2.2.1 Lysimeter

The lysimeter weighing data were processed in three steps:

1. elimination of outliers by an automated threshold filter;

2. smoothing of measurement signal with the AWAT filter routine on minutely basis;

3. estimation of hourly precipitation and evapotranspiration on the basis of the smoothed signal.

Outliers were removed from the data by limiting the maximum weight difference between two succeeding measurements for the soil column to 5 kg and for the leachate weight to 0.1 kg. The lysimeter readings are affected by large random fluctuations caused by wind and other factors that influence the measurement. Therefore, the AWAT filter (Peters et al., 2014) in a second correction step was applied on the minute-wise summed leachate and on the weights for each individual lysimeter. First, the AWAT routine gathers information about signal strength and data noise by fitting a polynomial to each data point within an interval of 31 min. The optimal order (k) of the polynomial is determined by testing different polynomial orders for the given interval (i.e. k: 1–6) and selecting the optimal k according Akaike's information criterion (Akaike, 1974; Hurvich and Tsai, 1989). The maximum order of k is limited to six for the AWAT filter preventing an erroneous fit caused by eventual outliers. Measures of $s_{\text{res},i}$ (Eq. 1) and $s_{\text{dat},i}$ (Eq. 2) lead to the quotient B_i, which gives information about the explained variance of the fit and is related to the coefficient of determination (R^2):

$$s_{\text{res},i} = \sqrt{\frac{1}{r} \sum_{j=1}^{r} [y_j - \hat{y}_j]^2} \qquad (1)$$

$$s_{\text{dat},i} = \sqrt{\frac{1}{r} \sum_{j=1}^{r} [y_j - \overline{y}]^2} \qquad (2)$$

$$B_i = \frac{s_{\text{res},i}}{s_{\text{dat},i}} = \sqrt{1 - R_i^2} \qquad (3)$$

where y_j [M] is the measured data, $\hat{y}_j$ [M] the fitted value at each interval time j, $\overline{y}$ [M] the mean of the measurements and r the number of measurements within the given interval of data point i. $B_i = 0$ indicates that the polynomial totally reproduces the range of data variation in contrast to $B_i = 1$ showing that nothing of the variation in the data is explained by the fitted polynomial. Second, AWAT smoothes the data using a moving

average for an adaptive window width w_i [T], which is a time dependent linear function of B_i (Eq. 4):

$$w_i(B_i) = \max(w_{min}, B_i w_{max}) \tag{4}$$

where w_{max} [T] and w_{min} [T] are maximum and minimum provided window width. For our study w_{min} was set to 11 min, w_{max} was 61 min. A low B_i requires less smoothing and therefore small time windows, whereas a B_i close to one requires a smoothing interval close to the allowed w_{max}. Third, AWAT applies an adaptive threshold δ_i (Eq. 5) to the data at each time step to distinguish between noise and signal due to the dynamics of mechanical disturbances:

$$\delta_i = s_{res,i} \cdot t_{97.5,r} \quad \text{for } \delta_{min} < s_{res,i} \cdot t_{97.5,r} < \delta_{max} \tag{5}$$

where δ_i [M] is a function of the interval residuals ($s_{res,i}$) [M] (see Eq. 1) and the Student t value ($t_{97.5,r}$) for the 95 % confidence level at each time step, δ_{min} [M] is the minimum and δ_{max} [M] is the maximum provided threshold for the mass change. The product of Student t and $s_{res,i}$ is a measure for the significance level of mass changes during flux calculation. Hence, the δ_i value indicates the range ($\pm s_{res,i} \cdot t_{97.5,r}$), where the interval data points differ not significantly from the fitted polynomial at the 95 % confidence level. Mass changes above the adaptive threshold δ_i are significant and interpreted as signal, whereas weight differences below δ_i are interpreted as noise. The adaptive threshold is limited by δ_{min} and δ_{max} to guarantee that (1) mass changes smaller than the lysimeter measurement accuracy are understood as remaining noise and therefore not considered for the flux calculation and (2) noise is not interpreted as signal during weather conditions, which produce noisy lysimeter readings (i.e. thunderstorms with strong wind gusts). Lysimeter calibration tests with standard weights at the study site indicate a system scale resolution of 0.05 kg. We chose a slightly higher threshold ($\delta_{min} = 0.055$ kg) with an adequate tolerance for our TERENO lysimeter devices. For the upper threshold $\delta_{max} = 0.24$ kg was taken, similar to the example presented by Peters et al. (2014).

For the separation of precipitation and actual evapotranspiration (ET_a) AWAT assumes that increases of minutely mean lysimeter and leachate weights are exclusively related to precipitation and negative differences are due to ET_a [MT^{-1}]. Supposing that no evapotranspiration occurs during a precipitation event and assuming a fixed water density of $1000\,kg\,m^{-3}$, precipitation (P) [MT^{-1}] can be derived from the lysimeter water balance (Eq. 6) as:

$$ET_a = P - L - \frac{dS_S}{dt} \qquad (6)$$

$$P = L + \frac{dS_S}{dt} \qquad (7)$$

where L is the amount of leachate water [MT^{-1}] and dS_S/dt is the change of soil water storage [MT^{-1}] with time. After smoothing the minutely fluxes were cumulated to hourly sums of P and ET_a.

Although the six lysimeters have a similar soil profile, technical configuration and management (i.e. grass cut, maintenance), differences in measured values between lysimeters are not exclusively related to random errors. Systematic weight variations may for example be caused by soil heterogeneity, mice infestation and differences in plant dynamics. For the analysis of P and ET_a we compared the estimations of the TB and the eddy covariance method with the mean of six redundant lysimeter devices (unless specified otherwise) assuming that the lysimeter average is the most representative for estimating precipitation and actual evapotranspiration.

2.2.2 Eddy covariance data

Eddy covariance raw measurements were taken with a frequency of 20 Hz and fluxes of sensible heat (H) and latent heat (LE) were subsequently calculated for intervals of 30 min by using the TK3.1 software package (Mauder and Foken, 2011). The complete post-processing was in line with the standardized strategy for EC data calculation and

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quality assurance presented by Mauder et al. (2013). It includes the application of site specific plausibility limits and a spike removal algorithm based on median absolute deviation on raw measurements, a time lag correction for vertical wind speed with temperature and water vapor concentration based on maximizing cross-correlations between the measurements of the used sensors, a planar fit coordinate rotation (Wilczak et al., 2001), corrections for high frequency spectral losses (Moore, 1986), the conversion of sonic temperature to air temperature (Schotanus et al., 1983) and the correction for density fluctuations (Webb et al., 1980). Processed half hourly fluxes and statistics were applied to a three-class quality flagging scheme, based on stationarity and integral turbulence tests (Foken and Wichura, 1996) and classified as high, moderate and low quality data. For this analysis only high and moderate quality data were used, while low quality data were treated as missing values. To assign half hourly fluxes with its source area the footprint model of Korman and Meixner (2001) was applied.

