Evaluation of precipitation measurement methods using data from precision lysimeter network

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Abstract. Accurate precipitation data are essential for assessing the water balance of ecosystems. Methods for point precipitation determination are influenced by wind, precipitation type and intensity and/or technical issues. High-precision weighable lysimeters provide precipitation measurements at ground level that are less affected by wind disturbances and are assumed to be relatively close to actual precipitation. The problem in previous studies was that the biases on precipitation data introduced by different precipitation measurement methods were not comprehensively compared and quantified with those obtained by lysimeters under different regions in Germany.

The aim was to quantify measurement errors of standard precipitation gauges as compared to the lysimeter reference and to analyse the effect of precipitation correction algorithms on the gauge data quality. Both correction methods rely on empirical constants to account for known external influences on the measurements, following a generic and a site-specific approach. Reference precipitation data were obtained from high-precision weighable lysimeters of the TERrestial Environmental Observatories (TERENO)-SOILCan lysimeter network. Gauge types included tipping bucket gauges (TBs), weighable gauges (WGs), acoustic sensors (ASs), and optical laser disdrometers (LDs). From 2015-2018, data were collected at three locations in Germany and 1-hour aggregated values for precipitation above a threshold of 0.1 mm h^{-1} were compared.

The results show that all investigated measurement methods underestimated the precipitation amounts relative to the lysimeter references for long-term precipitation totals with catch ratios (CRs) between 33–92 %. Data from ASs had overall biases of -0.25 to -0.07 mm h^{-1}, while data from WGs and LDs showed the lowest measurement biases (-0.14 to -0.06 mm h^{-1} and -0.01 to -0.02 mm h^{-1}). Two TBs showed systematic deviations with biases of -0.69 to -0.61 mm h^{-1}, while other TBs were in the previously reported range with biases of -0.2 mm h^{-1}. The site-specific and generic correction schemes reduced the hourly measurement bias by 0.13 and 0.08 mm h^{-1} for the TBs and by 0.09 and 0.07 mm h^{-1} for the WGs and increased long term CRs by 14 and 9 % and by 10 and 11 %, respectively.

It could be shown that the lysimeter reference operated with minor uncertainties in long-term measurements under different site and weather conditions. The results indicate that considerable precipitation measurement errors can occur even at well-maintained and professionally operated stations equipped with standard precipitation gauges. This generally leads to an underestimation of the actual precipitation amounts. The results suggest that the application of relatively simple correction schemes, manual or automated data quality checks, instrument calibrations and/or adequate choice of observation periods can help improve the data quality of gauge-based

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Margin comments:

Kommentiert [TS1]: Reviewer 2 (R2):
L15: change "true" to actual

Kommentiert [TS2]: R2:
L17: remove "under different climate conditions" -> your current data collection is limited in this regard (e.g., similar mean annual precipitation & temperatures, almost no snow events, heavy precipitation events)

Kommentiert [TS3]: R2:
L23: acoustic sensors

Kommentiert [TS4]: R2:
L24: rephrase: … 1-hour aggregated values above a threshold of 1mm h were compared.

Kommentiert [TS5]: R2:
L30: hourly measurement bias

Kommentiert [TS6]: Formatting

Kommentiert [TS7]: R2:
L30: hourly measurement bias

Kommentiert [TS8]: R2:
L17: remove "under different climate conditions" -> your current data collection is limited in this regard (e.g., similar mean annual precipitation & temperatures, almost no snow events, heavy precipitation events)

Kommentiert [TS9]: R2:
L34: rephrase: generally lead to recording lower precipitation amounts
L 35: rephrase: therefore might contain significant uncertainties.

Kommentiert [TS10R9]: Restructured and rephrased the sentence.

Kommentiert [TS11]: grammar

measurements for water balance calculations, ecosystem modelling, water management, assessment of agricultural irrigation needs or radar-based precipitation analyses.

1 Introduction

~~The terrestrial part of the hydrological cycle begins typically with events of precipitation or non-rainfall water.~~ Exact precipitation data are essential to determine the ecosystem water balance within the soil-plant-atmosphere continuum (Porporato and Rodriguez-Iturbe, 2002). To obtain information on local precipitation amounts, point precipitation measurements are carried out using catching and non-catching precipitation gauges (WMO, 2018). At regional and global
50 scales, precipitation measurement networks connecting a variety of rain gauges provide data to calibrate radar precipitation estimates, climate models and hydrological cycles (Michaelides et al., 2009; Tapiador et al., 2017). Therefore, point precipitation measurements have been intensively studied and several methods for determining precipitation have been developed (WMO, 2018). Depending on the design and functionality of the measuring devices, different errors were identified that affect the precipitation measurements (e.g., Fuchs et al., 2001; Sevruk, 1987; Sevruk and Chvíla, 2005) and therefore also
55 hydrological models (Bárdossy et al., 2022). Especially the influence of wind has been shown to negatively affect point precipitation measurements (Chvíla et al., 2005; Duchon and Essenberg, 2001; Pollock et al., 2018; Sevruk et al., 1989). The effect depends on wind speed, shielding, the shape of the precipitation gauge and the size, phase and fall velocity of the hydrometeors (Kochendorfer et al., 2017b; Sevruk and Nespor, 1994; Wolff et al., 2015). The use of wind shields (Alter, 1937; Nipher, 1878) can reduce the measurement bias, depending on the shields' design (Kochendorfer et al., 2017a; Watson et al.,
60 2008; Yang et al., 1999a). In order to quantify erroneous point precipitation measurements and to minimise the influence of wind, ground-level gauges were developed (Goodison et al., 1998; Lanza and Vuerich, 2009; Sevruk and Hamon, 1984). The data obtained from these gauges were used as a reference for comprehensive comparisons of precipitation gauges for solid (Goodison et al., 1998) and liquid precipitation (Lanza and Vuerich, 2009). The comparative studies led to the development of correction methods that are applied during the post-processing of the data (Førland et al., 1996; Richter, 1995; Sevruk,
65 1982).

Weighable lysimeters were recognised in the 1960s as reference system for precipitation gauge comparisons with measurements at the soil surface (McGuiness, 1966; Morgan and Lourence, 1969). Lysimeters were originally developed to determine and quantify soil and plant related processes such as drainage, evapotranspiration, ion exchange, root development and solute transport (Goss and Ehlers, 2009; Hertel and Unold, 2013). A direct determination of precipitation with weighable
70 lysimeters has been limited in the past by relative coarse temporal resolution (> 10 minutes to daily) and precision. Within the TERrestial Environmental Observatories (TERENO)-SOILCan lysimeter network, high-precision weighable lysimeters are used that are operating with a high temporal resolution (< 1 minute; Pütz et al., 2016). These lysimeters have been successfully used for monitoring precipitation, dew and hoar frost for soil-ecosystems (Gebler et al., 2015; Groh et al., 2018b; Schrader et al., 2013) with a greater resolution and precision than most common gauges (Xiao et al., 2009b).

75 To assure data quality and reliable accuracy of lysimeter-derived precipitation measurements, Marek et al. (2014) stated, that the pre- and post-processing of lysimeter data were highly important. Time series of lysimeter mass changes are oscillating and temporally autocorrelated (Herbrich and Gerke, 2016). Noise filtering algorithms have therefore been developed since the 2010s to reduce the influence of ambient noise on the data (Hannes et al., 2015; Nolz et al., 2013; Peters et al., 2014; Ross et al., 2020; Vaughan and Ayars, 2009) . The "adaptive window and threshold filter" (AWAT; Peters et al., 2014) executes two
80 steps to process the data towards a correction of time-variable noise levels (Peters et al., 2017; Peters et al., 2016). This filter solved the problem of underestimating the lysimeter mass change signals at the turning point from precipitation to evapotranspiration or vice versa; it yields an almost unbiased representation of the real signal which is especially important

Kommentiert [TS12]: R2:
L41 remove first sentence of introduction

for the quantification of smaller flux rates such as those caused for instance by dew formation (Groh et al., 2018b; Xiao et al., 2009a).

85   The increased lysimeter data quality (i.e. precision and temporal resolution) has already led to a number of studies that compared lysimeter measurements with those of other precipitation gauges (Gebler et al., 2015; Haselow et al., 2019; Hoffmann et al., 2016; Kohfahl and Saaltink, 2020; Schrader et al., 2013). Gebler et al. (2015) found a 16 % underestimation of tipping bucket gauge (TB) measured precipitation totals compared to lysimeter data for one year, with 17 % of the difference due to rime and dew and 5.5 % due to fog and drizzle. Snow formation also contributed to the deviations, although the authors

90   identified problems with snow bridges and snow drift interfering with the lysimeter measurements (Gebler et al., 2015). Haselow et al. (2019) compared precipitation measured with a piezoelectric precipitation sensor, a standard TB and a weighable lysimeter. They found an underestimation by the TB and an overestimate by the piezoelectric sensor compared to the lysimeter measurements. Kohfahl and Saaltink (2020) compared precipitation measurements of a precision lysimeter with two TBs and one weighable rain gauge. The authors found good agreement between the measured data from one TB rain gauge,

95   the weighable rain gauge and the lysimeter, while recommending correction of the data from the other TB which underestimates precipitation intensities compared to the lysimeter reference.

Within the framework of the TERENO-SOILCan lysimeter network, numerous point precipitation measurement gauges are under operation, producing data with 10-min resolution (Pütz et al., 2016). Up to four different rain gauges are installed in the immediate vicinity of the lysimeter stations and their data can be publicly accessed through the TERENO data platform

100   (https://ddp.tereno.net/ddp/; for details see "Data availability"; Kunkel et al., 2013). The lysimeter data available within the network is comprehensively processed and tested and has been used for a variety of studies in the field of soil and plant sciences (Groh et al., 2019; Groh et al., 2020a).

For this study, we hypothesise that values derived from hourly precipitation data of high-precision weighable lysimeters can function as reference for a comparison of multiple precipitation measurementing methods. To test this, data from multiple

105   lysimeters installed at respective test sites are graphically compared via scatter plots, a correlation coefficient, and deviations to the arithmetic mean. Furthermore, we hypothesise that if the precipitation measurements of the considered methods are affected by external influences, then the gauge measurements should be on average lower than the ones determined by the lysimeter references for all devices of the same gauge model at all sites. To test this, we compare hourly precipitation amounts as well as long-term precipitation totals determined by these measurement methods with reference data derived from high-

110   precision weighable lysimeter data via scatter plots and appropriate statistics for all three sites, also considering measurement uncertainties. The final hypothesis is that the use of precipitation correction methods that consider the influence of wind and other typical sources of error on the instruments will reduce the bias between reference and measurements and increase the data quality close to zero. Therefore, two correction methods are applied on the tipping bucket and weighable gauge data during post-processing, and the influence on the bias and overall deviations from the references is studied by comparing the

115   resulting data with the reference lysimeter-based precipitation.

To conduct this study, high-quality long-term data of four years (2015–2018) from 15 lysimeters, four different types of precipitation measurement methods (11 devices) of three research sites and local weather data with a resolution of 1 hour are available.

2 Material and methods

120   ### 2.1 Research sites

The data were collected at research sites near Dedelow (DD), Rollesbroich (RO) and Selhausen (SE) in Germany, which are all part of the TERENO-SOILCan network (Fig. 1; Pütz et al., 2016). The TERENO-SOILCan lysimeter network itself belongs to the TERENO project (Zacharias et al., 2011) and comprises twelve different lysimeter research sites in Germany (Pütz et al., 2016). The network purpose is to enable insights into effects of climate change on arable and grassland ecosystems,

125 including water balance components. To achieve this, a modified space-for-time concept was used, where lysimeters filled with four different soils have been transferred within the TERENO observatories to simulate a time-induced change of climate through a space-induced change of climate for studying effects on crop productivity and soil water and plant nutrient balances (Groh et al., 2020a; Groh et al., 2020b; Pütz et al., 2016). The lysimeters have been used to estimate precipitation and actual evapotranspiration (Gebler et al., 2015; Groh et al., 2019; Schrader et al., 2013) as well as non-rainfall water that arises from
130 the formation of dew, hoar frost and rime (Groh et al., 2018b; Meissner et al., 2007).
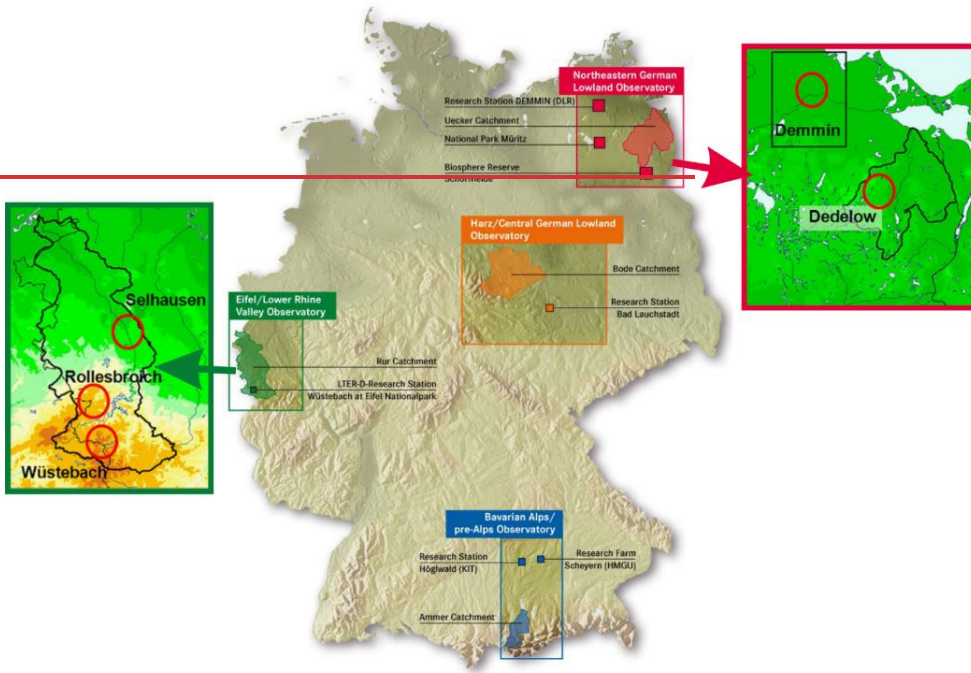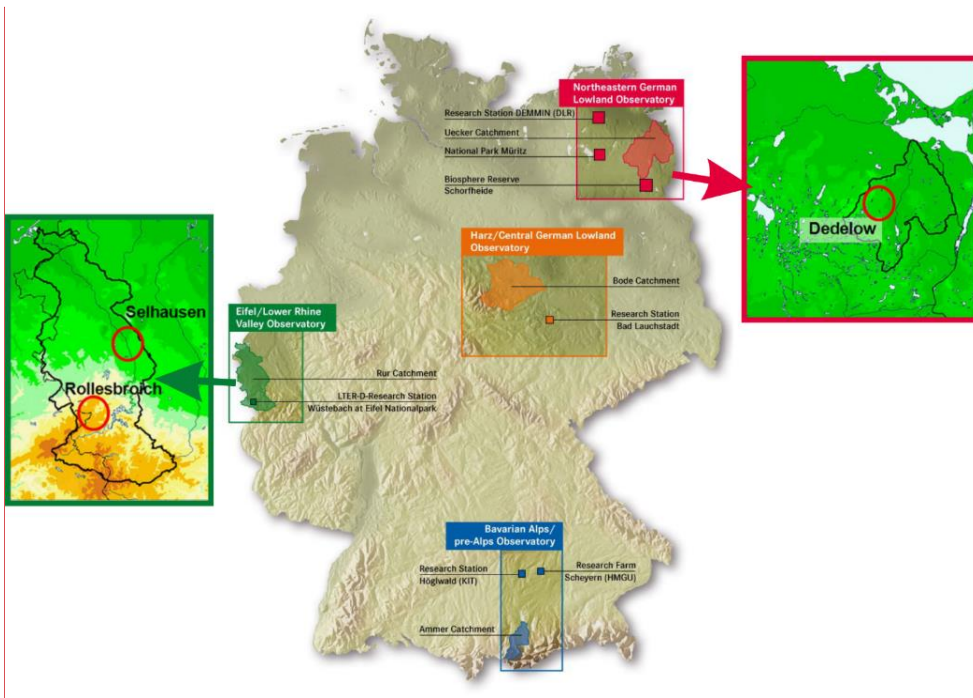
Figure 1: The TERrestial Environmental Observatories (TERENO)-SOILCan network (adapted from Pütz et al., 2016). The data for this study was collected at sites near Dedelow (Northeastern German Lowland Observatory), Rollesbroich and Selhausen (both Eifel/Lower Rhine Valley Observatory).

