Lysimeter based evaporation and condensation dynamics in a Mediterranean ecosystem

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Abstract.

The input of liquid water to terrestrial ecosystems is composed of rain and non-rainfall water input (NRWI). The latter comprises dew, fog, and adsorption of atmospheric vapor on soil particle surfaces. Although NRWIIs can be relevant to support ecosystem functioning in seasonally dry ecosystems, they are understudied, being relatively small, and therefore hard to measure. In this study, we test a routine for analyzing lysimeter data specifically to determine NRWI. We apply it on one year of data from large high-precision weighing lysimeters at a semi-arid Mediterranean site and quantify that NRWIIs occur for at least 3 h on 297 days (81 % of the year) with a mean diel duration of 6 hours. They reflect a pronounced seasonality as modulated by environmental conditions (i.e., temperature and net radiation). During the wet season, both dew and fog dominate NRWI, while during the dry season it is soil adsorption of atmospheric vapor. Although NRWI contributes only 7.4 % to the annual water input NRWI is the only water input to the ecosystem during 15 weeks, mainly in the dry season. Benefitting from the comprehensive set of measurements at the Majadas instrumental site, we show that our findings are in line with (i) independent model simulations forced with (near-) surface energy and moisture measurements and (ii) eddy covariance-derived latent heat flux estimates. This study shows that NRWI can be reliably quantified through high-resolution weighing lysimeters and a few additional measurements. Their main occurrence during night-time underlines the necessity to consider ecosystem water fluxes at high temporal resolution and with 24-hour coverage.

1 Introduction

Water availability at the land surface controls a variety of processes related to land-atmosphere exchange, such as the warming of the surface and air temperature (\(T_a, °C\)) (Seneviratne et al., 2010; Panwar et al., 2019), ecosystem carbon fluxes (Reichstein et al., 2007; El-Madany et al., 2021), and evapotranspiration (\(ET, mm\)) (Jung et al., 2010; Rodriguez-Iturbe et al., 2011).
Therefore, precise quantification of the water balance is crucial for understanding and simulating these processes. The largest atmospheric input of liquid water to ecosystems globally is rain. In addition, other liquid water inputs exist, which are summarized under the term non-rainfall water input (NRWI).

NRWIs comprise several types of processes: deposition (fog, horizontal precipitation), condensation (formation of dew, soil distillation, and hoar frost), and soil vapor adsorption (Kidron and Starinsky, 2019). These processes are mainly controlled by i) atmospheric vapor pressure ($e_a$, hPa), ii) surface temperature ($T_s$, °C) and iii) topsoil water potential. Fog is defined as water droplets suspended in the air at a concentration that reduces visibility below 1000 m (Feigenwinter et al., 2020). The droplets adhere to surfaces after contact. This fog deposition is commonly derived from relative humidity ($rH$, %) or visibility measurements (Feigenwinter et al., 2020; Zhang et al., 2019b). Condensation processes are induced by $T_s$ decreasing below the dewpoint temperature ($T_{dew}$, °C) of nearby air. This is referred to either as dew when the water originates from the atmosphere, or soil distillation when the water originates from the soil beneath. However, differentiating between these two origins is commonly not possible (Li et al., 2021b) and most literature summarizes both processes as dew. Dew is often measured with lysimeters (Meissner et al.; Groh et al., 2018; Zhang et al., 2019b) or by leaf wetness sensors (Feigenwinter et al., 2020).

In contact with soil, the water vapor is influenced by capillary and adsorptive forces due to pore shapes and the polarity of the solid material (Tuller et al., 1999). These forces increase in relevance as the soil dries out. They reduce the saturation vapor pressure as a function of soil dryness (Edlefsen et al., 1943), leading to condensation within the soil at $rH$ lower than 100%. The respective NRWI is the adsorption of atmospheric vapor. However, despite being well understood at pore and laboratory scales (Tuller et al., 1999; Arthur et al., 2016), this process was underrepresented in NRWI studies (Zhang et al., 2019b; Saaltink et al., 2020; Kohfahl et al., 2019).

So far, no standard technique has been developed to measure the different components of NRWI in the field. Partly, this is related to technical limitations in measuring capabilities (summarized in Feigenwinter et al., 2020). Modeling NRWI also remains a challenge, although a distinction must be made between modeling frequency and duration, and modeling the yields of the different NRWI fluxes. In the case of dew for example fewer studies have addressed the development of the latter models due to the overall complexity of heat and radiation exchange and many unknown necessary parameters (Tomaszkiewicz et al., 2015). The same is true for adsorption (Verhoef et al., 2006).