Almost every eddy covariance site shows an unclosed energy balance, which means that the available energy (net radiation minus ground heat flux) is found to be larger than the sum of the turbulent fluxes (sensible plus latent heat flux) (Foken, 2008). In this study the energy balance deficit (EBD) was determined using a 3 h moving window around the measurements (Kessomkiat et al., 2013):

$$\text{EBD}_{3\,h} = R_{n-3\,h} - (G_{3\,h} + \text{LE}_{3\,h} + H_{3\,h} + S_{3\,h}) \tag{8}$$

where $R_{n-3\,h}$ is average net radiation [MT^{-3}], $G_{3\,h}$ is average soil heat flux [MT^{-3}], $\text{LE}_{3\,h}$ is average latent heat flux [MT^{-3}], $H_{3\,h}$ is average sensible heat flux [MT^{-3}], and $S_{3\,h}$ is average heat storage (canopy air space, biomass and upper soil layer above ground heat flux plate) [MT^{-3}]. All these averages are obtained over a three hour period around a particular 30 min EC-measurement. It was assumed that the energy balance deficit is caused by an underestimation of the turbulent fluxes and therefore the turbulent fluxes are corrected according to the evaporative fraction. The evaporative fraction (EF) was determined for a time window of seven days:

$$EF = \frac{\overline{LE_{7d}}}{\overline{LE_{7d}} + \overline{H_{7d}}} \tag{9}$$

where $\overline{LE_{7d}}$ and $\overline{H_{7d}}$ [MT^{-3}] are the latent and sensible heat fluxes averaged over seven days. The chosen time period increases the reliability for EF calculation compared to single days. Dark days with small fluxes may not give meaningful results.

The energy balance corrected latent heat flux was determined by redistribution of the latent heat on the basis of the calculated evaporative fraction:

$$LE^*_{0.5h} = LE_{0.5h} + EBD_{3h}(EF) \tag{10}$$

where $LE^*_{0.5h}$ is the latent heat flux (for a certain measurement point in time; i.e. a 30 min period for our EC data) after the correction of energy balance deficit (EBD).

In this study, also the evapotranspiration (ET_a-EC) calculated with the original latent heat flux (not corrected for energy balance closure) will be presented for comparison. Furthermore, the most extreme case would be that the complete EBD is linked to an underestimation of the latent heat flux. Some authors argue (Ingwersen et al., 2011) that the EBD could be more related to underestimation of one of the two turbulent fluxes than the other turbulent flux. Therefore, as an extreme scenario the complete EBD is assigned to underestimation of the latent heat flux.

ET_a-EC is calculated from the latent heat flux according to:

$$ET_a = \frac{LE^*_h}{L(T_h)_{H_2O} \cdot \rho_{H_2O}} \tag{11}$$

where ET_a is ET_a-EC [LT^{-1}], LE^*_h is latent heat flux [MT^{-3}], ρ is the density of water [ML^{-3}] and $L(T_h)_{H_2O}$ is the vaporization energy [L^2T^{-2}] at a given temperature.

The lysimeters are thought to be representative for the EC footprint, although size and shape of the EC footprint are strongly temporally variable. However, the EC footprint is almost exclusively constrained to the grassland and the lysimeters are also covered by grass.

2.2.3 Grass reference evapotranspiration

The measurements of ET_a by the EC-method and lysimeters were in this study compared with hourly grass reference evapotranspiration that was calculated according to the single crop FAO-method (Food and Agriculture Organization), based on the Penman–Monteith equation (Allen, 2000):

$$ET0_h = \frac{0.408\Delta(R_n - G) + \gamma\frac{37}{T_h+273}u_2(e^\circ(T_h) - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (12)$$

where $ET0_h$ is the hourly reference evapotranspiration $[LT^{-1}]$, R_n is net radiation at the grass surface $[MT^{-3}]$, G is soil heat flux density $[MT^{-3}]$, T_h is mean hourly air temperature (θ), Δ slope of the saturated vapour pressure curve at T_h $[ML^{-1}T^{-2}\theta^{-1}]$, γ is psychrometric constant $[ML^{-1}T^{-2}\theta^{-1}]$, $e^\circ(T_h)$ is saturation vapour pressure for the given air temperature $[ML^{-1}T^{-2}]$, e_a is average hourly actual vapour pressure $[ML^{-1}T^{-2}]$, and u_2 is average hourly wind speed $[LT^{-1}]$ at 2 m height. All required meteorological input parameters for calculating the reference evapotranspiration were taken from the EC station. The wind speed data were corrected to the 2 m FAO-standard for ET_0 calculations using the wind profile relationship according to Allen (2000). For our ET_0 calculations we assume furthermore a fixed standard surface resistance of $70\,s\,m^{-1}$ and a crop height of 0.12 m.

According to Allen (2000) the reference ET (ET_c-FAO) for a specific crop can be obtained invoking a crop specific coefficient (K_c):

$$ET_c\text{-FAO} = K_c ET0_h \qquad (13)$$

where ET_c-FAO is the hourly crop evapotranspiration [LT^{-1}] and K_c is the crop co-efficient representing the vegetation and ground cover conditions during crop stage [–]. For our calculations we chose the constant rye grass hay coefficients (Allen, 2000) with different values for the initial stage ($K_{c\,ini}$), the growing season ($K_{c\,mid}$) and late sea-

5 son ($K_{c\,end}$). The beginning and end of the growing season were determined by using the grass length measurements (Fig. 7): $K_{c\,ini}$: 0.95 (1 January 2012–2 March 2012), $K_{c\,mid}$: 1.05 (2 March 2012–31 October 2012), $K_{c\,end}$: 1.0 (1 October 2012–31 December 2012). $K_{c\,mid}$ is averaged for cutting effects due to the variable cutting management at different study site locations. For determining ET only daytime (sunrise–sunset) ET

10 values were taken into account.

3   Results and discussion

3.1   Precipitation measurements

Table 1 shows the monthly precipitation sums measured by the tipping bucket (TB) and calculated from the lysimeter balance data for the year 2012. The precipitation differ-

15 ence between both devices for the year 2012 is 145.0 mm showing a 16.4 % larger average lysimeter precipitation than TB. For the individual lysimeters the yearly precipitation ranges from 996.2 to 1037.7 mm (-3.0 to $+1.0$ % compared to the lysimeter average). This implies that the minimum and maximum precipitation differences between individual lysimeters and TB were 114.1 mm (12.9 %) resp. 155.6 mm (17.6 %),

20 where precipitation for lysimeters was higher than for TB. The monthly precipitation sums for the period April–October measured by the tipping bucket are smaller than the ones from the lysimeter average and differences range between 1 % in July and 42 % in September. The winter months show higher relative differences. The highest difference was found in March 2012, when the lysimeters registered an amount of pre-

25 cipitation double as large as the TB. The precipitation sums measured by lysimeter and tipping bucket correlate well on an hourly basis, especially from April to October with

R^2 varying between 0.74 (April) and 0.99 (May), but with the exception of September (0.58). For winter months the explained variance is smaller with a minimum of 13 % for February 2012.