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RO, as part of the Eifel/Lower Rhine Valley Observatory, is situated in the northern part of the Eifel, which is a low mountain range in Western Germany (Bogena et al., 2018). The area is widely open, and comprises extensively used grassland and is located 511 m above sea level. The elevation of the site (511 m above sea level) leads to a mean annual precipitation of 1063 mm a⁻¹ (DWD, 2021a; 50°38'; 06°12') and a mean annual temperature of 7.7 °C (DWD, 2021b; 50°38', 06°12').

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The site in SE is situated in the plain lower Rhine valley and is surrounded by extensively used arable land (Bogena et al., 2018). It is located in the temperate maritime climate zone with a mean annual temperature of 9.8°C (DWD, 2021b; 50°56', 06°34') and a mean annual precipitation of 723 mm a⁻¹ (DWD, 2021a; 51°56', 06°34').

The test site near DD is in the Northeastern German Lowland Observatory of TERENO (Heinrich et al., 2018), approximately 100 km north of the city of Berlin. At the site, a hummocky ground moraine landscape is characterized by lakes and arable

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land (Heinrich et al., 2018). More information on the sites is provided in Table 1. The lysimeter station is surrounded by arable land. A mean annual temperature of 7.9 °C (DWD, 2021b; 53°19', 13°56') and a mean annual precipitation of 504 mm a⁻¹ (DWD, 2021a; 53°17', 13°56') have been determined for the area around the test site in Dedelow.

Table 1: Information on site characteristics, annual mean precipitation (DWD, 2021a) and annual mean temperature (DWD, 2021b) based on multi-year averages (1961 – 1999).

	Mean annual precipitation (mm)	Mean annual temperature (°C)	Coordinates (N ° ', E ° ')	Dominant land use (-)
Rollesbroich	1063	7.7	50°37', 06°18'	Grassland
Selhausen	723	9.8	50°52', 06°27'	Arable land
Dedelow	504	7.9	53°22', 13°48'	Arable land

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2.2 Equipment and data collection

2.1.1 TERENO-SOILCan Lysimeter

The weighable high-precision lysimeters used within the TERENO-SOILCan network are comparable to the "Scientific Field Lysimeter" described by Unold and Fank (2008). The lysimeters are equipped with soil moisture probes, soil water sampling
155 devices, tensiometer, a precision weighable system, a thermal flux sensor and silicon carbide porous suction cups (Pütz et al., 2016). Every lysimeter has a surface of 1 m² and a depth of 1.5 m. They are connected to a central service well which contains the power supply, data loggers, measuring transducers, pumps, seepage water tanks including weighable systems, sampling bottles and a data modem (Pütz et al., 2016). For detailed information about the installed sensors and the lysimeter filling, see Pütz et al. (2016) and Hertel and Unold (2013).
160 All lysimeters used in this study are of the same type and disposed in lysimeter stations which comprise at least one hexagon of six lysimeters placed around the central service well (Fig. 2 A~~B~~; Pütz et al., 2016). The hexagon area covers approximately 49 m² in total (Fig. 2A). The precipitation gauges and weather stations are located directly adjacent (Fig. 2 B), except for one tipping bucket gauge in Rollesbroich, which is located around 30 meters from the respective lysimeter hexagon.
The weighable systems within the lysimeter consist of three load cells (Model 3510, Tedea-Huntleigh, Canoga Parl, CA, USA)
165 with a resolution of 10 g $\cong$ 0.01 mm precipitation and are mounted at each lysimeters bottom. A gap between lysimeter and the concrete housing is closed with a synthetic resin collar, which is covered with surrounding soil. The small remaining gap between the collar and the lysimeter is closed with silicone foil fixed at the resin collar, but without any direct contact to the lysimeter vessel to prevent any disturbance on the lysimeter weighing. This ensures a smooth suspension and weighing of the
170 lysimeter (Pütz et al., 2016). The lysimeters were intensively maintained at least every week and the incoming data were daily checked for irregularities and anomalies. To ensure a stable environment for the observations, the type of lysimeter filling remains the same during the observation period. The surrounding areas were similarly managed as the lysimeters to prevent an "isle effect", that would have affected the determination of precipitation due to exposed vegetation (Hagenau et al., 2015). On the arable lysimeters the crop rotation was winter wheat, winter barley, winter rye and oat during the observation period (2015–2018). No catch crop between the growing seasons was grown. In general, the agricultural activities were in accordance
175 with common agricultural practice (Pütz et al., 2016). The grass lysimeters were cut three to four times per year.
Based on the mass changes of a lysimeter and a seepage water tank, the water fluxes across the soil surface were calculated using the lysimeter water balance (Schrader et al., 2013). The water balance equation for a lysimeter follows:

$$\Delta W = P + NRW~AWI - ET_a - D,\tag{1}$$

$$AWI = P + NRW,\tag{2}$$

180 where ΔW is the change in the lysimeter mass, AWI the atmospheric water input, ~~P the precipitation, NRW non-rainfall water,~~ ET_a the actual evapotranspiration,~~ and~~ D the drainage, P the precipitation and NRW non-rainfall water. The amount of precipitation is calculated from any increase in lysimeter mass after correction with water fluxes across the lysimeter bottom. It was assumed that no evaporation or transpiration occurred during the specific time period (Schneider et al., 2021; Schrader et al., 2013; Eq. 2~~3~~). Any decrease of the lysimeter mass change after the correction with fluxes across the lysimeter
185 bottom can thus be related to evapotranspiration if no precipitation occurred during this time interval (Eq. 3~~4~~).

$$AWIP_i = \begin{cases} WL_i - WL_{i-1} + WT_i - WT_{i-1} > 0 \\ 0\ for\ WL_i - WL_{i-1} + WT_i - WT_{i-1} \le 0 \end{cases},\tag{2\,3}$$

$$ET_i = \begin{cases} -(WL_i - WL_{i-1} + WT_i - WT_{i-1}) \\ for\ WL_i - WL_{i-1} + WT_i - WT_{i-1} < 0, \\ 0\ for\ WL_i - WL_{i-1} + WT_i - WT_{i-1} \ge 0 \end{cases},\tag{3\,4}$$

where $AWIP_i$ is the ~~precipitation amount~~ atmospheric water input during time interval i (kg), WL is the lysimeter mass in terms of the weight (kg), WT is the seepage tank weight (kg) and ET_i is the evapotranspiration amount during time interval i (kg).

Kommentiert [TS18]: R1:
"9) L151 – what is the hexagon area?"
Revision: Reference should be Fig. 2 A, not 2 B. Here the hexagon area is marked across the six lysimeters in equidistance to the control shaft in the middle. Fig. 2 B shows two of the hexagonal lysimeter arrangements in a row. We added a scale and more information to the plot.

Kommentiert [TS19R18]: Reference should be Fig. 2 A, not 2 B. Here the hexagon area is marked across the six lysimeters in equidistance to the control shaft in the middle. Fig. 2 B shows two of the hexagonal lysimeter arrangements in a row. We added a scale and more information to the plot.

Kommentiert [TS20]: R1:
"[...] There is no information about the size of the hexagon [...]"

Kommentiert [TS21]: Improved readability.

Kommentiert [TS22]: R1:
"2) Eq. 2: I assume P here includes NRE? It is unclear why NRE is presented in Eq. 1 but ignored until section 2.5.1. How come? Please clarify this."

Kommentiert [TS23R22]: We introduced the term AWI to differentiate between precipitation and non-rainfall water and to improve the accuracy of our formulations. We also adjusted chapter 2.3 and 2.4 accordingly.

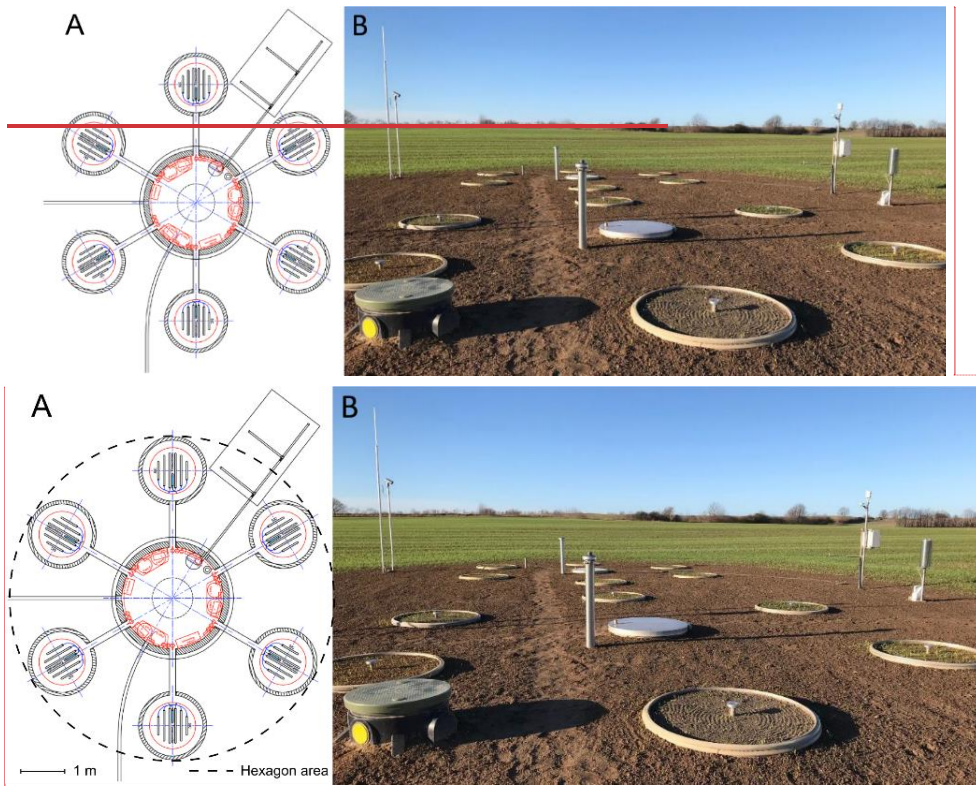



Figure 2: A) Technical drawing of the lysimeter hexagon from birds view (from Pütz et al., 2016, provided by UMS AG, Munich, Germany). Six lysimeter with surface areas of 1 m² each are located equidistant from the central service well. B) Two lysimeter hexagons at ZALF´s research station in Dedelow. Tipping bucket and acoustic sensor are installed directly adjacent to the lysimeter (photo by Hannah Kimmich).

Kommentiert [TS24]: R2:
Add distances in Figure 2A.

Kommentiert [TS25]: Clarification.

2.2.2 Precipitation gauges

Two variants of the same tipping bucket gauge model (TB; "ecoTech Umwelt-Meßsysteme GmbH", Bonn, Germany) are used at the test sites, which differ in the collecting surface of 200 cm² for SE and RO and 400 cm² for DD. ~~The measuring mechanism bases on a funnel with an inlet water pipe which leads the caught precipitation into a tipping bucket, which, when filled with a certain amount of water, tips to either side of the sharp edge pivot.~~ The measuring mechanism is based on a funnel with an inlet water pipe. This leads the caught precipitation into a tipping bucket, which, when filled with a certain amount of water, tips to either side of the sharp edge pivot. The motion is determined by the weight imbalance caused by the water dripping from above. The device registers the number of tips with a magnet mounted on the bucket, inducing a signal to a reed switch. A second TB in RO and the TB in DD are additionally equipped with a heating module. The resolution of the TBs is 0.1 mm which indicates an equal volume of one of the buckets compartments.

Kommentiert [TS26]: Shortened sentence and improved readability.

The weighable gauge (WG) used in this study is the model Pluvio² manufactured by Ott Hydromet, Kempten, Germany. It uses load cells to determine the differences in weight in the weighing chamber caused by collected precipitation. The gauge has an orifice with a collecting area of 400 cm², a resolution of 0.01 mm and a minimal cumulative precipitation threshold at 60 min collection time of 0.05 mm h^{-1}. The device outputs real-time and processed data with a time lag of a few minutes. A heating module is installed to prevent solid precipitation from blocking the gauges inlet. It merely heats the collecting ring around the orifice to avoid artificial loss due to evaporation. The model was used as reference gauge in multiple studies (Johannsen et al., 2020; Kochendorfer et al., 2017a; Ryu et al., 2016) and was one of the most widely used WGs according to

a survey within the WMO members in 2008 (Wong and Nitu, 2010). On the 2017/07/19, a single Alter wind shield was installed around the gauge in SE. This type of shield consists of loose hanging lamellas, which are mounted on a concentric ring around the gauge (Alter, 1937) and is widely established to prevent wind loss and recommended by several institutes (Dengel et al., 2018).

The weather station WXT510 (Vaisala Oyi, Helsinki, Finland) is installed at all sites to measure meteorological standard parameter such as wind speed, wind direction, air temperature, relative humidity, and barometric pressure at 2 m height. The station includes the Vaisala RAINCAP® sensor, an acoustic sensor (AS) with a resolution of 0.01 mm h^{-1} (Salmi and Ikonen, 2005). The AS relies on a piezoelectric detector with a surface of 60 cm², with which the impact of individual raindrops on the surface is measured. Raindrops collide with the surface at their terminal velocity, which is a function of the raindrop diameter. Depending on the terminal velocity and the mass of the raindrop, every collision creates a particular signal, which is proportional to the volume of the drops, and is then converted to an individual voltage by the piezoelectric detector (Winder and Paulson, 2012). The voltage pulses are filtered, amplified, digitized, and analysed. Knowing the voltage signals per unit time and the surface area, rain duration and -intensity can be determined. Each type of precipitation creates a distinguishable signal which enables the detection of liquid and solid precipitation. Since the terminal velocity of snow is low, the AS can only differentiate between rain and hail.

The laser disdrometer (LD; Adolf Thies GmbH & Co KG, Göttingen, Germany) is installed on the sites in RO and SE. The instruments use an infrared light-beam with a wavelength of 780 nm and a cross section of approx. 46 cm². It records the reduction of the transmitted light intensity by particles falling through the light-beam and can therefore derive the particle diameter. The strength and duration of the attenuation initiated by the falling particle allows for an inference of its diameter and velocity, such that the precipitation type, rain and snow, can be distinguished (Bloemink and Lanzinger, 2005; Fehlmann et al., 2020). The LD distinguishes precipitation with a diameter of 0.125 mm and derives the vertical velocity by the measured signal duration (Lanzinger et al., 2006). It offers a low sensitivity threshold with a resolution of 0.001 mm h^{-1}.

Weather data as well as precipitation data from TB, WG and AS are stored on a data logger at DD, RO, and SE (all "envilog Maxi", ecoTech, Bonn, Germany) at 10-minutes intervals (Pütz et al., 2016). Weighing data from the lysimeters are stored in a data logger (1-minute intervals, DT85, Datataker-Thermo Fisher Scientific Australia Pty Ltd., Scoresby, VIC, Australia), whereas the LD´s data is stored on a local memory card.

2.3 Data processing

Lysimeter data, which are available as time series of mass changes in minute resolution, were pre-processed in ~~three~~ four steps: i) check of the minutely monitored raw data time series' for plausibility (manually and automatically), ii) application of the AWAT-filter to reduce the impact of noise on the raw data of the lysimeter mass changes (Peters et al., 2017), iii) classifying ET$_a$ and AWI data according to Eq. 1-4 assuming that only ET$_a$ or AWI can occur within the respective 1-minute time step, and iv) summing the minutely to hourly values; note that hours with missing values were marked as not available (NA).

Weather and gauge precipitation data were similarly treated with a plausibility check (manually and automatically) and an aggregation to hourly values. For this, the precipitation measurements present for 10-minutes intervals were summed, while the 10-minutes measurements from the climate stations such as temperature (°C), wind speed (m s^{-1}) and wind direction (°) were averaged over one hour.

To determine whether the gauge data then add up to comparable hourly values and to be able to eliminate potential time lags between all devices, representative precipitation events were analysed by comparing the 10-minutes with the hourly resolution (Appendix A1). Since the lysimeter measurements functioned as reference for the comparison, they ~~are~~ were intended to mark the beginning of an event as well as significant peaks within a precipitation event. The comparison revealed a time lag of ten minutes between lysimeter and gauge data, which ~~is~~ was due to time stamps from different data loggers. Another time lag for

Kommentiert [TS27]: See comment and answer line 175

Kommentiert [TS28]: R1: "10) L225: "iii) summing the minutely to hourly values" – do you mean the raw data or after the application of Eq 1,2, 3?"