Furthermore, the relatively small contribution of NRWI for the annual water balance lead to an underestimation of their relevance for ecosystem functioning. But NRWI subsidies can extend or sustain ecosystem functioning when rain and soil moisture are low (Weathers et al., 2020; Tomaszkiewicz et al., 2015). This is long known for arid ecosystems (Duvdevani, 1963; Agam and Berliner, 2006; Kidron and Starinsky, 2019) but an increasing number of studies suggest ecological relevance also in the context of seasonal dry spells (Jacobs et al., 2006; Li et al., 2021b; Groh et al., 2018; Dawson and Goldsmith, 2018). As leaf wetting events, dew and fog can affect leaf water status directly and alter the surface water and energy balance by changing leaf temperature, albedo, and water vapor deficit (Dawson and Goldsmith, 2018; Gerlein-Safdi et al., 2018; Aparecido et al., 2017). Uptake of water at the leaf surface was observed across ecosystems, species, and plant types relieving daily water and carbon stress (Dawson and Goldsmith, 2018; Berry et al., 2014; Aparecido et al., 2017). Secondary effects of
NRWIs related to changes in canopy micro-climate have also been shown to reduce plant water stress and increase water use efficiency (Ben-Asher et al., 2010). Respiration in dry seasons of organisms like biocrusts (Kidron and Kronenfeld, 2020a), microbes within the soil (McHugh et al., 2015), and on standing litter (Evans et al., 2019; Gliksman et al., 2017) was sustained due to dew and adsorption. Nevertheless, the role of NRWIs in connection with the carbon cycle across ecosystems has not yet been fully understood and quantified (Dawson and Goldsmith, 2018; Weathers et al., 2020; Kidron and Starinsky, 2019). Research about the role of NRWI remains limited by too few measurements of their actual amounts (Berry et al., 2019). Appropriate measurement facilities to analyze and quantify the local circumstances of NRWI occurrence seem sparse. Past studies were often based on micro-lysimeters covering time periods of few weeks to some months. Recently Kidron and Kronenfeld (2020b) found that temperature inside the micro-lysimeters deviated from that in the surrounding soil, and also that instrument structure, such as column length and parent material, were impacting flux sums. These issues are partly overcome for large high precision weighing lysimeters, where lower boundary control systems were developed which equilibrate soil temperature and moisture content between the inside of the lysimeter and the surrounding soil to prevent biases (Groh et al., 2016). Therefore, data collected with large weighing lysimeters can further contribute to the identification and quantification of NRWIs. Yet, relatively few stations are located in semi-arid and arid environments (Perez-Priego et al., 2017; Dijkema et al., 2018; Kohfahl et al., 2019; Zhang et al., 2019b) where NRWIs are expected to be particularly relevant.

In this study, we implement and test a processing scheme for identifying and quantifying NRWIs in a seasonally dry ecosystem in continental Spain. The aims of this paper are to (i) extend and refine processing routines for water flux partitioning to distinguish between ET, rain, and individual NRWIs, based on lysimeter and meteorological data; (ii) analyze the seasonal NRWI dynamics and their contribution to the annual water input at the site; and (iii) evaluate our results against independent observations and empirical models.

2 Material and Methods

2.1 Study site

All data investigated in this study originates from the experimental field site Majadas de Tietar, Caceres in Extremadura, Spain (39°56′25.12″ N, 5°46′28.70″ W). Average diel \( T_a \) is 16.7°C with diel minimum and maximum \( T_a \) of 3.1°C to 12.5°C in January and 18.6°C to 39.8°C in August. The rain mainly falls between October and April, with mean annual amounts of ca. 650 mm, with large interannual variations (El-Madany et al., 2020). The ecosystem is a typical Mediterranean semi-arid tree-grass ecosystem (Dehesa) with low-density oak tree cover (Quercus Ilex (L.), 20 trees ha\(^{-1}\)) (Bogdanovich et al., 2021). The herbaceous layer consists of native annual grasses, forbs, and legumes (Migliavacca et al., 2017) with a seasonally varying fractional cover mainly influenced by moisture availability (Luo et al., 2020). The growing season for the herbaceous layer begins after the first rains after summer (typically in mid-October) and is inhibited by low temperatures in winter before peaking in spring before the dry season. During the dry season, the herbaceous species are inactive until the return of rain (Perez-Priego et al., 2018). The site is managed with low-intensity grazing by cows during the growing season (El-Madany et al., 2018). An exclusion cage was used to avoid cows stepping into the lysimeters. However, the structure of the cage allowed
for grazing to maintain the lysimeters comparable with the rest of the plot. The soil is formed of alluvial deposits and classified as Abruptic Luvisol (IUSS Working Group WRB, 2015) with sandy topsoil of 74% sand, 20% silt, and 6% clay (Nair et al., 2019). A clay layer rests at a variable depth between 30 cm to 100 cm. Although the trees also play a role in the water balance at the ecosystem scale, herbaceous vegetation dominates $ET$ (Perez-Priego et al., 2017). This work focuses on the water fluxes in open areas where lysimeters are located (Migliavacca et al., 2017).