Measured precipitation differences between individual lysimeter devices show a similar temporal pattern as differences between lysimeter and TB. Low correlations correspond with the larger differences; high correlations correspond with smaller differences. The period April–August shows the smallest precipitation differences with monthly values of ±5 % in relation to the lysimeter average. In contrast, February, September, and December exhibit the highest absolute and relative precipitation differences with variations between −13 and 13 mm (±35 %) with respect to the mean. Figure 4 shows the absolute daily differences in precipitation between lysimeter and TB measurements. It shows that the cases where lysimeters register slightly higher monthly precipitation sums than TB are related to single heavy rainfall events (June, July). In contrast, especially for February, the beginning of March, and the first half of December, larger fluctuations in differences between daily precipitation measured by TB and lysimeter are found, with less precipitation for TB than for lysimeters most of the days. These periods coincide with freezing conditions and frequent episodes with sleet or snowfall. According to Nešpor and Sevruk (1999) these weather conditions are typically associated with a large tipping bucket undercatch because snowflakes are easier transported with the deformed wind field around a rain gauge. The surveillance system, which is installed at the lysimeter site, gives support for these findings. For example, a sleet precipitation event on 7 March explains 70 % (8.5 mm) of the monthly precipitation difference between lysimeter and TB. At this day the wind speed during the precipitation event was relatively high (4.4 m s^{-1}) and precipitation intensity varied between 0.6 and 2.9 mm h^{-1}. In general, winter measurement inaccuracies can be caused by frozen sensors and snow or ice deposit on the lysimeter surface. This situation may cause ponding effects close to the soil surface in the lysimeter and superficial runoff.

In order to explain differences in precipitation amounts between lysimeter and tipping bucket the contribution of dew and rime to the total yearly precipitation amount was

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determined. The hourly data of lysimeter and TB were filtered using distinct meteorological conditions. Selected were small precipitation amounts in the lysimeter data occurring before sunrise and after sunset associated with high relative humidity ($> 90\%$), negative net radiation and low wind speed ($< 3.5\,\mathrm{m\,s^{-1}}$). Under these meteorological
5 conditions it is probable that dew or rime is formed after sunset and before sunrise on cloud free days. These filter criteria also include fog and mist periods. For these days the difference in precipitation between TB and lysimeter is calculated if TB shows no precipitation signal or if the lysimeter has no precipitation signal. For the first case (P-TB = 0) the total amount of the lysimeter precipitation is 24.5 mm, which contributes
10 16.9% to the total yearly precipitation difference with the TB (and 2.4% of the yearly lysimeter precipitation). The period from April to August shows in general smaller precipitation amounts related to such situations. In contrast, likely dew and rime conditions where lysimeter precipitation is zero have a registered amount of TB-precipitation of 1.7 mm, which is only 0.2% of the total measured TB amount for the considered pe-
15 riod. A closer inspection of the precipitation data shows that both devices are able to capture dew and rime. However, a delay of some hours between TB and lysimeters was found. It is supposed that dew or fog precipitation was cumulating in the TB device until the resolution threshold of 0.1 mm was exceeded. This indicates that the TB resolution of 0.1 mm is too coarse to detect small dew and rime amounts in a proper
20 temporal assignment. This confirms the expected ability of the lysimeter to measure rime and dew better than Hellman type pluviometers or tipping bucket devices. The surveillance system was used to check whether indeed dew/rime was formed on the before-mentioned days. On days which fulfilled the criteria and air temperatures close to or below 0 °C rime was seen on the photos. For days that fulfilled the conditions and
25 temperatures above 0 °C camera lenses were often covered with small droplets.

Weather conditons with drizzle or fog occur frequently at the study site. This is related to humid air masses from the Atlantic which are transported with the dominating Southwestern winds and lifted against the hills in this region. The surveillance system was used to detect fog and drizzle situations during the year 2012. For those situations,

a difference in precipitation between TB and lysimeters of 8 mm was found (6 mm for TB and 14 mm for LYS), which contributes 5.5 % to the yearly difference of both devices. Figure 5 illustrates the example of 5–6 May 2012. The hourly photos of the site show drizzle, light rain and fog for this period. For both days the air temperature is close to the dew point temperature. The precipitation difference between tipping bucket and lysimeter over this period was 4.0 mm (Σ TB: 12.8 mm, Σ LYS: 16.8). The maximum difference was 0.5 mm and found at 6 h on the 5 May in combination with fog. On 5 May during these conditions hourly TB precipitation is often zero and LYS mean precipitation rates are small (0.02–$0.2 \, \mathrm{mm \, h^{-1}}$). The comparison of individual lysimeter devices shows that not every lysimeter exceeds the predefined lower threshold of 0.055 mm for the AWAT filter (i.e. 5 May 15:00 LT, 6 May 01:00–03:00 LT). However, in these cases at least three lysimeters show a weight increase, which supports the assumption that a real signal was measured instead of noise.

With the purpose of explaining the remaining difference in precipitation amount between TB and lysimeter the relationship between wind speed and the precipitation differences was examined. Although the determined precipitation differences could in theory be explained by undercatch related to wind (Sevruk, 1981, 1996), a general correlation between wind speed and precipitation residuals was not found ($R^2 = 0.02$). A possible explanation is that other potential dew or rime situations are not properly filtered by the used criteria (e.g. dew occurs in case the net radiation is slightly positive or close to zero). Additionally, the correlation between undercatch and wind speed is dependent on precipitation type, intensity and drop size, for which information was limited during the investigation period. To investigate these relations we classified the precipitation type with the help of air temperatures assuming that temperatures below $0\,°\mathrm{C}$ result in solid precipitation and above $4\,°\mathrm{C}$ only liquid precipitation occurs. The contribution of liquid precipitation to total yearly precipitation is 80.9 % for the TB and 74.7 % for the lysimeters. The relative amount of solid precipitation was also different between the two measurement methods. Whereas for the lysimeters 7.8 % (79.7 mm) was classified as solid precipitation, the TB had only 0.6 % (5.6 mm) during periods