Kommentiert [TS29R28]: After application of Eq. 1-3

Kommentiert [TS30]: Consistent wording.

Kommentiert [TS31]: Consistent use of tenses.

Kommentiert [TS32]: Consistent use of tenses.

the WG data was induced by gauge-internal processing. Adjusting the overall gauge data with a 10-minutes inverse time lag and using the raw WG data solved the problem.

2.4 Reference precipitation values and their uncertainties

The derivation of a reference precipitation intensity (P_{ref}; mm h^{-1}) for the comparison of precipitation data is critical for further investigations. It was chosen to compute the mean measured precipitation among the lysimeters for each hourly data point (Eq. 5~~4~~), when at least half of the lysimeters data were available for that hour. This way it is ensured that the mean is not depending on single measurements and that too many data points are discarded because of missing values. At sites (SE and DD) where only three lysimeters of the same soil-ecosystem are operated, the mean is calculated when at least two lysimeters provide measurements. The procedure is conducted for precipitation and NRW simultaneously; the following equations refer to the calculation for the reference precipitation, for which we only use AWI above 0.1 mm h^{-1}, which is assumed to be dominantly contributed by precipitation. The identification of non-rainfall water is covered in chapter 2.5.1.~~.~~

$$P_{ref} = \begin{cases} \frac{1}{n}\sum_{i=1}^{n} x_i \; for \; n \geq n_{\underline{na}\sout{iana}} \\ NA \; for \; n < n_{\underline{na}\sout{iana}} \end{cases}, \tag{4\underline{5}}$$

where n is the number of lysimeters providing observations during time interval i (-), x_i the precipitation intensity measured by each lysimeter in the given interval i (mm h^{-1}) and $\underline{n_{na}}$ ~~n_{ia}~~ is the number of lysimeters with ~~missing~~non-available data during time interval i (-).

Following WMO (2018), a rain intensity gauge is required to not exceed defined uncertainties while measuring rain precipitation intensities (P_{gauge}). Under field conditions, an uncertainty of 5 mm h^{-1} for P_{gauge} < 100 mm h^{-1} should not be exceeded. An approach conducted by Vuerich et al. (2009) derives P_{ref} from the mean of four different reference pit gauges. They calculated the uncertainty for the reference values from standard deviations of precipitation measurements from the pit gauges. The authors use the 95 % confidence level (k=2) deducted from two times the standard deviation of the measurements. To adapt the concept, it was decided to proceed as follows: ~~It is assumed that measurements of the same precipitation event conducted by all available lysimeters are normally distributed.~~ It is assumed that the aggregated hourly precipitation amounts determined by all available lysimeters are normally distributed around P_{ref}. Thus, the standard deviation (SD) between measurements of all lysimeters with the same vegetation cover at each site can be calculated for each hour, where data from all lysimeters is available (Eq. 6~~5~~). After calculating the lysimeter uncertainties within the 95% confidence level (U_{ref}; Eq. 7~~6~~) each hour is assigned to a category according to its precipitation intensity value~~., whereby e~~Each category comprises a span of 0.1 mm h^{-1} ~~mm, resulting in 200 categories~~ for P_{ref} between~~of~~ 0 and~~to~~ $P_{ref\,max}$ ~~20 mm h^{-1}~~, which was the maximum observed precipitation intensity during the observation period ~~across all sites~~at each site ($P_{ref\,max}$: 23.21 mm h^{-1} (RO); 12.91 mm h^{-1} (SE); 32.24 mm h^{-1} (DD)). All uncertainty values for hours within the respective category are then averaged and the computed mean is attributed back to the respective hours. This assigns an individual uncertainty value to each precipitation intensity interval. The WMO (2018) recommends to add 5 % of P_{ref} to the gauges uncertainties (here lysimeter uncertaintie~~s~~s; U_{fin}; Eq. 8~~7~~) as an upper limit for uncertainties of rain gauges. The final uncertainties are then plotted and smoothed using the "*geom_smooth*" function (R, Package: ggplot2; Wickham, 2016) with cubic splines using the R software (R Core Team, 2020) to provide an uncertainty range for the gauge comparison via scatter plots.

$$SD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}}, \tag{6\underline{5}}$$

$$U_{ref} = P_{ref} \pm 2 * SD, \tag{7\underline{6}}$$

$$U_{fin} = U_{ref} \pm 0.05 * P_{ref}, \tag{8\underline{7}}$$

with n being the number of observations (-), x_i the precipitation intensities measured by each lysimeter during time interval i (mm h^{-1}), $\bar{x}$ the empiric mean of the lysimeter measurements at the site during time interval i (mm h^{-1}),

~~P_{ref} the reference precipitation intensity during time interval i (mm h − 1).~~U_{ref} the uncertainty of the lysimeter reference during time interval i (mm h^{-1}) and U_{fin} the final uncertainty for the gauge comparison for time interval i (mm h^{-1}). To additionally reduce potential uncertainties and achieve more comparable results when comparing the measurement methods

295 with the lysimeter reference, only data is used with P$_{ref}$ and P$_{gauge}$ both being ≥ 0.1 mm h^{-1}, which is the smallest common resolution of all measuring instruments.

2.5 Determination of key parameters

2.5.1 Non-rainfall ~~event~~water

Non-rainfall water~~events~~ (NR~~E~~WE) comprise the formation of dew, hoar frost, and fog. ~~Hourly precipitation data was~~
300 ~~categorised as NRE, if no rain gauge except the lysimeters or the disdrometer registered precipitation. The disdrometer was~~
~~excluded because it could detect fog.~~ Often, combined observations on ~~NREs~~ NRW by leaf wetness (for dew and hoar frost) or visibility sensors (fog) and weighable lysimeters are used to identify ~~NREs~~ NRW (Zhang et al., 2019). No such sensors were available for our sites. Therefore, we followed the approach by Groh et al. (2018b); hourly precipitation data were categorised as NRW, if no rain gauge except the lysimeters or the disdrometer registered precipitation. The disdrometer was
305 excluded because it could detect fog.~~, who restricted the~~ Additionally, ~~occurrence~~the occurrence of NR~~E~~WE was limited to the period between sunset and sunrise ~~without any rainfall detected by WG~~and the hourly ~~NRE~~ NRW intensity to a maximum rate of 0.07 mm h^{-1} according to assumptions on dew formation by Monteith and Unsworth (2013).

2.5.2 Precipitation type and intensity classification

The piezoelectric sensor as well as the optical disdrometer could identify the mentioned precipitation types in a sufficient way
310 (Bloemink and Lanzinger, 2005; Fehlmann et al., 2020; Salmi and Ikonen, 2005). Due to an incomplete data situation, an approach was carried out to derive the precipitation type from the air temperature at the sites. For gauge intercomparisons, temperature ranges of +4 to 0 °C (Gebler et al., 2015), +2.5 to -2.5 °C (Kochendorfer et al., 2017b), +2 to 0 °C (Førland et al., 1996) and +2 to -2 °C (Ryu et al., 2016) were chosen for mixed precipitation. Here the latter threshold of +2°C and -2°C was used in this study for mixed precipitation (~~Table 1~~Table 2). Thus, temperatures above 2°C are used to classify liquid
315 precipitation (rain) and temperatures below -2°C classify solid precipitation (snow). The small number of precipitation events classified as "snow" can be explained by the pre-filtering of the lysimeter measurements influenced by snow bridges or ice formation. Due to the small number of "snow" events and the uncertainties involved in quantifying snow and mixed precipitation with lysimeters and precipitation gauges, hours within both categories are excluded from further investigation.

~~Table 1: Number of hours of three main precipitation types for the years 2015–2018 according to the lysimeter reference. Hours with no~~
320 ~~precipitation registered by the lysimeters and non-rainfall events are excluded.~~

~~Site~~	~~Rain~~	~~Mixed~~	~~Snow~~
~~-~~	~~(h)~~	~~(h)~~	~~(h)~~
~~Rollesbroich~~	~~4695~~	~~763~~	~~21~~
~~Selhausen~~	~~3949~~	~~186~~	~~8~~
~~Dedelow~~	~~2949~~	~~260~~	~~4~~

The precipitation intensities were classified according to~~The classification of precipitation intensities was done in accordance~~ ~~to~~ WMO (2018). Here, observations were classified according to the precipitation registered by the lysimeter reference. Hours with 0.1 ≤ P$_{ref}$ < 2.5 mm h^{-1} were regarded as "slight", 2.5 ≤ P$_{ref}$ < 10 mm h^{-1} as "moderate" and 10 ≤ P$_{ref}$ < 50 mm h^{-1} indicated
325 "heavy" rainfall (Table 2~~Table 2~~). More details on the precipitation intensity distributions are provided in Appendix B1 and B2.

Table 2~~3Table 2~~: Number of hours classified according to the reference ~~precipitation~~rain intensity (P$_{ref}$) and number of hours with precipitation classified as "mixed" and "snow" for the years 2015–2018. Hours for which no reference could be calculated due to missing

Kommentiert [TS40]: Repitition.

Kommentiert [TS41]: We replaced the term "non-rainfall event" (NRE) with "non-rainfall water" (NRW) to be consistent with terms used in Eq. 2

Kommentiert [TS42]: Adjusted the sentence structure to improve readability.

Kommentiert [TS43]: Spelling

Kommentiert [TS44]: R2:
The hours of slight, moderate and heavy precipitation (Table 2) should add up to Rain + Mixed + Snow or Rain only (that would be my preferred option because you excluded the mixed and snow events right?) in Table 1. Currently the numbers do not add up. You could combine Table 1 & 2 in one table Rain (slight, moderate, heavy), Mixed, Snow.

Kommentiert [TS45R44]: We merged table 1 & 2 by showing the hours of slight, moderate, and heavy rain and all intensity ranges for mixed and snow. Also, we ensured the correctness and consistency of the displayed values.

Kommentiert [TS46]: wording

Kommentiert [TS47]: Clarification

Kommentiert [TS48]: R1:
"6) The highest observed precipitation rate is 20 mm/h. Can you provide some info about this value so the reader would know what part of the precipitation rate distribution the analysis is covering?"

Kommentiert [TS49R48]: Added table with more information on the precipitation rate distribution in Appendix B.

Kommentiert [TS50]: Adjusted the statistics to be consistent with the overall analysis. Only hours with precipitation ≥ 0.1 mm/h are displayed, as these are mostly relevant for the analysis.

data and hours with P$_{ref}$ < 0.1 are excluded. ~~Hours with no precipitation registered by the lysimeters and hours with non-rainfall events are excluded.~~

Site	Slight ~~precipitation~~ rain ($0.1 \leq$ P$_{ref}$ < 2.5 mm h^{-1}) (h)	Moderate ~~precipitation~~ rain (2.5 $\leq$ P$_{ref}$ < 10 mm h^{-1}) (h)	Heavy ~~precipitation~~ rain (10 $\leq$ P$_{ref}$ < 50 mm h^{-1}) (h)	Mixed ($0.1 \leq$ P$_{ref}$ < 50 mm h^{-1}) (h)	Snow (h)
Rollesbroich	~~5179~~3338	~~269~~257	~~10~~10	639	26
Selhausen	~~3976~~2675	~~160~~55	4	146	9
Dedelow	~~3073~~2047	~~127~~32	4	261	14

2.6 Correlation analyses

The precipitation measurements between the reference values and those obtained from the gauges were compared based on x–y scatter plots (e.g., Haselow et al., 2019; Liu et al., 2013; Yang, 2014). Within a plot, the uncertainty range, the bias (Eq. ~~8~~9) as well as the standard deviation of the measurement differences (SDD, Eq. ~~9~~10), the R²-value (Eq. ~~10~~11), the number of observations (n) and the linear regression line (Eq. ~~11~~12) are given. To enhance the visualisation, additional plots and statistics for slight precipitation events are provided.

$$Bias = \sum_{i=1}^{n} \frac{(x_i - y_i)}{n} , \tag{$\cancel{8}$9}$$

$$SDD = \sqrt{\frac{\sum_{i=1}^{n}(x_i - y_i)^2}{n-1}} , \tag{$\cancel{9}$10}$$

$$R^2 = \frac{\sum(y_i - \bar{x})^2}{\sum x_i - \bar{x}} \; with \; \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i , \tag{$\cancel{10}$11}$$

where n is the number of observations (-), x_i the reference precipitation intensity during time interval i (mm h^{-1}) and y_i the precipitation intensity determined by the precipitation gauge during time interval i (mm h^{-1}).

The bias is the average difference between the precipitation measured by the gauge and the reference measurement, so positive or negative values indicate that the gauges generally over- or underestimated precipitation, respectively. The SDD quantifies the distribution of the differences and thus the spread of the data points around the 1:1 reference line. The nondimensional coefficient of determination, R², describes how well the linear regression model, displayed in the plot, fits to the data. Due to its derivation, it is also closely related to the extent of the spread of the data but does not consider the spread around the 1:1 reference line. The regression lines follow the standard linear regression (Eq. ~~11~~12) performed in R (R Core Team, 2020), using the "*ggplot2*" package (Wickham, 2016).

$$y_i = \alpha + \beta x_i, \tag{$\cancel{11}$12}$$

where α and β are regression coefficients.

While interpreting the bias, SDD, R²-value and regression lines, it must be considered that these statistics and methods base on the assumption of normally distributed data. ~~Since p~~Precipitation data does not follow such a distribution~~.~~ ~~L~~low precipitation intensities occur more often than higher intensities and therefore the residuals are heteroscedastic. ~~, the~~ Thus, the statistics might not be ~~not~~ enough to describe the data distribution. ~~Therefore, a~~An additional, visual illustration of the data was required, as presented by the scatter plots.

2.7 Wind error analysis

To analyse the influence of wind speed at gauge height (v$_g$) on the gauge's precipitation measurements, the catch ratio (CR; Eq. 1~~3~~2) is used. The CR can be described as a function of wind speed and temperature (Goodison et al., 1998; Yang et al., 1998). CRs of different gauges were calculated with regression analyses on the basis of reference measurements at multiple

Kommentiert [TS51]: R1: 16) Eq. 8-10: Use either small or capital letters consistently.

Kommentiert [TS52]: R1: 14) Eq. 9: index i is missing

Kommentiert [TS53]: R1: 15) I think something is wrong with Eq. 10; please correct

Kommentiert [TS54]: Shortened sentences.

Kommentiert [TS55]: Grammar

Kommentiert [TS56]: Improved readability.

sites (Chen et al., 2015; Goodison et al., 1998; Sugiura et al., 2006; Yang et al., 2000). The CR of a gauge and reference values can also be described with following equation:

$$CR = \frac{P_{gauge}}{P_{ref}} * 100 .$$
(~~12~~13)

Since the influence of the temperature can be neglected due to the exclusion of mixed and solid precipitation, the primary parameter to consider is the wind speed at gauge height, which can be derived from the measured wind speed at 2 m above ground (Eq. ~~13~~14; Goodison et al., 1998):

$$v_g = [log(\tfrac{h_g}{z_0}) \,/\, log(\tfrac{h}{z_0})] * v_h,$$

$$v_g = \frac{log(\frac{h_g}{z_0})}{log(\frac{h}{z_0})} * v_h,$$
(~~13~~14)

where v_g is the wind speed at the height of the gauge orifice (m s⁻¹), h_g the height of gauge orifice above ground (m), z_0 the roughness length (0.01 m in winter, 0.03 m in summer), h the height of the wind speed measuring instrument above ground (m) and v_h the wind speed measured by the measuring instrument (m s⁻¹). The CRs of each gauge were binned according to the site-specific ranges of v_g with each bin representing an interval of 0.1 m s⁻¹ and then averaged within the bin to reduce the overall amounts of observations and identify possible trends.

2.8 Precipitation data corrections

Sevruk (1982) provides a general equation for the correction of precipitation measurements which is adjusted with regard to an improved readability to the notation by Førland et al. (1996; Eq. ~~14~~15):

$$P_{cor} = k(P_m + P_w + P_e + P_t) ,$$
(~~14~~15)

with P_{cor} being the corrected precipitation (mm), k the correction factor for wind (-), P_m the measured precipitation (mm), P_w the wetting loss (mm), P_e the evaporation loss (mm) and P_t the loss by trace precipitation (mm).