with temperature $< 0\,°C$. In relation to the total precipitation difference of 145 mm this means that 51 % of the difference was associated with solid precipitation events and 37 % with liquid precipitation events, which indicates the relatively large contribution of solid precipitation events to the total difference. The transition range (0–4 °C) makes up 12 % of the total difference. Moreover, it was found that 78.7 % of the solid precipitation come along with small precipitation intensities ($< 1.0\,mm\,h^{-1}$) and low wind speeds ($< 2.0\,m\,s^{-1}$). The surveillance system allowed to further investigate these large precipitation differences for air temperatures below zero. The snow depth at the lysimeters and surrounding areas is also an indication of precipitation amounts, assuming that 1 cm snow height corresponds to 1 mm precipitation. This method revealed that for conditions of light to moderate snowfall ($< 4\,mm\,h^{-1}$ precipitation intensity) the TB had a precipitation undercatch during winter weather conditions in January, February and December of 11.4 mm (7.9 % of total precipitation difference). The registered precipitation amount of the lysimeter under those conditions was realistic. However, during periods where the lysimeters were completely covered by snow (e.g. 1–15 February) precipitation estimates by lysimeter (up to $16\,mm\,day^{-1}$ difference with tipping bucket) could not be confirmed by the camera system and were most probably influenced by snow drift or snow bridges. These situations explain 35.8 % (51.9 mm) of the total precipitation difference for 2012. For solid precipitation events a relationship ($R^2 = 0.5$) between precipitation differences and wind speed was found, but the number of datapoints was very limited ($n = 7$). For conditions of liquid precipitation no correlation was found between residuals and wind speed ($R^2 < 0.02$).

3.2 Comparison of evapotranspiration

In general, the yearly sums of ET_a-EC and ET_a-LYS were slightly higher than ET_c-FAO; 1.6 % for ET_a-EC and 5.6 % for ET_a-LYS. The minimum ET_a of the individual lysimeter measurements (ET_a-LYSmin) is 467.1 mm, which is 7.9 % smaller than the lysimeter average (507.4 mm); the maximum (ET_a-LYSmax) is 523.1 mm (+3.1 %). ET_a-EC is close to the calculated ET_c-FAO. This indicates that in general over the year 2012

evapotranspiration was limited by energy and not by water. Table 3 lists the evapotranspiration results of January–December 2012. For the period from April to August the monthly evapotranspiration sums calculated from hourly lysimeter data (ET_a-LYS) and eddy covariance data (ET_a-EC) are clearly higher than the calculated FAO evapotranspiration (ET_c-FAO), confirming that in these months evapotranspiration was not limited by soil moisture content, but energy. However, for May, June and July ET_c-FAO and ET_a-EC are within the range of the individual ET_a-LYS. In contrast, March and November exhibit smaller monthly sums of ET_a-LYS and ET_a-EC compared to ET_c-FAO. Root mean square errors of hourly ET_a sums vary between $0.01\,\mathrm{mm\,h^{-1}}$ in winter and $0.11\,\mathrm{mm\,h^{-1}}$ in summer months and are in phase with the seasonal ET dynamics.

We focus now on the comparison of monthly ET_a-LYS and ET_a-EC sums within the investigated period. During winter periods with low air temperatures and snowfall ET_a-LYS and ET_a-EC showed larger relative differences. For the period March to May ET_a-LYS and ET_a-EC differ approx. 6 % and ET_a-LYS exceeds ET_a-EC from June to August by 12 %. The larger difference in August (23 %) explains the yearly difference between ET_a-EC and ET_a-LYS. Hourly actual evapotranspiration from lysimeter and hourly actual evapotranspiration from EC are strongly correlated, but correlation is lower in the winter months. The registered monthly ET by the different lysimeters shows the largest variations in July with amounts that are up to $14.0\,\mathrm{mm}$ lower and $8.0\,\mathrm{mm}$ higher than the ET averaged over all six lysimeters.

Figure 6 shows the cumulative curve of the daily ET_a-LYS and ET_a-EC compared to ET_c-FAO for 2012. From end of March 2012 the sums of ET_a-LYS and ET_a-EC tend to converge, but at the end of May ET_a-EC exceeds ET_a-LYS. In June and July ET_a-LYS and ET_a-EC are very similar, but in August ET_a-LYS is larger than ET_a-EC. After August the difference between ET_a-LYS and ET_a-EC does not increase further. The area in grey represents the range of minimum and maximum cumulative ET_a-LYS, measured by individual lysimeters. Until August ET_a-EC and ET_c-FAO are slightly higher or close to the maximum measured ET_a-LYS. Later ET_a-EC is close to the lower limit and ET_c-FAO falls below the minimum lysimeter value. Additionally, Fig. 6 shows the course of

the ET_a-EC without correction for EBD and for an extreme correction (ET_a-EC max.) where all EBD is attributed to underestimation of the latent heat flux. ET_a-uncorr is ca. 411 mm over this period, whereas ET_a-EC max is 567 mm, which shows the large potential uncertainty of the EC-data. The comparison illustrates that the application of the Bowen ratio correction to the EC data results in an actual evapotranspiration estimate close to the actual evapotranspiration from the lysimeter, whereas ET_a-EC uncorr is much smaller than the lysimeter evapotranspiration. Table 4 lists the monthly latent heat fluxes, the corrected LE fluxes (on the basis of the Bowen ratio) and the mean differences between both. It was found that the absolute difference is between 29.8 W m^{-2} (August 2012) and 3.2 W m^{-2} (February 2012). The EBD ranges from 12.6–24.2 % for the period April to September The yearly maximum was found in February with 36.9 %. EB deficits are site-specific, but these findings confirm the importance of EC data correction as suggested by Chavez et al. (2009).

In order to explain the differences between ET_c-FAO, ET_a-EC and ET_a-LYS, we investigated the variations in radiation, vegetation and temperature regime and their impact on ET in more detail. The albedo could be estimated according to the measured outgoing shortwave radiation at the EC-station divided by the incoming shortwave radiation, also measured at the EC-station. The yearly mean albedo is 0.228, which is close to the assumed albedo of 0.23 for grassland. However, some periods (i.e. periods with snow cover) have a much higher albedo. Albedo differences cannot explain the fact that reference ET is smaller than ET_a-LYS.

Hence, we examined the effects of vegetation growth with the help of grass length. Figure 7 shows that the grass length measured at the Rollesbroich site is up to 80 cm before cutting. Unfortunately, grass height measurements are not available for the lysimeters but only for the surrounding field. It is assumed, on the basis of information from the video surveilance system, that grass heights generally are in good agreement between lysimeters (lysimeter site) and the surrounding field (lysimeter field). However, the grass harvesting dates of lysimeters and surrounding field deviate in August and September and are given for the lysimeters in Fig. 7. Figure 8 illustrates the differ-

ences of the measured daily ET_a sums between lysimeter and EC. High positive and negative differences up to 2.1 mm day^{-1} were found from March–September 2012. In general, the differences of ET_a-EC and ET_c-FAO show smaller fluctuations than the differences of ET_a-LYS and ET_c-FAO. It is found that lysimeter harvesting affects the ET differences between ET_a-LYS and ET_c-FAO/ET_a-EC. The differences were positiv before harvesting and negative after harvesting indicating ET_a reduction due to the grass cutting effects. For the period from 21 May to 3 July, grass lengths were estimated and linearly interpolated on a daily basis. For this period grass length at the lysimeter site and ET_a-differences between ET_a-LYS and ET_c-FAO correlate well (R^2 = 0.50). These results reflect the discrepancy in ET estimated on the basis of ET_c-FAO calculations with constant K_c and actual ET under conditions of a higher grass height. ET_a differences caused by variations in grass length are also found for the comparison of ET_a-EC with ET_a-LYS. For the period from the 24 May to the 24 June, a period with high grass length differences (Fig. 7) between the lysimeter site and the field behind the EC-station, ET_a differences (ET_a-EC - ET_a-LYS) and grass length differences show a good correlation (R^2 = 0.52). During the period with maximum grass length difference (24 May–1 June) ET_a-EC is 26 % higher than ET_a-LYS. The differences between ET_a-EC and ET_c-FAO do not show such a significant correlation with grass heights. This could be related to the EC-footprint, which might include other fields with different grass heights. 80 % of the EC footprint is located within a radius of 100 m of the EC tower, and 70 % in a radius of 40 m, which is the approximate lysimeter distance. Therefore, the ET_a-EC estimations represent a spatial mean of a wider area, where cutting effects are averaged compared to the lysimeter point measurements. Figure 9 shows the mean hourly ET_a rates of lysimeter and EC as well as the FAO reference for 2012. In general, the daily courses and the daily maxima of ET_a-LYS, ET_c-FAO and ET_a-EC correspond well. ET_a-EC shows higher peaks at noon in May and September compared to ET_a-LYS and ET_c-FAO. In contrast, ET_a-LYS exhibits the highest rates from June to August. The absence of a harvest of the lysimeter in August and the first September decade (in contrast to the surrounding fields) leads to potentially increased

lysimeter ET_a measurements as compared to the surroundings due to an island position.

The grass length affects the K_c value, but differences between the reference evapotranspiration and measured actual evapotranspiration can also be related to the weather conditions. Nolz and Cepuder (2013) showed that K_c values of 1.1–1.5 are likely for grassland after rain events (i.e. June, July) and high soil moisture conditions.

In order to examine whether lysimeter measurements could have been affected by a soil temperature regime different from the field, the temperature regimes of the lysimeters were compared to the field temperature. Figure 10 shows the daily mean soil temperature differences between the lysimeters, a nearby SoilNet device (SN 30) and the mean of all available SoilNet devices installed at the southern study site. SoilNet temperatures were measured 5 cm below surface; lysimeter temperature measurements were conducted with SIS sensors in 10 cm depth. The temperature differences between the lysimeter and the nearby SoilNet device and the SoilNet mean are less than 1 K, which is as well the range of variation of the SoilNet device with respect to the SoilNet mean. In general the temperature differences increase until noon and then decrease again. Positive differences from May to July indicate warmer lysimeter soil temperatures than the surroundings. However, a clear indicator for a bias caused by an oasis effect in the lysimeter measurements was not found. Feldhake and Boyer (1986) describe the effect of soil temperature on evapotranspiration for different grass types, which allow an estimation of ET_a increase caused by a differing lysimeter temperature regime. They showed that daily ET_a rates can increase with an increase of soil temperature (i.e. daily Bermuda grass ET_a rate increases from 4.3 to 6.4 mm day^{-1} (49 %) for a soil temperature increase from 13 to 29 °C). We used this linear relationship to roughly estimate the effect on ET_a for the period May–August on a daily basis. For this period the measured soil temperature with SN(30) for daylight hours ranged between 9.5 and 15.1 °C and between 9.3 and 15.5 °C for the lysimeter mean (SIS sensors). The mean difference is 0.67 K. This results in a total ET_a increase of 8.8 mm or 2.5 % in relation to the total ET_a-LYS of 349 mm on the basis of hourly ET. Therefore, the

effect of increased soil temperature in the lysimeter is most probably limited, but not negligible.

4 Conclusions

This study compares evapotranspiration and precipitation estimates calculated using a set of six redundant weighable lysimeters with nearby eddy covariance and precipitation measurements at a TERENO grassland site in the Eifel (Germany) for one year (2012). The minutely resolved lysimeter data are processed with the AWAT filter (Peters et al., 2014), which takes account of the lysimeter noise due to random fluctuations caused by changing weather conditions. Additional precipitation measurements were conducted with a classical Hellmann type tipping bucket and compared with lysimeter data. For the ET_a comparison eddy covariance (EC) data is corrected for the energy balance deficit using the Bowen ratio method. FAO standard grass reference evapotranspiration corrected for grass height variations (ET_c-FAO) was calculated according to the FAO crop approach for grassland (Allen, 2000).

The estimated hourly precipitation amounts derived by lysimeter and tipping bucket data show significant differences and the total precipitation measured by the lysimeter is 16.4 % larger than the tipping bucket amount. The relative differences in the monthly precipitation sums are small in the summer period, whereas high differences are found during the winter season. The winter months with snow precipitation exhibit the lowest correlations between lysimeter and tipping bucket amounts. Precipitation was measured by six different lysimeters and yearly amounts for individual lysimeters showed variations of −3.0 to 1.0 % compared to the yearly precipitation mean over all lysimeters. In order to explain the differences in precipitation between the devices the contribution of dew, rime and fog to the yearly precipitation was analyzed. This was done by filtering the data for typical weather conditions like high relative humidity, low wind speed and negative net radiation which promote the development of dew and rime. For the identified cases a check was made with a visual surveillance sys-

tem whether dew/rime was visible. During these conditions the lysimeter shows clearly larger precipitation amounts than the TB, which explains 16.9 % of the yearly precipitation difference. Fog and drizzling rain conditions, additionally identified with the help of the on-site camera system, explain another 5.5 % of the yearly precipitation differences. These findings indicate an improved ability of the lysimeters to measure dew and rime as well as fog and drizzling rain. The remaining 78 % of the precipitation difference between lysimeters and tipping bucket is strongly related to snowfall events, as under those conditions large differences were found. Lysimeter precipitation measurements are affected by a relatively high measurement uncertainty during winter weather conditions similar to TB and other common measurement methods. Thus, the limitations for the lysimeter precipitation measurements during those periods need further investigation. We found that during conditions where the lysimeters were completely covered by snow, lysimeter records were unreliable, and contributed to 36 % of the total precipitation difference.