Few of the correction methods based on Eq. (~~14~~15) are developed to correct precipitation measurements on an hourly basis, due to the absence or small numbers of automatic gauge types in the last decades. Førland et al. (1996) published the dynamic correction model (DCM) with which Michelson (2004) corrected hourly precipitation data of four different gauge models mainly used in Scandinavian countries. The correction factor for wind loss, k, can thus be adjusted for hourly rain measurements following the DCM (Førland et al., 1996; Michelson, 2004; Eq. ~~15~~16):

$$k = exp\begin{bmatrix} -0.00101 * ln(P_{gauge}) - 0.012177 * v_g \; \cancel{vg} * ln(P_{gauge}) + \\ 0.034331 * v_g + 0.007697 + c \end{bmatrix},$$
(~~15~~16)

where c is the gauge constant (mm 12 h⁻¹).

Michelson (2004) offers empiric constants for wetting loss, evaporation loss as well as the wind induced error for four different gauge models and precipitation types (Table ~~3~~3-~~4~~4). The empiric constants apply for 12 h measuring intervals, which can be derived to an hourly basis. Since evaporation does not account for WGs if it is supressed with an oil film (WMO, 2008), only the gauge constant for determining the wind error has to be chosen for the WG. Michelson (2004) states that precipitation gauge designs, that are similar to the WG used here, have a slightly improved gauge constant compared to the Hellmann gauge (0.0 mm 12 h⁻¹), thus a gauge constant of -0.05 mm 12 h⁻¹ is chosen for the WG.

To compensate the loss by trace precipitation for the TB, an empiric value provided by Yang et al. (2001) with a loss of 0.1 mm d⁻¹ is assumed for days with at least one precipitation event.

Table ~~3~~2: Wetting and gauge constants for Eq. (~~15~~16) provided by Michelson (2004) for multiple gauge types. SMHI: Gauge used by the Swedish Meteorological and Hydrological Institute.

Precipitation	Constant	SMHI	Hellmann

phase		(mm 12 h^{-1})	(mm 12 h^{-1})
Liquid	Gauge	-0.05	0.00
Liquid	Wetting	0.07	0.14

Table 4~~3~~: Daily evaporation loss constants for Eq. (~~15~~16) as provided by Michelson (2004) for the Hellmann-type gauge. ~~multiple gauge types. SMHI: Gauge used by the Swedish Meteorological and Hydrological Institute.~~

Kommentiert [TS62]: Adjusted text to fit to the table.

Month	Hellmann (mm 12 h^{-1})
January	0.01
February	0.02
March	0.03
April	0.04
May	0.09
June	0.15
July	0.16
August	0.08
September	0.02
October	0.01
November	0.01
December	0.01

400

Richter (1995) developed a correction method especially for German Hellmann-type gauges installed at sites, where no wind speed can be determined. He used factors depending on the shielding of the site and the precipitation type, based on long term precipitation measurements. The derived daily correction amount includes all relevant losses (including wind, evaporation, trace, and wetting). To test the potential of the correction method by Richter (1995) to be applied on hourly precipitation data,

405 a similar approach to the one published by Gebler et al. (2017) is chosen. The authors initially calculated corrections for daily precipitation data according to Richter (1995; Eq. ~~16~~17 and ~~17~~18) and then redistributed it to hourly measurements via the ratio of daily measured to daily corrected data. Here it was decided to redistribute the daily corrections via the number of precipitation hours within a day (Eq. ~~18~~19):

$$P_d^{cor} = P_d + \Delta P_d, \tag{16 17}$$

410
$$\Delta P_d = b * P_d^{\varepsilon}, \tag{17 18}$$

$$P_h^{cor} = \frac{P_d^{cor}}{n_{Pevent}} + P_h, \tag{18 19}$$

where P_d^{cor} is the corrected daily precipitation (mm d^{-1}), P_d the daily precipitation measured by gauge (mm d^{-1}), ΔP_d the amount of daily additional precipitation (mm d^{-1}), b the coefficient for the influence of wind exposition at the measurements site (-), P_d^{ε} the empiric coefficient for the precipitation type (-), P_h^{cor} the corrected hourly precipitation (mm h^{-1}), n_{Pevent} the

415 number of hours with P$_{ref}$ ≥ 0.1 mm h^{-1} within a day (-) and P_h the hourly precipitation measured by the gauge (mm h^{-1}).

Kommentiert [TS63]: Clarification

3 Results

3.1 Uncertainty range of the lysimeters

With increasing P$_{ref}$ values, the measurement uncertainties from the lysimeters decrease at all sites. The uncertainty ranges indicate that between 1 and 2.5 mm h^{-1} the relative ~~measuring~~ measurement differences decrease to values below 5 % (Fig. 3).

Kommentiert [TS64]: Consistency

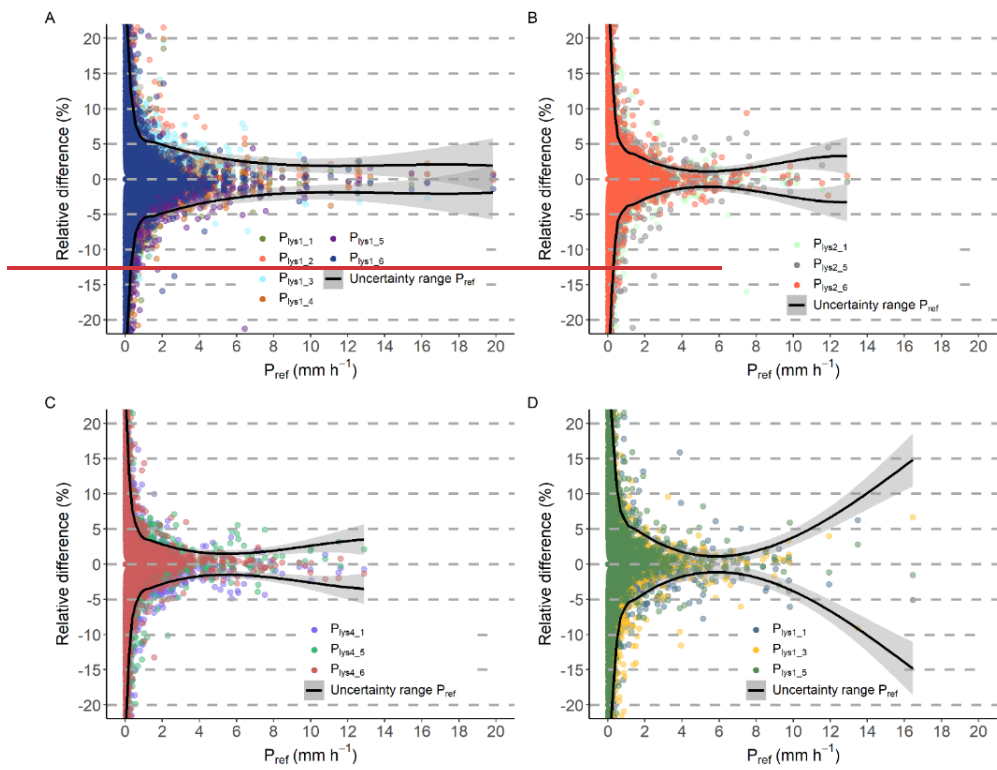
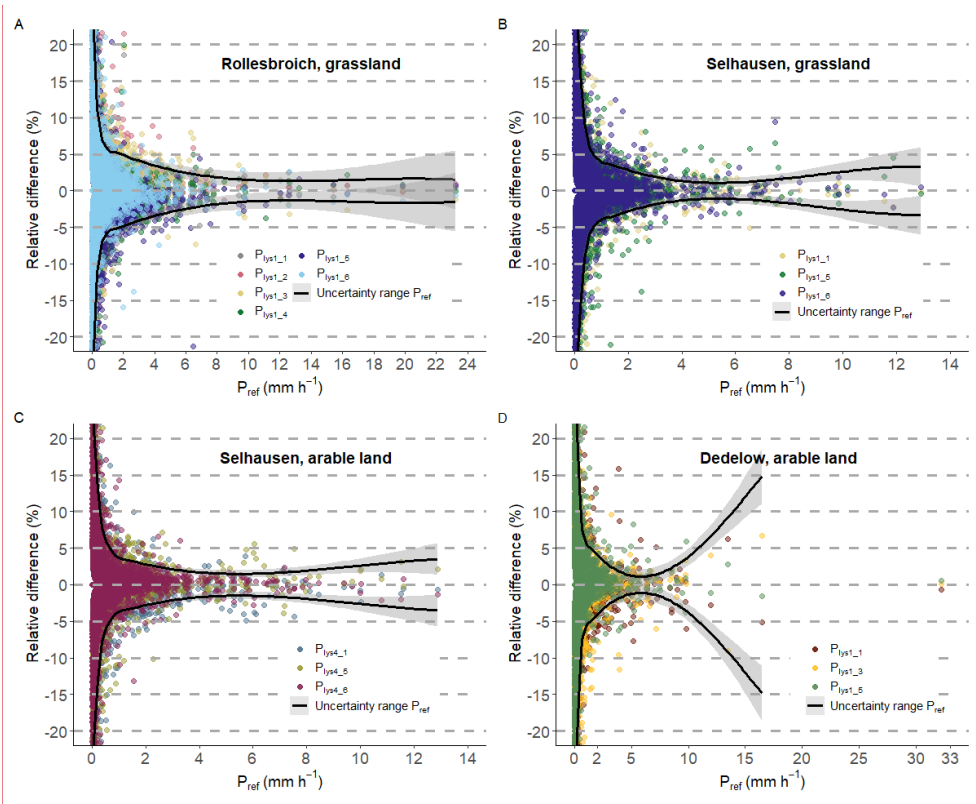
420 For P$_{ref}$ > 8 mm h^{-1}, the lack of data does not allow to delineate a clear area of uncertainty. In DD, three rain events with precipitation intensities > 11 mm h^{-1} were associated with increased deviations within the lysimeter measurements, which bias the regression line and therefore the predicted uncertainty range at these precipitation intensities (Fig. 3D).

Kommentiert [TS65]: Figure revised with adapted Pref-ranges and adapted with colour-blind friendly colours

Figure 3: Uncertainty ranges of lysimeter references (P_ref), delimited through solid lines, and differences of each lysimeter measurement relative to P_ref. A: Rollesbroich lysimeter station, lysimeter with grassland. B: Selhausen lysimeter station, lysimeter with grassland. C: Selhausen lysimeter station, lysimeter with arable land. D: Dedelow lysimeter station, lysimeter with arable land.

3.2 Annual precipitation values

During hours in which all devices at a site were available and at least one gauge (TB, WG or AS) and the lysimeters measured a precipitation intensity of 0.1 mm h^{-1} or higher (Table 5), the TB1 in Rollesbroich (RO) registered 22.9–47.1 % of P_ref within each individual year of operation. The TB in Selhausen (SE) caught 20.4–40.7 %, TB2 (RO) 79.2–83.8 % and the TB in Dedelow (DD) 72.8–84.0 %. The WGs caught 82.2–89.0 % (RO) and 89.4–94.5 % (SE), respectively. The AS measured 62.8–78.2 % (RO), 70.0–82.1 % (SE) and 82.6–91.3 % (DD). The LD (RO) measured 85.7–95.3 %, while the LD (SE) measured 73.6–96.1 %. Deviations between the precipitation totals of the lysimeters with different vegetation cover in SE are considerably low with CRs of 99.8–101.4 %.

Table 5Table 5: Precipitation sums (P) and catching ratios (CR) of all investigated gauges compared to the references per year. Only hours are considered, where all devices at a site were active, at least one device, tipping bucket (TB), weighable gauge (WG) or acoustic sensor (AS) and the lysimeters did measure a precipitation intensity of at least 0.1 mm h^{-1} and the precipitation is classified as "Rain".

Kommentiert [TS66]: R2:
Consider estimating NRE for your lysimeter sites and adding the total (annual) amount of NRE in table 5 or at a later point in the manuscript (I understand that there are uncertainties, however an estimate would be helpful).

Site	Year	n	P_ref	P_lys_crop	CR_lys_crop	P_TB1	CR_TB1	P_TB2	CR_TB2	P_WG	CR_WG	P_AS	CR_AS	P_LD	CR_LD
		(-)	(h)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
Rolles-broich	2015	793	709			334	47.1	594	83.8	606	85.5	499	70.4	676	95.3
	2016	989	801			184	22.9	634	79.2	659	82.2	526	65.6	687	85.7
	2017	1007	881			273	30.9	732	83.1	744	84.5	553	62.8	795	90.2
	2018	694	583			189	32.4	471	80.8	519	89.0	456	78.2	522	89.6

Kommentiert [TS67R66]: Added a table with more information on NRW to Appendix E, including estimation of annual amounts of NRW.

3.3 Precipitation intensities

On an hourly basis, all TBs tend to underestimate precipitation relative to the reference (Fig. 4). Measurements of the TBs showed little scattering, indicating consistent measurements with R²-values above or near 0.8 for all devices, except for TB1 in RO (Fig. 4 A2) with $R^2 = 0.53$. However, TB1 (RO; Fig. 4 A1) as well as the TB (SE; Fig. 4 C1) showed biases of -0.69 and -0.61 mm h^{-1} and SDDs of 0.90 and 0.85 mm h^{-1} for all rainfall events with $P_{ref} \geq 0.1$ mm h^{-1}. In hours of intensities between 0.1 to 2.5 mm h^{-1} the biases were -0.48 and -0.44 mm h^{-1} and the SDDs 0.40 and 0.38 mm h^{-1} (Fig. 4 A2 and C2). Measurements from TB2 (RO; Fig. 4 B1) showed a bias of -0.18 mm h^{-1} and an SDD of 0.31 mm h^{-1} while the TB (DD; Fig. 4 D1) measures with a bias of -0.20 mm h^{-1} and an SDD of 0.41 mm h^{-1}. For slight precipitation intensities, measurements from TB2 (RO) had a bias of -0.16 mm h^{-1} and an SDD of 0.20 mm h^{-1} and TB (DD) a bias of -0.14 mm h^{-1} and an SDD of 0.2 mm h^{-1}, respectively (Fig. 4 B2 and D2).

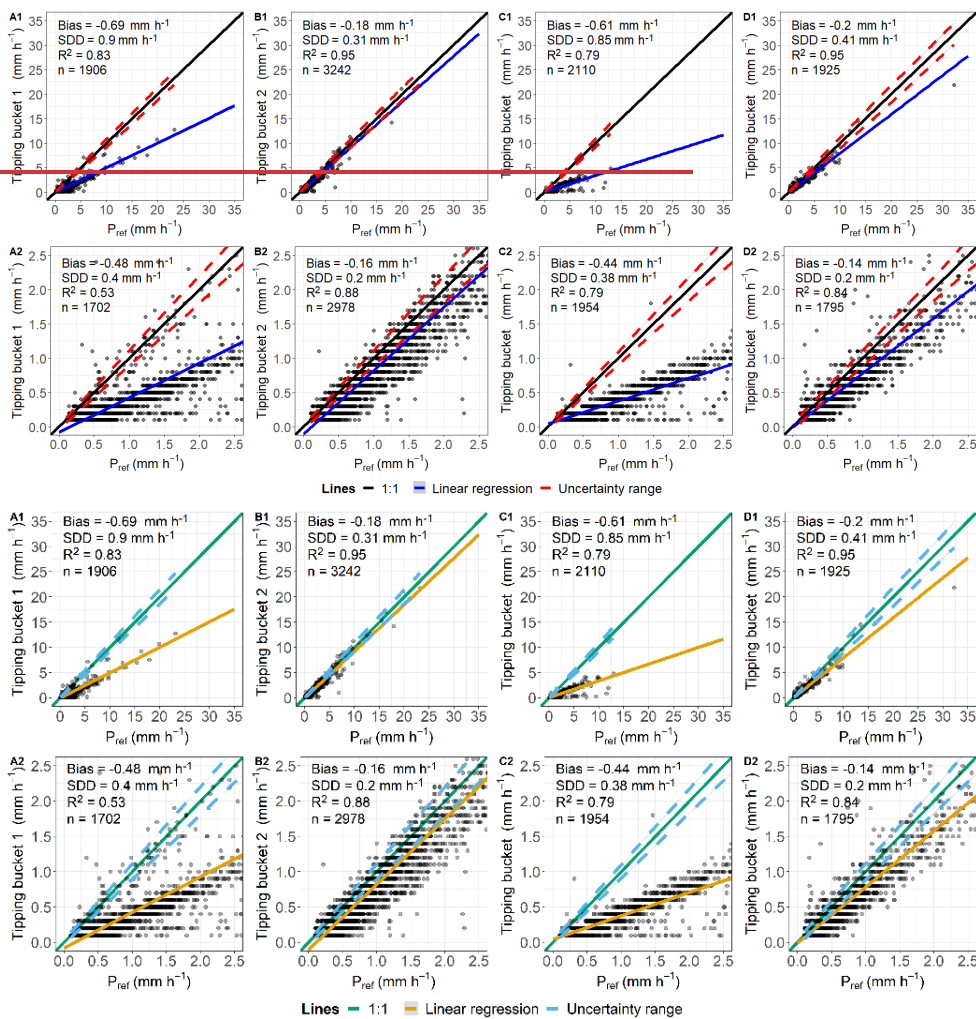



Figure 4: Comparison of hourly data determined by tipping buckets and lysimeters (P_{ref}) and classified as "Rain". Plots A1–D1 include all measurements taken where both P_{gauge} and P_{ref} are $\geq$ 0.1 mm h^{-1}. Plots A2–D2 show slight precipitation events and key values are calculated for P_{ref} between 0.1–2.5 mm h^{-1}. A1, A2: Rollesbroich lysimeter station. B1, B2: Rollesbroich EC station. C1, C2: Selhausen lysimeter station. D1, D2: Dedelow lysimeter station.