Actual evapotranspiration measured by the eddy covariance method (ET_a-EC) and lysimeter (ET_a-LYS) showed a good correspondence for 2012, with larger relative differences and low correlations in winter in contrast to high correlations and smaller relative differences in summer. The variability of ET_a of the individual lysimeters in relation to the lysimeter average was –7.9 to 3.1 % in 2012 with larger absolute differences in summer. Both ET_a-EC and ET_a-LYS, were close to the calculated crop reference evapotranspiration (ET_c-FAO), which indicates that evapotranspiration at the site was not limited by soil moisture, but by energy. The differences between ET_a-LYS, ET_a-EC and ET_c-FAO were mainly related to harvesting management at the study site. A relationship between grass length at the lysimeter and differences between ET_c-FAO and ET_a-LYS was found. Variable grass cutting dates for different fields around the EC-station and the lysimeter harvest lead to differences in actual evapotranspiration up to 2.1 mm day^{-1} for periods with larger grass length discrepancies.

The correction of the energy balance deficit with the Bowen ratio method resulted in ET_a-EC which was close to ET_a-LYS. If the correction was not applied, ET_a was

16 % smaller than for the case where it was applied. In contrast, if the EB-deficit was completely attributed to the latent heat flux ET_a was 15.7 % larger than for the default case. These results point to the importance of adequate EC data correction.

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Table 1. Monthly precipitation sums for lysimeter and tipping bucket, and a comparison between the hourly precipitation values of lysimeter and TB in terms of coefficient of determination (R^2), root mean square errors and other statistics at the Rollesbroich study site for 2012. Missing data provides the percentage of hourly precipitation not available for comparison.

Month	Lysimeter average [mm]	Min./Max. lysimeter [mm]	Tipping bucket [mm]	R^2	RMSE	LYS/TB %	Missing data %
Jan	70.9	57.6/79.3	94.0	0.48	0.30	75.6	11.2
Feb	36.2	31.4/48.9	21.1	0.13	0.32	171.6	46.1
Mar	17.3	16.2/18.8	5.1	0.18	0.16	339.2	16.4
Apr	72.5	71.1/74.6	65.3	0.90	0.09	111.0	0.0
May	90.7	89.4/94.1	79.3	0.99	0.09	114.4	0.0
Jun	139.9	137.5/143.1	134.7	0.96	0.21	103.9	0.0
Jul	148.5	146.3/152.2	147.0	0.95	0.28	101.0	0.0
Aug	105.7	100.4/109.4	84.5	0.94	0.15	125.1	0.0
Sep	36.5	23.5/39.2	25.6	0.58	0.13	142.6	0.0
Oct	67.5	65.7/69.5	66.2	0.74	0.23	102.0	13.4
Nov	55.3	52.7/56.9	38.3	0.84	0.08	144.4	0.0
Dec	186.0	178.5/194.4	121.0	0.30	0.35	153.7	0.0
SUM/MEAN	1027.1	996.2/1037.7	882.1	0.88	0.47	116.4	7.1

Table 2. Monthly ET_a (by lysimeter and EC), ET_c-FAO sums and R^2 between different ET data products on an hourly basis for 2012. Missing data provides the percentage of hourly daytime ET (ET_a-EC, ET_a-LYS) not available for comparison. Hence, the total yearly ET amount is ca. 18 % reduced compared to gap free ET estimations. Missing data provides the percentage of hourly evapotranspiration data (sunrise–sunset) not available for comparison.

| | 2012 | | | | | | | | | | | | |
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Sum/Mean
ET_a-EC [mm]	5.2	1.3	27.8	38.4	84.3	62.7	80.3	94.2	56.0	25.2	9.3	3.6	**488.3**
ET_c-FAO [mm]	3.9	1.5	33.2	35.3	80.9	61.3	77.3	94.0	55.3	25.8	9.4	2.7	**480.5**
ET_a-LYS [mm]	2.5	2.2	26.4	35.6	80.2	65.7	82.7	121.7	52.7	23.9	7.6	5.9	**507.4**
Min./Max. ET_a-LYS [mm]	2.1/ 2.7	1.3/ 3.1	25.9/ 26.8	34.4/ 37.6	75.2/ 85.2	62.1/ 68.2	67.8/ 91.0	116.8/ 125.2	49.6/ 58.8	21.9/ 27.1	6.8/ 8.9	3.0/ 8.7	**467.1/ 523.1**
R^2 ET_a-EC – ET_a-LYS	0.02	0.02	0.82	0.76	0.79	0.84	0.86	0.86	0.66	0.66	0.39	0.06	**0.81**
R^2 ET_a-LYS – ET_c-FAO	0.13	0.03	0.87	0.81	0.82	0.89	0.87	0.95	0.68	0.70	0.42	0.08	**0.85**
R^2 ET_a-EC – ET_c-FAO	0.12	0.00	0.94	0.92	0.96	0.92	0.90	0.90	0.94	0.83	0.74	0.45	**0.93**
Missing Data %	33.2	36.9	8.1	23.5	21.5	26.5	21.9	12.9	14.0	25.8	25.0	45.3	**24.5**

Table 3. Measured mean monthly latent heat fluxes and corrections for EBD for 2012.

Month	Mean LE $[\mathrm{W\,m^{-1}}]$	Mean LE corr. $[\mathrm{W\,m^{-1}}]$	Differences LE corr. – LE	Difference mean LE corr. – LE %
Jan	21.9	29.8	7.9	36.2
Feb	8.7	11.9	3.2	36.9
Mar	78.1	94.0	15.9	20.4
Apr	86.4	101.8	15.3	17.7
May	138.7	164.6	25.9	18.7
Jun	111.8	125.8	14.0	12.6
Jul	136.3	157.2	20.9	15.3
Aug	151.6	181.4	29.8	19.6
Sep	104.0	129.2	25.2	24.2
Oct	61.3	79.6	18.3	29.9
Nov	24.4	32.1	7.7	31.4
Dec	22.0	28.3	6.3	28.5
SUM/MEAN	78.8	94.6	15.9	24.3
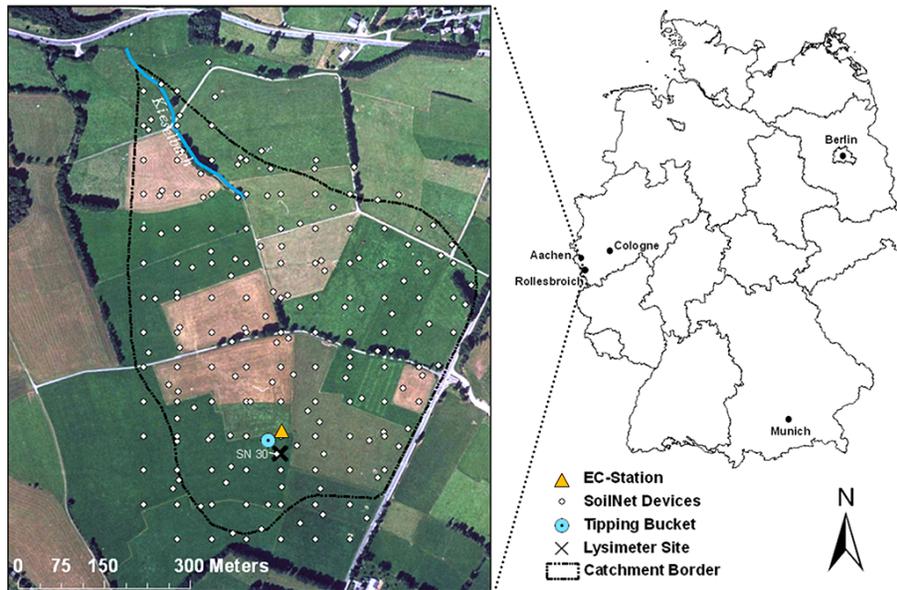
Figure 1. Overview of the Rollesbroich study site (left panel) showing the locations of the lysimeter, the rain gauge, the eddy covariance station, the catchment boundaries and the Soil-Net devices. All devices are arranged within a radius of 50 m including the nearest SoilNet device (SN 30) for comparisons of temperature and soil water content with the surrounding field. The map on the right shows the location of the Rollesbroich catchment in Germany.

Figure 2. The lysimeter set-up of the Rollesbroich study site (November 2012).
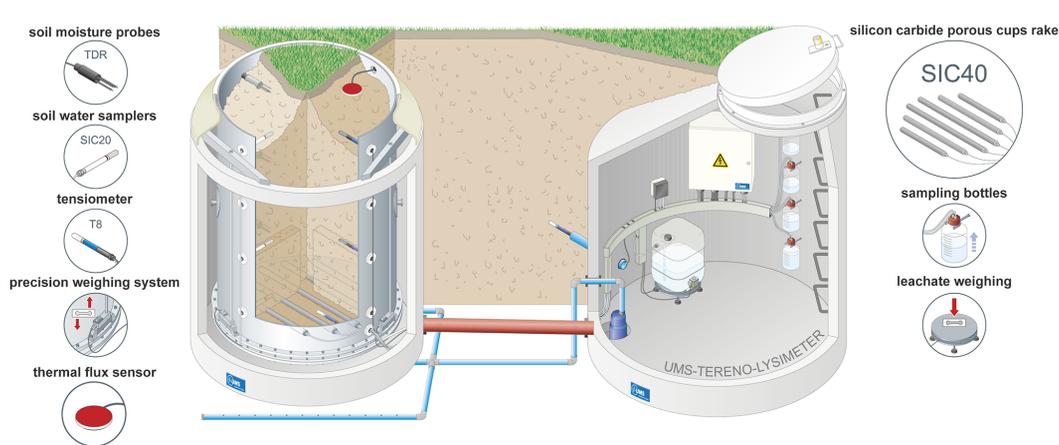
Figure 3. Schematic drawing of the lysimeter soil monolith (left panel) and service well (right panel) used in the TERENO-SoilCan project. The illustration of the lysimeter (left panel) shows the weighted soil column container with slots for soil moisture (TDR), temperature (SIS, TS1), matric potential sensors (SIS), soil water sampler (SIC20) and silicon porous suction cup rake (SIC40) installation inside and outside the monolith. The service well contains the weighted drainage tank and sampling tubes for each affiliated lysimeter (courtesy of UMS GmbH Munich, 2014, used by permission).
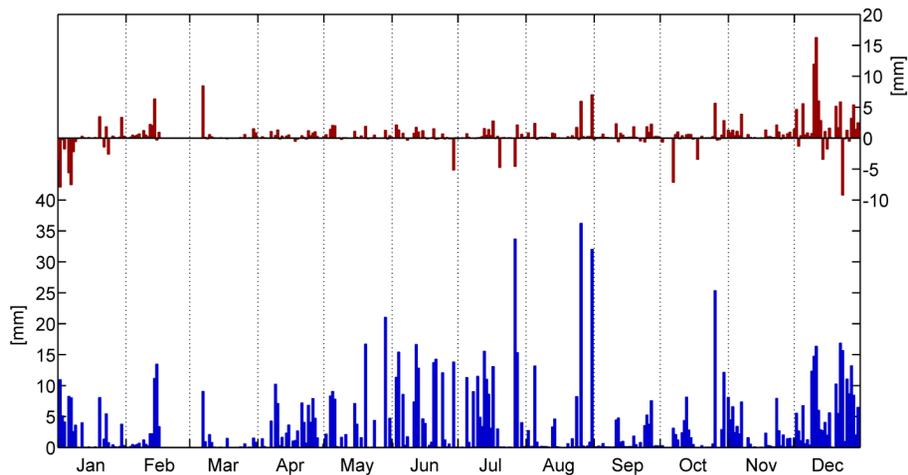
Figure 4. Daily precipitation sums of tipping bucket (blue) and difference in precipitation measurements between lysimeter and TB (red) at the Rollesbroich study site for 2012.
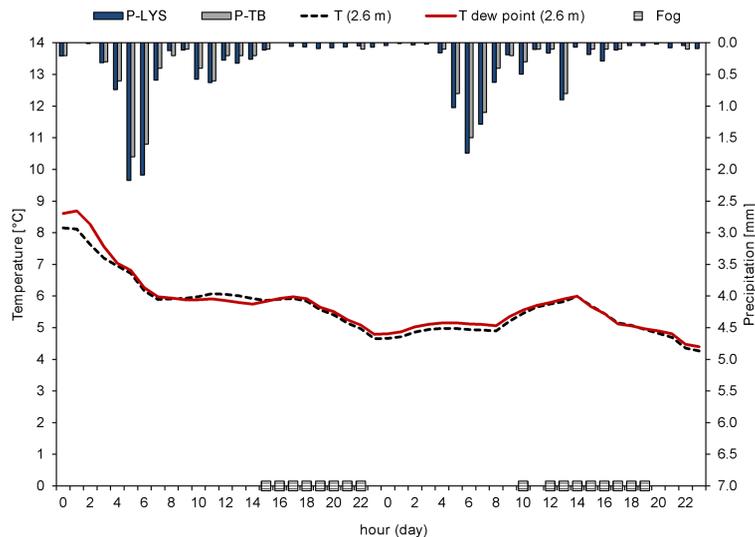
Figure 5. Precipitation, temperature and dew point temperature from 5–6 May 2012 at the Rollesbroich site. The fog symbol indicates the hours with fog occurrence (detected with installed surveillance system) for the investigated period.
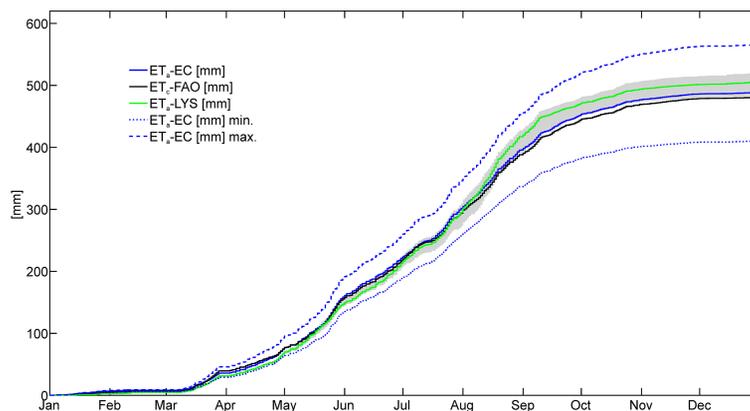
Figure 6. Cumulative ET_a-LYS, ET_a-EC (corrected according to Bowen ratio) and ET_c-FAO on hourly basis for 2012. Displayed are also ET_a-EC max. and ET_a-EC min. The area in grey shows the range of minimum and maximum cumulated ET_a for the individual lysimeters. For explanation see text.