Kommentiert [TS68]: Adapted all scatter-plots with colour-blind friendly colours, no changes in content.

Measurements conducted by the WG (RO; Fig. 5 A1) showed a bias of -0.15 mm h^{-1} and an SDD of 0.24 mm h^{-1}. For the time without wind shield, measurements from the WG (SE; Fig. 5 B1) had a bias of -0.08 mm h^{-1} and an SDD of 0.18 mm h^{-1}, while with shield the bias was -0.04 mm h^{-1} and the SDD 0.14 mm h^{-1} (Fig. 5 C1). At $P_{ref} \leq$ 2.5 mm h^{-1}, the bias decreased from 0.07 to 0.04 mm h^{-1} and the SDD from 0.16 to 0.12 mm h^{-1} after the installation of the wind shield (Fig. 5 B2 and C2) in comparison with the WG (RO; Fig. 5 A2) which's measurements for $P_{ref} \leq$ 2.5 mm h^{-1} had a bias of -0.11 mm h^{-1} and an SDD of 0.16 mm h^{-1}.

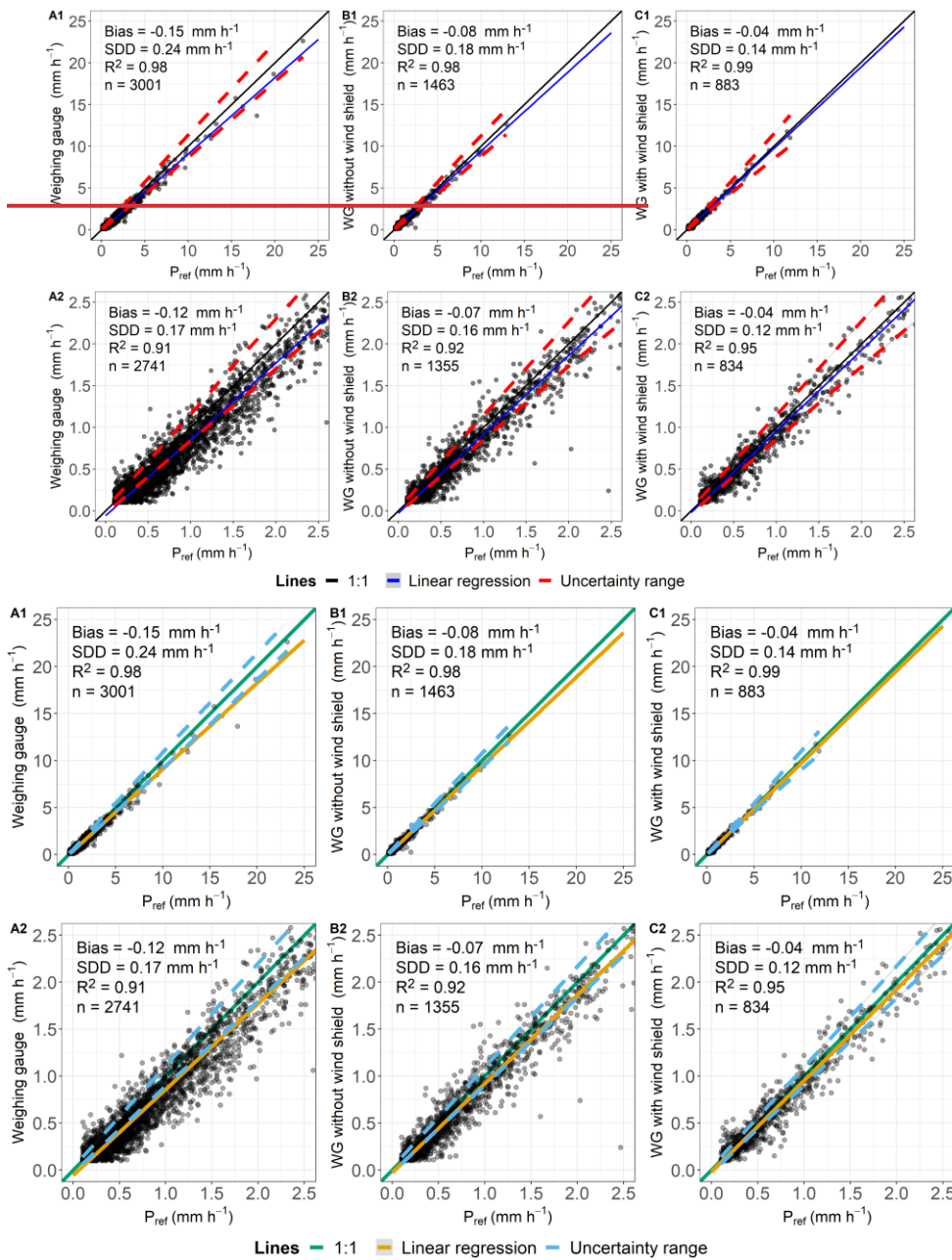



Figure 5: Comparison of hourly data determined by weighable gauges and lysimeters (P_{ref}) and classified as "Rain". Plots A1–C1 include all measurements taken with both P_{gauge} and P_{ref} are ≥ 0.1 mm h^{-1}. Plots A2–C2 show slight precipitation events and key values are calculated for P_{ref} between 0.1–2.5 mm h^{-1}. A1, A2: Rollesbroich lysimeter station. B1, B2: Selhausen lysimeter station without installed wind shield around the weighable gauge. C1, C2: Selhausen lysimeter station with installed wind shield around the weighable gauge.

The ASs data scattered largely around the 1:1-line with the tendency of the ASs to underestimate the precipitation intensity (Fig. 6 A1 to C2). Especially for slight precipitation intensities, the measurements correlated poorly with the reference data.

470 To exclude possible errors during the data processing, hourly values were calculated additionally, implementing a positive and negative 10-minutes lag on the data. This led to an even lower degree of agreement with the reference measurements, resulting in higher bias and SDDs than shown in Fig. 6. Additionally, a discrepancy between the measurement intervals from the ASs and reference would also result in false positives because only sensor data would show precipitation. A plot with the data including $P_{ref} = 0$ (not shown here) reveals no suspicious occurrence of these false positives. Therefore, the data from the ASs

475 was evaluated as valid. Measurements from the AS (RO; Fig. 6 A1) had a bias of -0.25 mm h^{-1} and an SDD of 0.7 mm h^{-1}. A bias of -0.22 mm h^{-1} and an SDD of 0.46 mm h^{-1} was calculated for $P_{ref} \leq 2.5$ mm h^{-1} (Fig. 6 A2). The R²-value was 0.80 and 0.54, respectively. Measurements by the AS (SE) had a bias of -0.23 mm h^{-1}, an SDD of 0.57 mm h^{-1} and a R²-value of 0.79 (Fig. 6 B1). For intensities classified as "slight", the sensor measured with a bias of -0.18 mm h^{-1}, an SDD of 0.37 mm h^{-1} and a R²-value of 0.62 (Fig. 6 B2). The measurements from the AS in DD had a bias of 0.07 mm h^{-1} and an SDD of 0.66 mm h^{-1}

480 with R² being 0.85 (Fig. 6 C1). Slight precipitation was measured with a bias of -0.07 mm h^{-1}, an SDD of 0.42 mm h^{-1} and a R²-value of 0.60 (Fig. 6 C2).

485

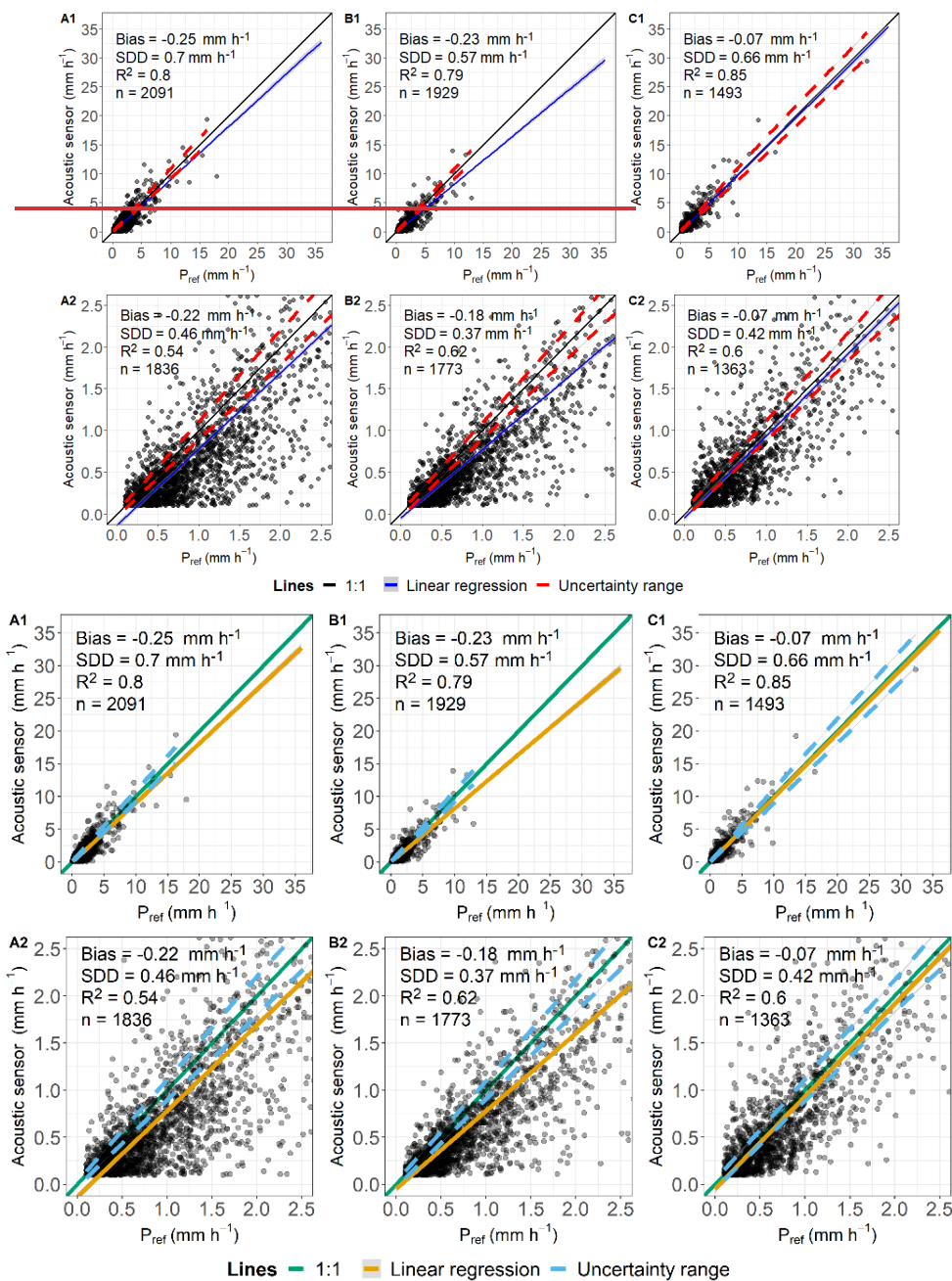



Figure 6: Comparison of hourly data determined by acoustic sensors and lysimeters (P_{ref}) and classified as "Rain". Plots A1–C1 include all measurements taken with both P_{gauge} and P_{ref} are $\geq$ 0.1 mm h^{-1}. Plots A2–C2 show slight precipitation events and key values are calculated for P_{ref} between 0.1–2.5 mm h^{-1}. A1, A2: Rollesbroich lysimeter station. B1, B2: Selhausen lysimeter station. C1, C2: Dedelow lysimeter station.

The LD (RO) tended to overestimate the precipitation with a general bias of 0.01 mm h^{-1} and an SDD of 0.37 mm h^{-1} (Fig. 7 A1). The R²-value of 0.95 suggests a good correlation with the reference. For slight precipitation events, the bias was 0.00 mm h^{-1} with the SDD being 0.18 mm h^{-1} and R² 0.90 (Fig. 7 A2).

The LD (SE) showed biases of 0.02 mm h^{-1} for all measurements and 0.04 mm h^{-1} for $P_{ref} < 2.50$ mm h^{-1} (Fig. 7 B1 and B2). The SDDs were 0.61 and 0.43 mm h^{-1} respectively. The R²-values (0.75 and 0.58) were lower compared to the ones from the other disdrometer at RO. The number of recorded hours with precipitation occurring at both sides was higher for the plots with the disdrometers compared to the plots of the other gauges due to the high measuring resolution of the disdrometer.

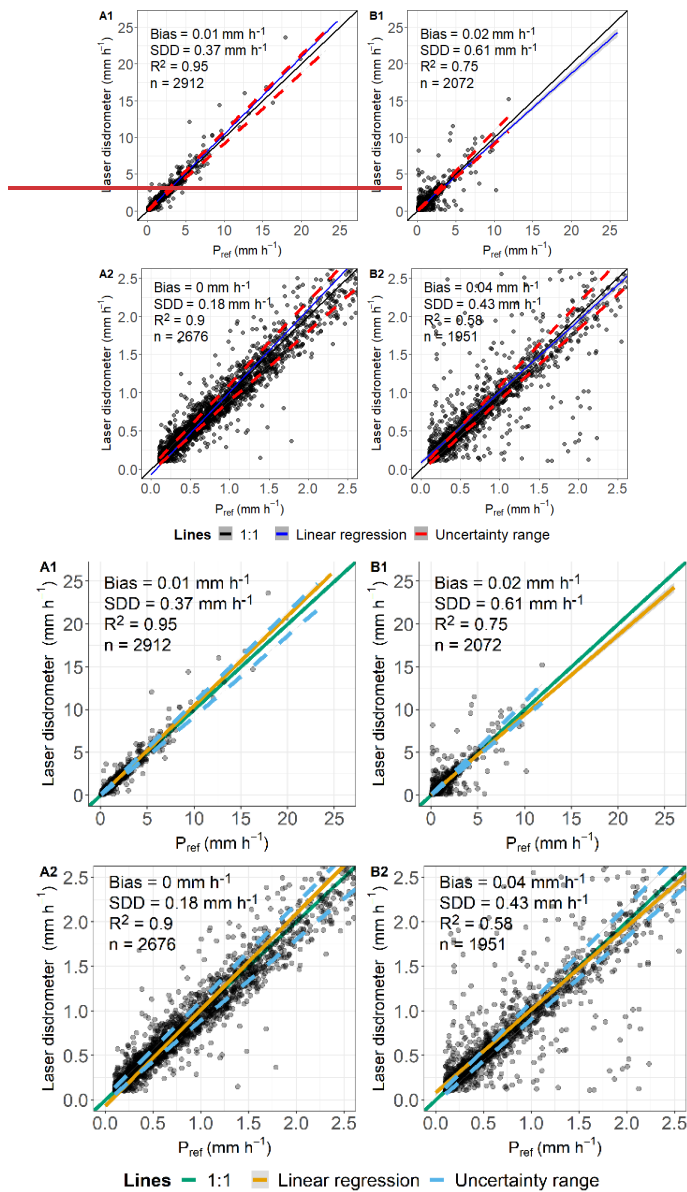



Figure 7: Comparison of hourly data determined by laser disdrometer and lysimeters (P$_{ref}$) and classified as "Rain". Plots A1–B1 include all measurements taken with both P$_{gauge}$ and P$_{ref}$ being ≥ 0.1 mm h^{-1}. Plots A2–B2 show slight precipitation events and key values are calculated for P$_{ref}$ between 0.1–2.5 mm h^{-1}. A1, A2: Rollesbroich lysimeter station. B1, B2: Selhausen lysimeter station.