Figure 7. Grass heights at the lysimeter field and the field behind the EC station for 2012. The EC device is centrally located in between these two fields. The star (∗) indicates the presence of a snow cover. Grass cutting dates on lysimeter devices are marked by dashed lines. For further explanations see text.

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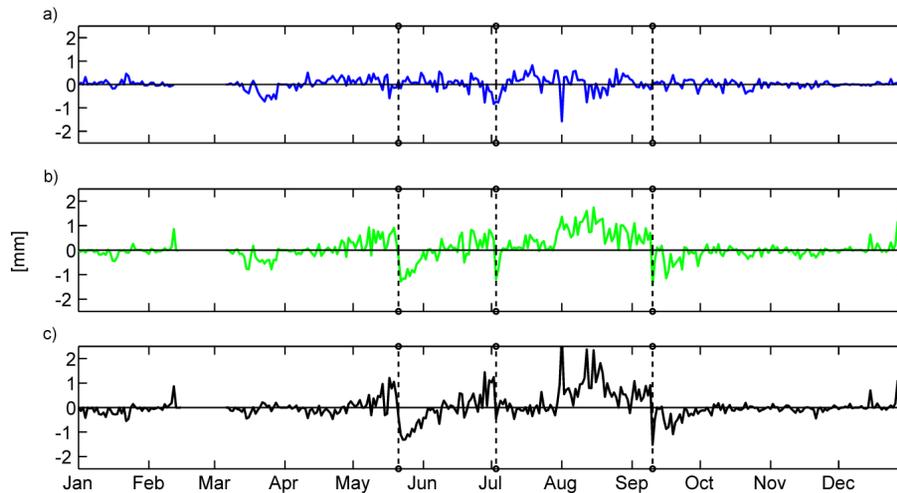
Figure 8. Differences between daily ET for 2012. Displayed are ET_a-EC − ET_c-FAO **(a)**, ET_a-LYS − ET_c-FAO **(b)** and ET_a-LYS − ET_a-EC **(c)**. The dashed lines indicate harvest at lysimeters. For explanation see text.
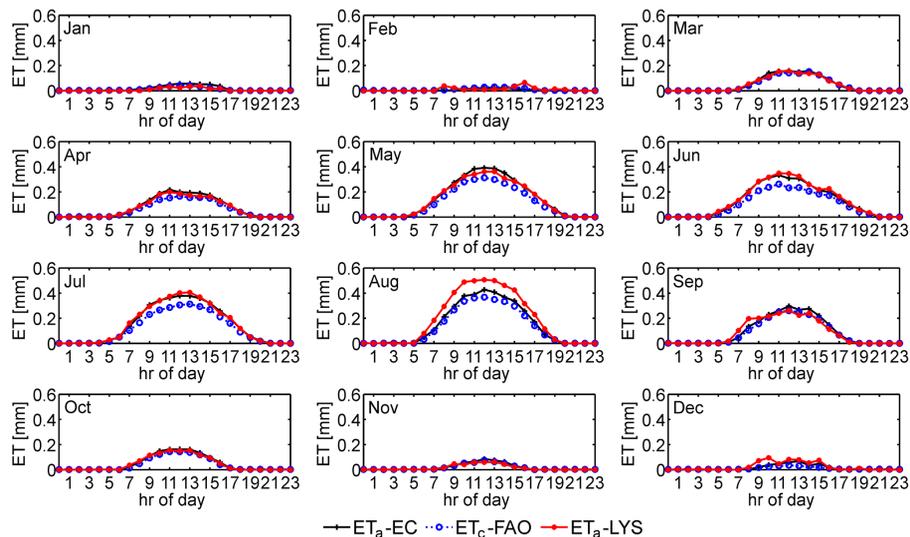
Figure 9. Mean hourly rates of ET_a-LYS, ET_a-EC and ET_c calculated according FAO for 2012.
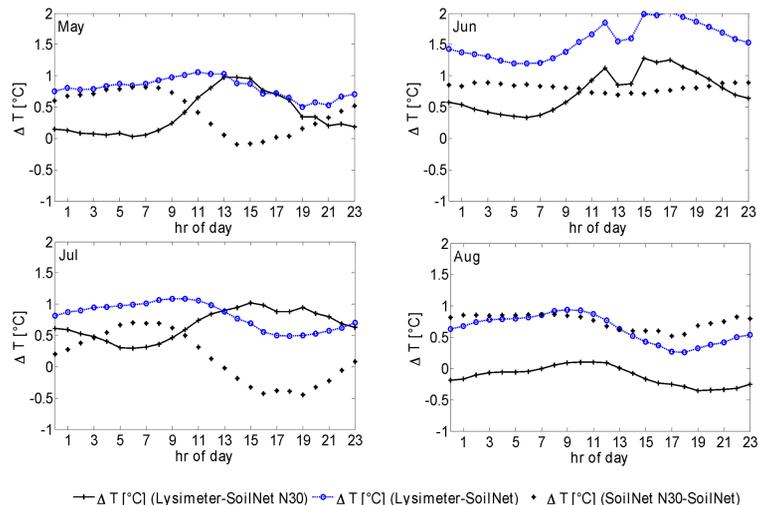
Figure 10. Differences in daily mean soil temperature (averaged over the six lysimeters), a nearby SoilNet device (SN 30) and the mean of all available SoilNet devices located at the study site.