3.4 Influence of wind speed

The CRs from TB1 (RO) and TB (SE) as functions of the wind speed at gauge height were mostly in the range of 30–100 % (Fig. 8 A and C). CRs of TB1 (RO) show higher values for wind speeds above 8 m s^{-1}, while those from TB (SE)~~and~~ did not in- or decrease with increasing wind speed. ~~(Fig. 8 A and C). A major influence of the wind on hourly~~

~~precipitation data therefore could not be identified.~~ The CRs from TB2 (RO) showed a tendency to decrease at higher wind speeds ~~greater than 5 m s⁻¹~~ (Fig. 8 B). In contrast, the CRs from TB (DD) tended to be above 100 % after exceeding wind speeds of 6 m s⁻¹ ~~after the same threshold~~ and the regression line ~~implies~~ implied a positive correlation with the wind speed (Fig. 8 D). The CRs from the WGs did not exhibit any correlation between the hourly precipitation data and the wind speed (Fig. 9 A to C), e~~ven with the separation according to the availability of the wind shield~~xcept for WG (SE) without wind shield, for which the CRs tended to decrease with increasing wind speed.

Figure 8: Catching ratios (CRs) of the tipping buckets as functions of the wind speed at gauge height for all sites, $P_{ref} \geq 0.1$ mm h⁻¹ and precipitation classified as "Rain". Data was binned and averaged with each bin representing a wind speed range of 0.1 m s⁻¹. A: Rollesbroich lysimeter station. B: Rollesbroich EC station. C: Selhausen lysimeter station. D: Dedelow lysimeter station.

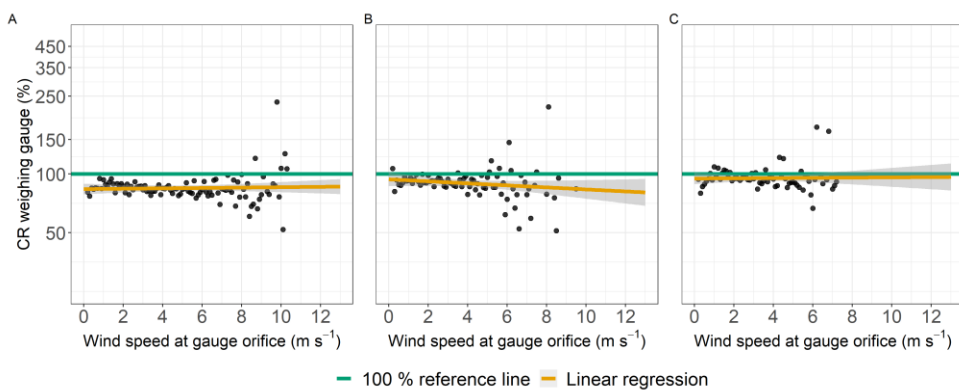
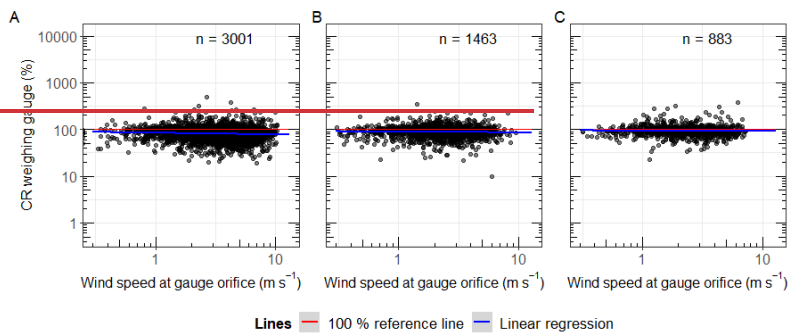



Figure 9: Catching ratios (CRs) of the weighable gauges as functions of the wind speed at gauge height, $P_{ref} \geq 0.1$ mm h^{-1} and precipitation classified as "Rain". Data was binned and averaged with each bin representing a wind speed range of 0.1 m s^{-1}. A: Rollesbroich lysimeter station. B: Selhausen lysimeter station, before wind shield was installed. C: Selhausen lysimeter station, after wind shield was installed.

At all sites A slight increase ofthe CRs of the ASs increased with at higher wind speeds could be traced back to an influence of the wind speed for the ASs at all sites (Fig. 10 A to C). The CRs of the LDs generally also did not indicated slight dependencies on the wind speed at gauge height (Fig. 11 A to B), while. tThe CRs of the LD in SE generally spread to a greater extend around the 100 % reference line compared to LD in RO.

Kommentiert [TS71]: Adjusted text according to results of the newly introduced binning procedure.

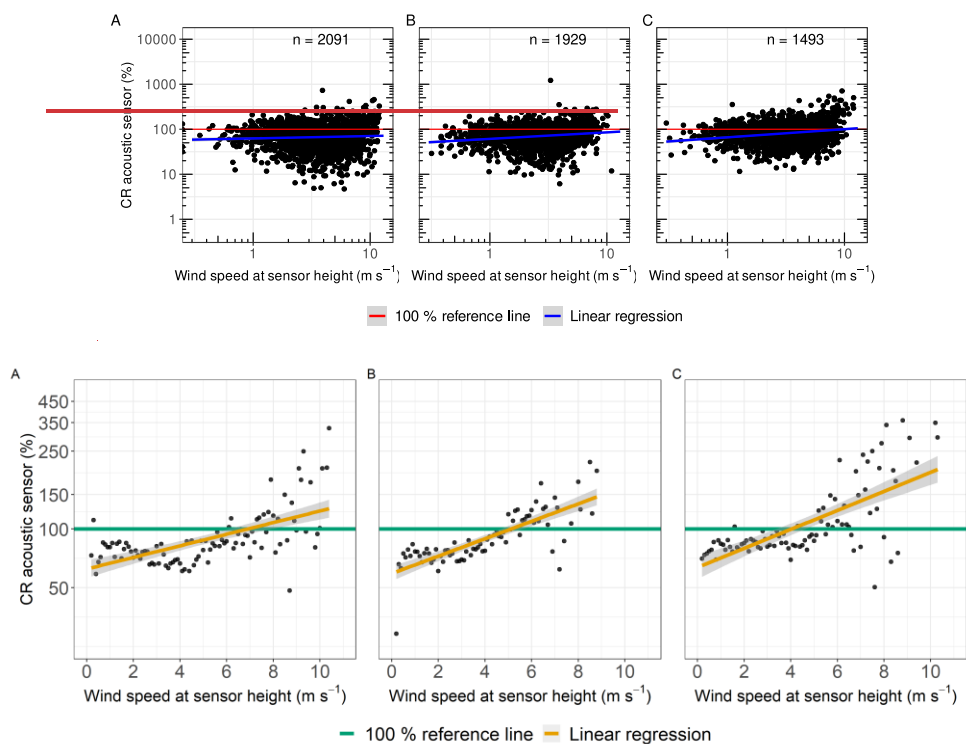



Figure 10. Catching ratios (CRs) of the acoustic sensors as functions of the wind speed at gauge height for all sites, $P_{ref} \geq 0.1$ mm h^{-1} and precipitation classified as "Rain". Data was binned and averaged with each bin representing a wind speed range of 0.1 m s^{-1}. A: Rollesbroich lysimeter station. B: Selhausen lysimeter station. C: Dedelow lysimeter station.

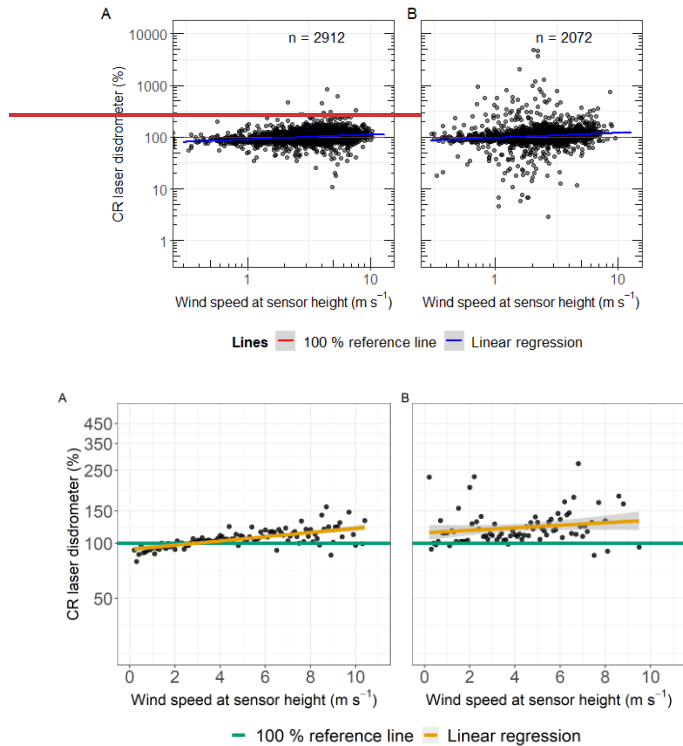



Figure 11. Catching ratios (CRs) of the laser disdrometers as functions of the wind speed at gauge height for all sites, $P_{ref} \geq 0.1$ mm h^{-1} and precipitation classified as "Rain". Data was binned and averaged with each bin representing a wind speed range of 0.1 m s^{-1}. A: Rollesbroich lysimeter station. B: Selhausen lysimeter station.

3.5 Precipitation correction

Applying the dynamic correction model (DCM) and the approach derived from Richter (1995) reduced the bias of all corrected measurements for the TBs and WGs (Table 6). Generally, the DCM resulted in a greater bias reduction than the other method. Both correction methods had no systematic effect on the SDD and R²-values, but the CRs have been increased by 14 and 9 % for the TBs and by 10 and 11% for the WGs due to the application of the DCM and method after Richter, respectively. The data correction also led to an increased number of hours exceeding the threshold of 0.1 mm h^{-1} for the WGs (Table 6 and 7). For the TBs, the aggregation of hourly to daily precipitation data during a processing step of the method derived from Richter resulted in a reduction of observations.

Table 6~6: Statistics of the corrected precipitation data classified as "Rain" for tipping bucket (TB) and weighable gauges (WG) at sites in Rollesbroich (RO), Selhausen (SE) and Dedelow (DD). ~~Due to the aggregation of hourly values and therefore the number of days with incomplete data as well as the threshold of 0.1 mm, which is met only after the correction, the number of observations (n) differed depending on the correction method.~~ The number of observations (n) varied depending on the correction method due to hourly value aggregation and the presence of incomplete data, as well as the 0.1 mm h^{-1} threshold, which was only met after the correction. "Intercept" and "Slope" show the intercept and slope of the linear regression of P_{gauge} and P_{ref}.

Kommentiert [TS72]: Rephrased for clarification.

Site	Device	Cor. method	Intercept	Slope	Bias	SDD	R²	n
			(mm h^{-1})	(-)	(mm h^{-1})	(mm h^{-1})	(-)	(-)
Rollesbroich	TB1	-	-0.08	0.50	-0.69	0.90	0.83	1906
	TB1	DCM	-0.01	0.47	-0.56	0.88	0.82	1906
	TB1	Richter	0.00	0.51	-0.61	0.90	0.83	1831

Site								
	TB2	-	-0.11	0.93	-0.18	0.31	0.95	3242
	TB2	DCM	0.01	0.96	-0.03	0.30	0.95	3242
	TB2	Richter	-0.03	0.94	-0.09	0.30	0.95	3224
Selhausen	TB	-	-0.04	0.33	-0.61	0.85	0.79	2110
	TB	DCM	0.13	0.35	-0.51	0.83	0.78	2110
	TB	Richter	0.11	0.34	-0.54	0.85	0.78	2019
Dedelow	TB	-	-0.01	0.79	-0.20	0.41	0.95	1925
	TB	DCM	0.11	0.81	-0.06	0.42	0.93	1925
	TB	Richter	0.07	0.80	-0.11	0.41	0.94	1925
Rollesbroich	WG	-	-0.06	0.91	-0.15	0.24	0.98	3001
	WG	DCM	0.01	0.95	-0.04	0.22	0.98	3107
	WG	Richter	0.01	0.93	-0.06	0.23	0.98	3185
Selhausen	WG	-	-0.02	0.95	-0.07	0.17	0.98	2346
	WG	DCM	0.01	0.99	0.01	0.17	0.98	2439
	WG	Richter	0.05	0.97	0.03	0.16	0.98	2497

550

Table 77: Catching ratios (CRs) of corrected tipping bucket (TB) and weighable gauge (WG) data (DCM = Dynamic Correction Model; RI = correction based on the method derived from Richter, 1995). Only numbers (n) of hours are considered, when all devices at a site were active and at least one device (TB, WG, AS) did measure precipitation (P) classified as "Rain" of at least 0.1 mm h^{-1}. Latter conditions are differently met after the correction with the two correction methods, resulting in divergent numbers of observations and associated P_{ref}.

Site	Year	n DCM	n RI	P_{ref} DCM	P_{ref} RI	CR_{TB1} DCM	CR_{TB1} RI	CR_{TB2} DCM	CR_{TB2} RI	CR_{WG} DCM	CR_{WG} RI
	(-)	(h)	(h)	(mm)	(mm)	(%)	(%)	(%)	(%)	(%)	(%)
Rollesbroich	2015	799	801	710	693	57.8	53.0	99.9	92.2	97.4	94.0
	2016	1009	1054	803	805	29.5	26.9	95.0	88.7	92.4	92.0
	2017	1027	1020	882	856	39.6	36.5	98.3	93.0	94.7	94.0
	2018	709	705	584	557	41.3	38.0	96.3	90.8	99.7	99.1
Selhausen	2015	760	744	601.36	552.4	52.5	48.9			100.5	103.7
	2016	721	733	556.31	529	51.4	48.1			97.3	100.8
	2017	598	616	432.88	411.6	51.3	48.0			99.6	105.5
	2018	570	611	389.81	391.6	28.8	25.8			104.5	107.5
Dedelow	2015	571	571	407.52	407.5	103.3	97.2				
	2016	641	641	410.68	410.7	97.2	91.8				
	2017	719	719	682.1	682.1	87.5	83.1				
	2018	407	407	271.31	271.3	106.7	100.9				

4 Discussion

4.1 Lysimeter measurements, reference values and the influence of non-rainfall ~~events~~water

The uncertainty ranges of the reference values and the overall strong correlation between the ~~intensity~~ measurements of the lysimeters within a site (Appendix ~~B~~C1-3, D1) demonstrate, that under field conditions and ~~at different climates~~locations, the lysimeter measurements were in good agreement with each other over the entire observation period at all sites. The uncertainties of the reference values meet the requirements defined by the WMO (2018) for gauges used in the field. They decreased with increasing precipitation intensity, reaching a threshold of 5 % at about 1 to 2 mm h^{-1}, which was observed at all study sites and regardless of the vegetation cover of the lysimeters. Additionally, lysimeter data at the sites showed R^2-values of 1 with a maximum bias of 0.01 mm h^{-1} and a maximum SDD of 0.05 mm h^{-1} (Appendix ~~B1~~C1 to ~~B3~~C3), indicating

Kommentiert [TS73]: Clarification

565 a good correlation. Since lysimeter measurement uncertainties increase exponentially with decreasing precipitation intensity from $P_{ref} < 1$ mm h^{-1}, calculating an average intensity from multiple lysimeters seems necessary for these data. For long-term periods, uncertainties were probably less important because of the assumed normally distributed deviations from the average. Relevant influences of spatial autocorrelation of precipitation were not found, which might go back to the temporal resolution of the data, the uniform environment without shielding and the overall small areas covered by the lysimeters and measuring

570 methods.

In total, when comparing the cumulated precipitation within a certain period, the lysimeters registered more precipitation than any other precipitation gauge. It could therefore be assumed that the lysimeter measurements and therefore the reference values are closer to the ~~"true"~~ actual precipitation than any of the other measurement method compared. The results therefore also indicate that the procedure to distinguish between water loss by ET and water input by AWI on a minutely basis prevented the

575 significant loss of registered AWI due to ET. However, comparing total precipitation amounts over long-term periods between the gauges and lysimeters, even if filtered carefully, might be biased because of non-rainfall water~~events~~ (~~NRE~~NRW), which contributed to the recorded precipitation measured by the lysimeters. ~~NREs~~ NRW which ~~occurred~~ deposited before, during or after a regular precipitation event within respective time interval were hence classified as precipitation, while other precipitation gauges did not record these. ~~NRE~~ NRW could thus lead to overestimations of lysimeter precipitation intensities,

580 although the average NRW intensity (RO: 0.011 mm h^{-1}; SE: 0.009 mm h^{-1}; DD: 0.012 mm h^{-1}; Appendix E1) ~~of a NRE was~~ is small compared to the precipitation intensity ~~(RO: 0.012 mm h^{-1}; SE: 0.009 mm h^{-1}; DD: 0.013 mm h^{-1})~~ and the distribution of ~~NRE~~ NRW intensities (Fig. 12 A to C) indicated that these presumably did not heavily bias hours with regular precipitation. Applying these averages for ~~NRE~~ NRW intensities on all hours which were investigated for the comparison of precipitation totals (Table 5~~6~~), only 1~~0.3~~7 % (RO), 1.2~~0.6~~ % (SE) and 1~~0.6~~8 % (DD) of the total registered precipitation would have been

585 attributed to ~~NRE~~NRW. This indicates a possibly small impact of ~~NREs~~ NRW on the results of this study. However, ~~NRE~~ NRW (i.e., dew, hoar frost and fog) can contribute a substantial amount of water for the ecosystem at the annual scale (Forstner et al., 2021; Groh et al., 2019), which demonstrates clearly that high-precision lysimeters are ideal tools measuring ~~the different NRE~~different ~~NRW of ecosystems. A higher temporal resolution of the data, possibly 10-min intervals, could help to temporally delineate precipitation events and ~~NRE~~NRW, as used by Groh et al. (2018b).

Figure 12: Distribution of ~~water~~ non-rainfall water ~~amounts~~amounts ~~formed during non-rainfall events~~ ($P_{ref} > 0$ mm h^{-1}; $P_{gauge} = 0$ mm h^{-1}) occurring between sunset and sunrise. Hourly values of non-rainfall events were limited to a maximum value of 0.07 mm h^{-1} according to Monteith and Unsworth (2013). A: Rollesbroich lysimeter station. B: Selhausen lysimeter station. C: Dedelow lysimeter station.

4.2 Evaluation of gauge types for the comparison of precipitation data

The systematic deviations between the reference values and the precipitation intensity measurements by TB1 in RO (Fig. 4 A) and the TB in SE (Fig. 4 C) on one side and the better fitting data from TB2 (RO; Fig 5 B) and TB in DD (Fig. 4 D) on the other side, can only be explained by divergent calibrations. All TBs were of the same type and only differed in the equipped heating module~~., which~~ This did not affect the measurements compared, since ~~it~~ the module only worked at low temperatures and was intended to melt solid precipitation. The TB (DD) also had a greater catching surface area of 400 cm² compared to 200 cm² at other sites. However, this effect should be deducted by the internal processing. A spatial influence on the measurements was also unlikely since TB2 in RO was installed 30 m away from the lysimeter station and measured values closer to the reference than TB1, which was located only 5 m beside the lysimeters. The maintenance and service intervals were nearly equal at all sites. No or incorrect calibration could lead to a systematic underestimation of precipitation measurements, especially regarding TBs (Calder and Kidd, 1978; Niemczynowicz, 1986; Shedekar et al., 2016). If the precipitation amount of the internal processing software does not agree with the amount of liquid, which is poured by a tip of the bucket, the bias increases with the amounts of tips. Thus, an increased underestimation of the precipitation intensity can be recognized with increasing reference values. Kohfahl and Saaltink (2020) also found that TBs located at the same site differed in the amount of precipitation measured during six rain events compared to a high-precision weighable lysimeter for bare soil conditions. The authors assumed that the TB, which showed significant errors with minor amounts of rainfall, was affected by an individual technical problem. However, also the TB2 (RO; Fig. 4 D) showed a systematic underestimation of precipitation intensities, in particular for slight precipitation intensities. The TB (DD) was also prone to this circumstance and

showed in addition outlier up to 9 mm h^{-1} at slight precipitation events. This might also be fixed with a dynamic calibration, although the occurrence of outliers towards an overestimation was exceptional compared to the other TBs. Considering that the hourly deviations led to underestimations of up to 67.7 % compared to the reference (TB RO; n = 3483 h), calibrations should be conducted regularly when operating a TB. TBs were also subject to the wetting loss, since precipitation can adhere on the gauge's inlet due to rough material surfaces and thus can be evaporated or sublimated without being measured (Sevruk, 1974). Due to the gauge´s specific resolution, which is limited for TB gauges by the volume of a bucket, certain amounts of precipitation could not be registered and therefore got lost (loss of trace precipitation; Seibert and Morén, 1999; Sugiura et al., 2003; Yang et al., 1999b). This is particularly relevant because a minimum threshold of 0.1 mm h^{-1} can be set for the overall comparison, but precipitation amounts below or above the gauge's resolution were not recorded by the respective TBs, but only by the lysimeters. This could lead to an underestimation of precipitation amounts compared to the reference. In addition to other external influences such as wind and temperature, this is reflected in the slight, systematic underestimation of the better performing TBs.

The WGs had the best correlation with low biases and small deviations in the precipitation totals, when the internally unprocessed data was compared to the reference. At both investigation sites, the devices underestimated the precipitation intensity consistently but within or close to the uncertainty range of the reference values. The weighable gauge (WG; RO) had a slightly lower R²-value and SDD, which might go back to generally higher wind speeds at the site. The installation of the wind shield had a positive effect on reducing the bias and SDD of the WG (SE; Fig. 5). This results agreed well with a previous study which showed that Alter wind shield on a WG (Pluvio²) reduced the bias and increased the accuracy compared to an unshielded WG (Kochendorfer et al., 2017a). Overall, the WG also achieved the highest CR in the comparison of absolute precipitation at both sites. Here, too, there was a difference of 14.7–8.0 % compared to the reference, which could be explained by the gauge's resolution and the wind effect. These results generally support approaches from other studies (e.g., Fehlmann et al., 2020; Johannsen et al., 2020) that used the WG as a reference device to study other gauges. Although the deviations of the WG data from the lysimeter data were still relatively high, this was the best correlation of all the investigated gauges in this study.

The hourly precipitation intensities determined by the AS were inaccurate compared to the reference with both, over- and underestimated intensities, shown by SDDs of up to 0.7 mm h^{-1}. External or internal data processing implementing an artificial time lag would lead to similar broad scattering (Fig. 6). However the data were tested for known errors indicating a time lag and no such influence could be identified. Salmi and Ikonen (2005) pointed out, that variations of the AS measurements were more of a stochastic than systematic origin. Variation in the shape and velocity of the hydrometeors caused by air movements were the main reason for erroneous measurements. Stochastic errors were also produced by the surface wetness and construction of the sensor itself due to sensitivity variations over the sensor area. In a comparison of multiple instruments to measure precipitation, Liu et al. (2013) found the lowest correlation coefficient and the largest SD while comparing their reference, a TB, with the AS with a temporal resolution of one minute. Moreover, the AS overestimated the rainfall accumulation and recorded little higher rain intensity compared to their reference, when the rain intensity was less than 20 mm h^{-1} (Liu et al., 2013). According to Haselow et al. (2019), the AS showed overestimations by highly positive error values, compared to lysimeter reference data on a daily basis. Even though the hourly deviations in precipitation intensity were partly above the reference values, less absolute precipitation was measured by the ASs at all research sites than specified by the reference values. However, there were major differences between the sites. The different ASs in RO and SE registered 69.2 % and 73.2 % of the reference values, respectively, and in DD 86.8 %. The variation between the sites may exist due to the selection of hours with precipitation recorded by either the TB, AS or WG. The latter was absent in DD, so the threshold of 0.1 mm h^{-1} was more often reached by the AS at this site compared to the other sites. Therefore, precipitation registered only by the WG is not affecting the CRs of the ASs at DD.

Precipitation measurements performed by the LD had a small bias compared to the reference, which was probably primarily due to the resolution of the measuring device of 0.001 mm h^{-1}. The overall good correlations are reflected in the absolute values measured over a longer period, which can be compared with the CRs of the WGs. The deviations from the reference could be attributed to stochastic influences of drop size distributions and conversions during the processing of the measured data. According to a study by Johannsen et al. (2020), recorded drop sizes, velocity distributions, and kinetic energy intensity relationships were device-specific and showed similarities only for disdrometers of the same type across measurement sites. Liu et al. (2013) found that small raindrops tend to be omitted in larger size raindrops due to shadow effects of light. Also, two adjacent particles could appear as a large particle, resulting in wrong precipitation intensities (Lanzinger et al., 2006). The wind direction could also influence measurements of optical instruments as well as splashing of large raindrops off the device (Dengel et al., 2018). Hence an investigation of CRs as functions of the wind direction could reveal such interrelations.

Furthermore, the number of erroneous measurements was high compared to the other gauges. For the LD (SE) 534 hours must be manually filtered, compared to 42 hours for the LD (RO). The data showed abrupt and isolated occurring hours with high precipitation intensities (> 50 mm h^{-1}) as well as consecutive hours with varying precipitation intensities, which were clearly decoupled from actual precipitation events. This could be explained by foreign objects interfering with the laser beam. Additionally, prolonged time periods occurred when the disdrometer continuously recorded fluctuating precipitation intensities with notable deviations from the reference. This error might be triggered by spider webs or insects intercepting the laser, or water and dust particles on the sensor, which were known to cause such errors on optical disdrometer measurements (Adirosi et al., 2018; Heyn et al., 2018).

Ultimately, all the gauges studied tended to underestimate precipitation amounts compared to the reference, both on an hourly basis and over longer time periods. This means that calibrating large-scale weather simulations with such biased gauge data could lead to an underestimation of actual precipitation amounts in these models. The use of a less accurate precipitation data set in environmental model calibration compromises parameter identification and reduces the ability of the model to simulate processes associated with water and solute transport in the critical zone (e.g., Groh et al., 2018a). For the calculation of small-scale water balances, biased precipitation data as an input variable could also distort the overall research results.

4.3 Influence of wind speed on gauge precipitation measurements

Of the two best performing TBs, one (TB2, RO) exhibited generally lower CRs with increasing wind speed (Fig. 8 B). This finding agreed with the general assumption of the effects of wind-field formations on Hellmann-design gauges (Sevruk et al., 1989). The TB (DD) revealed increased CRs at higher wind speeds (Fig. 8 D). Usually, the contrary effect is assumed (Duchon and Biddle, 2010; La Barbera et al., 2002). A connection of this phenomenon to the precipitation intensity was not evident. The AS at the site also had a higher CR than the reference at high wind speeds (Fig. 10 D), but this pattern occurred also at other sites (Fig. 10 B to D). The TB (DD) is the only TB installed directly within the crop field. Thus, during crop season, water from the surrounding vegetation might have dripped into the funnel and the crop might have functioned as wind protection. However, a comparison of data from the respective months with (April–July) and without available crops does not indicate such an effect.

The CRs of the WG (RO) did not indicate ~~significant~~ clear influences of wind speed on the precipitation data (Fig. 9) even though the splitting of the WGs (SE) dataset according to the availability of a wind shield eventually revealed such influences affecting the measured precipitation intensities of the WGs. The CRs for the AS data ~~might~~ imply a bias towards overestimation of precipitation intensity with increasing wind speeds. This phenomenon was recognized in the literature (Liu et al., 2013) and could be traced back to the gauges measuring principle. An wind induced, increased terminal velocity with which a hydrometeor hits the sensors surface, ~~was~~ could be directly converted to higher precipitation intensities (Salmi and Ikonen, 2005). Both LDs tended to have increased CRs along with higher wind speeds, which might be related to the conversion from recorded drop size distribution and vertical velocity of the raindrops to precipitation intensities.

Kommentiert [TS85]: Wording.

Kommentiert [TS86]: Adjustment based on reworked CR plots.

Kommentiert [TS87]: Wording.

Kommentiert [TS88]: Grammar

4.4 Evaluation of the precipitation data correction methods for TB and WG data

To improve data quality with precipitation data correction during post-processing, the correction method must be selected and adapted to the measuring device collecting the data (WMO, 2018). Here, two different correction methods were applied to TB

700 and WG data to examine their impact on the respective hourly precipitation data. Both methods were based on empirical data obtained at different locations than the test sites. However, the driving forces for data correction were wind speed and gauge design, which in this study were similar to those of the original data correction studies. Both approaches reduced the bias of the TB data relative to the reference, which was a key goal of the precipitation data correction. The dynamic correction model (DCM) led to a generally greater reduction of the bias (TBs: -0.13 mm h^{-1}; WGs: -0.09 mm h^{-1}) for all gauges than the approach

705 derived from the method of Richter (1995; TBs: -0.08 mm h^{-1}; WGs: -0.07 mm h^{-1}). As a result of the corrections, considerable amounts of precipitation have been added to the precipitation totals in the period under study. Especially the correction of data from TB2 (RO), WG (RO) and WG (SE) led to CRs of 97.4 (+15.7 %), 96.0 (+10.7 %) and 100.5 % (+8.5 %) compared to the lysimeter reference. This indicates that the correction methods showed the best effect for the data with the initially highest quality, but possibly could lead to overestimations, which was found in overcorrection of precipitation data for WG (Se; Table

710 7).

Haselow et al. (2019) used the linear scaling method to reduce the bias of daily precipitation data from multiple rain gauges compared to lysimeter measurements. To do this, they applied the ratio between the monthly rainfall totals from lysimeters and rain gauges to the daily rainfall totals of the rain gauges. The method successfully reduced the bias of the daily precipitation data despite for periods of high precipitation intensities (Haselow et al., 2019). However, a distinction must be made between

715 correction methods that correct precipitation data solely on the basis of reference data (e.g., Fang et al., 2015) and methods such as the DCM used in this study that correct individual physical and technical induced errors like wind field deformation and evaporation. For the latter approach, the availability of results from comparable studies with weighable lysimeter references is limited. For TB1 (RO) and TB (SE), the correction was not sufficient to compensate for the systematic biases from the reference, although the distortion probably came from calibration issues that were not intended to be corrected by the

720 DCM. An overcorrection of the precipitation intensities for the WGs at high wind speeds cannot be ruled out, especially since the Alter wind shield has already reduced the influence of the wind on the WG (SE). Michelson (2004) found that the DCM resulted in more accurate precipitation estimates, although uncertainties in the treatment of measurements for some gauge types remain, which can be confirmed by the results of this work. The results also showed that the biases for all corrected TBs were reduced by applying the adjusted correction method according to Richter (1995), although high biases still remain for the

725 TB1 (RO), TB (SE) and TB (DD). It must be taken into account that the orders of magnitude of these correction amounts were detached from individual environmental influences at the sites and only related to the manual Hellmann type gauge (Richter, 1995). Richter (1995) also stated that due to the large daily variability of the individual error-causing parameters, the statistical error of the calculations based on mean ratios was inevitably large and mainly in the magnitude of the correction amount. Therefore, the adjustment to correct the hourly measurements increased the statistical error. Based on given data availability

730 of reference, gauge, and weather data, machine learning algorithms might be a promising tool to further optimise device-specific precipitation data corrections.

5 Conclusions

Precipitation data from three research sites of the TERENO-SOILCan network based on high-precision weighable lysimeters were used as reference to investigate the functionality and data quality of four different precipitation measurement methods.

735 ~~The arithmetic mean of the lysimeter measurements has proven to be an almost unbiased reference for the precipitation measurement method.~~ The low bias in hourly lysimeter measurements indicated the suitability of their arithmetic mean as a reference for comparing precipitation methods. The results of this study revealed that each gauge-based method (i.e., tipping

Kommentiert [TS89]: R1:
7) Section 2.8: Precipitation data corrections: This section proposes correction procedures that seem very empirical. How much can we trust these methods in the general case? How applicable are they for locations different than their development?"

Kommentiert [TS90R89]: We agree that the correction methods are based on empirical data. The method after Richter has been developed especially for different locations with scarce data coverage. Therefore, the parametrisation is done loosely based on specific location characteristics. Here, the measurement method is important since the original method has been exclusively developed for Hellmann-type gauges. For the Dynamic Correction Method, factors for precipitation type, wind speed and gauge model are defined. The only site-specific factor appears to be the wind speed, which varies according to the site. Since the method has been developed covering a range of wind speeds including those measured at the sites, the factors should cover the issue.

Kommentiert [TS91]: R1:
"8) The following sentence appears in the conclusion section (L677): "The arithmetic mean of the lysimeter measurements has proven to be an almost unbiased reference for the precipitation measurement method". I don't think this was proved, but rather the assumption was the basis for the error analysis. Please clarify or correct."

Kommentiert [TS92R91]: The corresponding passage was adapted.

bucket gauges, weighable gauges, acoustic sensors, and optical laser disdrometers) was affected differently by wind, precipitation intensity, measurement resolution and technical errors. All precipitation measurement methods underestimated the precipitation amounts for the observation period with deviations of 8 % to 67 % from the reference if only hours with precipitation intensities greater than 0.1 mm h^{-1} were considered. This implies that point precipitation data should be treated as minimum values, especially when looking at cumulative totals over long time periods. When using hourly data for water balances or local projections of climate change, an uncertainty regarding over- and underestimation of point precipitation data must be taken into account, depending on the gauge type. The results confirmed that correction algorithms, which consider the influence of wind and other typical sources of error on the instruments, reduced the bias between reference and measurements and improved the catching rations of hourly precipitation data from rain gauges (tipping bucket and weighable gauge) under different climatic conditions at three different TERENO-SOILCan test sites. The Dynamic Correction Model achieved higher average catch ratios compared to the correction approach derived from Richter. Therefore, only the Dynamic Correction Model might be the right tool to correct hourly precipitation data. Adequate reference data are crucial for testing and developing correction methods to overcome errors in precipitation measurements from standard point gauges. Observations from weighable, high-precision lysimeter (e.g., TERENO-SOILCan network) provide such data to improve estimates of point scale precipitation under different climatic conditions. Unbiased point-scale precipitation estimates are essential when estimating precipitation at larger scales remotely from either ground-based weather radars or from satellites. Precipitation is the main driver of the hydrological cycle and accurate data help to improve local weather and climate forecasts, which is particularly relevant in the context of climate change.

Appendix A

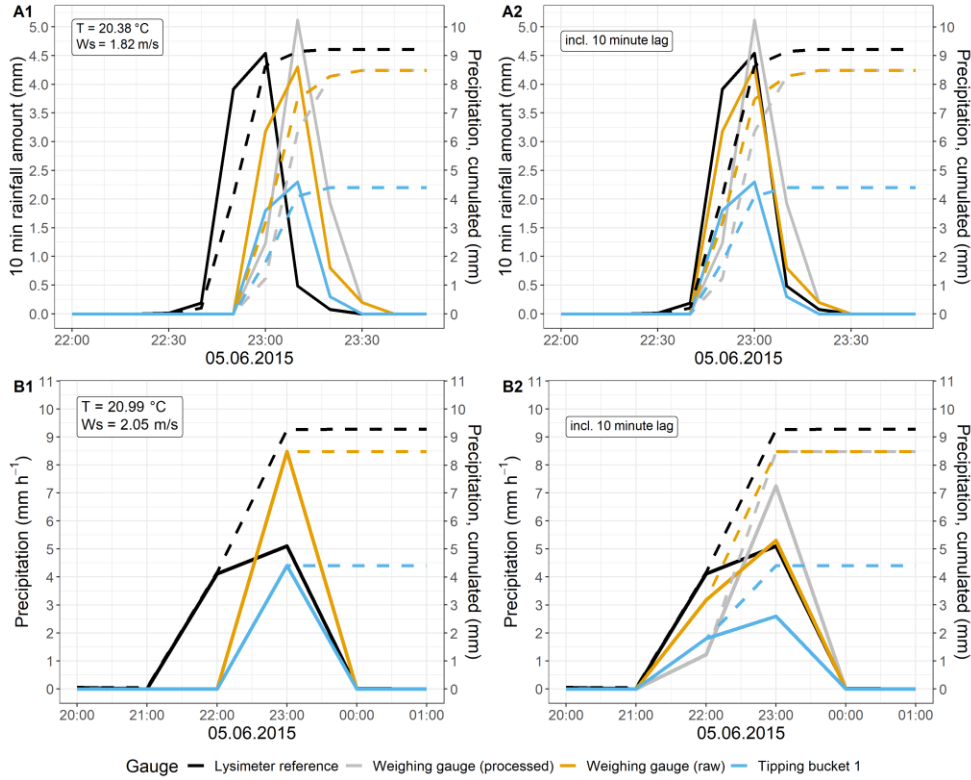



Figure A1: Time series of a precipitation event in Selhausen with a temporal resolution of A: 10 minutes, B: one hour. Solid lines display the precipitation intensity (left y-axis) and dashed lines the cumulative precipitation (right y-axis). A1 and B1 show original data. A2 and B2 show data with an implemented reverse time lag of 10 minutes for the tipping bucket and weighable gauge.

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Appendix B

Table B1: Distribution of precipitation rates determined by the lysimeters over the observation period for $P_{ref} \geq 0.1$ mm h^{-1}, as used for the gauge comparison.

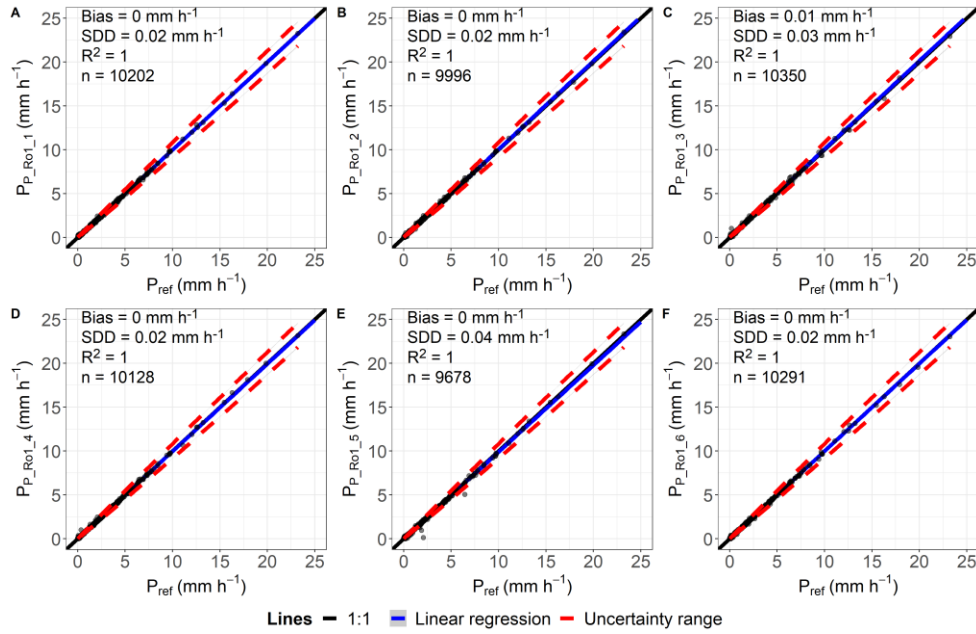
Site	Min	Max	Mean	Median	Quantiles				
					5.00 %	25.00 %	50.00 %	75.00 %	95.00 %
	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})			(mm h^{-1})		
Rollesbroich	0.100	32.243	0.822	0.413	0.114	0.202	0.413	0.885	2.813
Selhausen	0.100	23.210	0.941	0.519	0.120	0.248	0.519	1.145	2.941
Dedelow	0.100	12.910	0.819	0.446	0.116	0.209	0.446	0.973	2.626

765 **Table B2:** Distribution of precipitation rates determined by the lysimeters over the observation period for $P_{ref} > 0$ mm h^{-1}, including non-rainfall water.

Site	Min	Max	Mean	Median	Quantiles				
					5.00 %	25.00 %	50.00 %	75.00 %	95.00 %
	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})			(mm h^{-1})		
Rollesbroich	0.001	32.243	0.177	0.013	0.001	0.005	0.013	0.052	0.883
Selhausen	0.001	23.210	0.297	0.017	0.001	0.006	0.017	0.195	1.536
Dedelow	0.001	12.910	0.220	0.014	0.001	0.005	0.014	0.106	1.189

Kommentiert [TS93]: R1:
"6) The highest observed precipitation rate is 20 mm/h. Can you provide some info about this value so the reader would know what part of the precipitation rate distribution the analysis is covering?"
13) It would be good to show the CDFs of hourly values of precipitation and ET.

Kommentiert [TS94R93]: In this table we provide more information on the catch rate distributions. Due to lack of data on ETa, we could not provide more data on this topic.

Appendix C

 Figure C1: Comparison of hourly precipitation data classified as "Rain", determined by lysimeter and reference data (P_{ref}) for the lysimeter station in Rollesbroich. Plots A–F include all hours of measurements taken where both P_{lys} and P_{ref} are ≥ 0.001 mm h^{-1}. The vegetation grown on the lysimeter is of a grassland type.

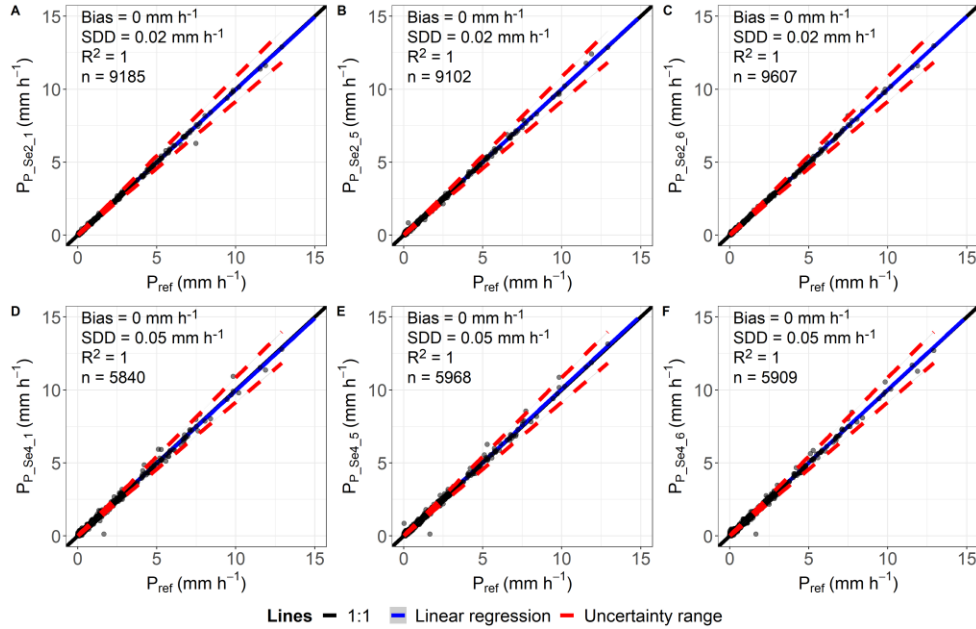



Figure C2: Comparison of hourly precipitation data classified as "Rain", determined by lysimeter and reference data (P_{ref}) for the lysimeter
775   station in Selhausen. Plots A–C include all hours of measurements taken where both P_{lys} and P_{ref} are ≥ 0.001 mm h^{-1} and the vegetation

grown on the lysimeter is of a grassland type. Plots D–F include all hours of measurements taken where both P_{lys} and P_{ref} are ≥ 0.001 mm h^{-1} and the vegetation grown on the lysimeter is of an arable land type.

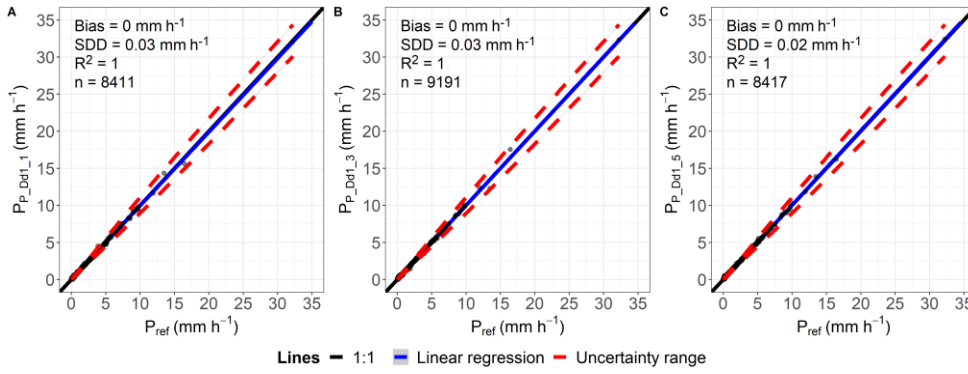



Figure CB3: Comparison of hourly precipitation data classified as "Rain", determined by lysimeter and reference data (P_{ref}) for the lysimeter station in Dedelow. Plots A–C include all hours of measurements taken where both P_{lys} and P_{ref} are ≥ 0.001 mm h^{-1}. The vegetation grown on the lysimeter is of an arable land type.

Appendix D

Table D1: Mean and variance for all measurements taken by the lysimeter at each site for hours in which every lysimeter at a site has been available during the investigation period (2015 – 2018). Data filtered for "rain" and P > 0.1 mm h^{-1}.

	Lysimeter	Rollesbroich	Selhausen	Dedelow
Mean (mm h^{-1})	1	0.887	0.824	0.815
	2	0.901	0.826	0.823
	3	0.907	0.824	0.829
	4	0.884	0.822	
	5	0.877	0.826	
	6	0.893	0.828	
Variance (mm h^{-1})^2	1	1.67	1.27	1.93
	2	1.69	1.28	1.96
	3	1.69	1.28	1.97
	4	1.67	1.27	
	5	1.64	1.30	
	6	1.66	1.28	

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Appendix E

Table E1: Statistics on non-rainfall water (NRW) recorded by the lysimeter within the investigated period. NRW was identified, when no gauge but the lysimeter or disdrometer recorded atmospheric water input (AWI) between sunrise and sunset. The statistics are given for NRW ≤ 0.07 mm h^{-1}.

Site	Year	Sum	Mean	Median	Standard deviation	n	n (NRW > 0.07 mm h^{-1})
(-)	(-)	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})	(mm h^{-1})	(h)	(h)
Rollesbroich	2015	14.3	0.012	0.010	0.010	1245	18
	2016	20.1	0.011	0.008	0.011	1807	53
	2017	18.7	0.012	0.009	0.011	1585	46
	2018	16.1	0.010	0.007	0.009	1639	29
Selhausen	2015	15.8	0.011	0.008	0.010	1505	22
	2016	14.1	0.009	0.006	0.008	1636	16
	2017	14.3	0.009	0.007	0.009	1544	19
	2018	12.9	0.008	0.006	0.007	1636	16
Dedelow	2015	22.0	0.012	0.009	0.011	1767	40
	2016	24.0	0.012	0.007	0.013	1944	63
	2017	20.4	0.013	0.009	0.013	1532	61
	2018	16.3	0.009	0.005	0.010	1838	61

Kommentiert [TS97]: R2:
As pointed out by referee 1 the effect of ET during the 1-hour rainfall aggregates and the effect of NRE needs to be explained and potential uncertainties of ET need to be discussed in the revised version of the manuscript. Consider estimating NRE for your lysimeter sites and adding the total (annual) amount of NRE in table 5 or at a later point in the manuscript (I understand that there are uncertainties, however an estimate would be helpful).

Kommentiert [TS98R97]: Provided more data on NRW.

Data availability

All raw data for the specific lysimeters, precipitation gauges and weather stations from Rollesbroich and Selhausen can be
freely obtained from the TERENO data portal (https://teodoor.icg.kfa-juelich.de/ddp/index.jsp (last access: 07 October 2022;
Kunkel et al., 2013) with respective ID codes.

Rollesbroich lysimeter station: RO_BKY_010 (gauge and weather data), RO_Y_01 (lysimeter data).

Rollesbroich Eddy covariance station: RO_EC_001 (gauge data).

Selhausen lysimeter station: SE_BDK_002 (gauge and weather data), SE_Y_02 (lysimeter: Se_Y_021, Se_Y_025,
Se_Y_026), SE_Y_04 (lysimeter: Se_Y_041, Se_Y_045, Se_Y_046).

Dedelow lysimeter station: Dd_K_01 (gauge and weather data), Dd_Y_01 (lysimeter data). The data for the experimental
station in Dedelow can be acquired upon request from Jannis Groh.

Author contributions

TP conceived the experiments. JG, TP, and TS had the idea and designed the study. JG provided the data for the corresponding
lysimeter stations. HHG and BR guided the conceptualization and the internal review process. TS performed the data analysis
and wrote the paper with equal contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Harms and Leander Fürst (Rollesbroich and Selhausen).

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