2.1.1 Lysimeter technical specifications

The site is equipped with three lysimeter stations, each containing two weighable high-precision lysimeters (UGT, Müncheberg, Germany), for a total of 6 columns. Each column has a 1 m$^2$ surface area and 1.20 m column depth. They rest of the weighing systems consisting of three precision shear-stress cells, respectively (Model 3510, Stainless Steel Shear Beam Load Cell, VPG Transducers, Heilbronn, Germany). The weight measurements are collected every 1 min with a measurement precision of 10 g (0.01 mm). Each lysimeter station is equipped with a lower boundary control system to avoid deviations from natural conditions due to the isolation of the lysimeter columns (Groh et al., 2016). Porous ceramic bars at the bottom of the lysimeters maintain the soil water potential within the column comparable with the soil surrounding them. Soil temperature ($T_{soil}, ^\circ C$) is controlled with a heat exchange system (for further details, see Perez-Priego et al. (2017)). $SWC$ and $T_{soil}$ are measured every 15 min within the columns at 0.1, 0.3, 0.75, and 1 m depth (UMP-1, Umwelt-Geräte-Technik GmbH, Müncheberg, Germany). Soil matric potential ($\Psi$, hPa) is measured every 15 min at 0.1 m depth with a porous ceramic cone full range pH meter (ecoTech Umwelt-Meßsysteme GmbH, Bonn, Germany).

The stations were installed in 2015 at open grassland patches with 104 m, 91 m, and 24 m distance to each other, respectively. The closest tree is $\sim$9 m away. To test the application of data processing and flux classification across seasons, we analyze a period of one year from June 1st, 2019 to May 31st, 2020.

2.1.2 Ancillary measurements outside the lysimeters

For partitioning the lysimeter weight changes ($\Delta W$, kg min$^{-1}$) into different water fluxes and modeling (see Section 2.2.1, 2.3.1, and 2.3.2) we used additional field measurements collected every 30 min. Meteorological variables monitored are rain, which is measured with a weighing rain gauge (TRwS 514 precipitation sensor, MPS systém, Slovakia), $T_a$, and $rH$ at 1 m (Pt–100 capacitive humidity sensor CPK1–5, MELA Sensortechnik, Germany). $T_{dew}$ was calculated based on $T_a$ and $rH$ (see Appendix A2). Actual vapor pressure ($e_a$, hPa) is calculated from $T_a$ and $rH$.

Short- ($SW$, W m$^{-2}$) and longwave ($LW$, W m$^{-2}$) incoming (↓) and outgoing (↑) radiation of the herbaceous layer was observed with a net radiometer (CNR4, Kipp and Zonen, Delft, Netherlands) at a measurement height of $\sim$2 m. $T_a$ is calculated from $LW$ (equations in Appendix A2). Ground heat flux ($G$, W m$^{-2}$) was monitored with soil heat flux plates (Heatflux Ramco HP3, McVan Instruments, Mulgrave, Australia).

$T_{soil}$ and $SWC$ were measured along a profile outside the lysimeters at 0.05 m, 0.10 m, and 0.2 m depth, respectively (Delta-ML3, Delta-T Devices Ltd, Burwell Cambridge, UK).
Fluxes of latent heat ($\lambda E$, W m$^{-2}$), wind speed ($u$, m s$^{-1}$) and friction velocity ($u^*$, m s$^{-1}$) were measured by an eddy covariance (EC) system, consisting of a sonic anemometer (R3–50 Gill Instruments, Lymingon UK) and an infra-red gas analyzer (LI-7200, Licor Biosciences, Lincoln, USA) at 1.6 m sampling height and targeting the herbaceous layer (Perez-Priego et al., 2017). For further details on the EC data processing, see El-Madany et al. (2018).

### 2.2 Data analysis

#### 2.2.1 Lysimeter data processing

The processing of lysimeter data comprises several steps: (a) raw weight data filtering, (b) time-series smoothing, and (c) flux partitioning. The processing workflow is displayed in figure 1. All code used in the analysis is available for reproducibility in the open-source R environment for statistical programming (R Core Team, 2020). See the data and code availability statement for more details.

**a) Raw data processing:** changes in the water reservoir through the lower boundary system and lysimeter column weights are added together. Outliers are filtered out by setting plausible threshold values: $-0.5$ kg min$^{-1} < \Delta W < 1$ kg min$^{-1}$ (Schrader et al., 2013). Additionally, outliers within these threshold values were identified by comparing $\Delta W$ across the six columns. If $\Delta W$ is due to rain, we expect similar responses across lysimeters. In contrast, if only one lysimeter column shows an anomalous $\Delta W$ we considered this as an artifact (e.g., animal stepping on the column or issues with the boundary control) that can be removed from the time series (Hannes et al., 2015). For identifying these values, we calculated the mean $\Delta W$ of all six lysimeters for an interval $i$ of one minute. This value was then subtracted from the individual $\Delta W$ measurements during $i$. The resulting value is a normalized weight change ($\Delta W_{\text{normalized},i}$, kg) for each column. Then, an average standard deviation ($\sigma$, kg) was calculated from $\Delta W_{\text{normalized},i-3}$ to $\Delta W_{\text{normalized},i+3}$. $\Delta W_{\text{normalized},i} > (1.5 \times |\sigma|)$ are replaced by not a number (NA).

**b) Time-series smoothing:** is necessary to remove noise from the time series before the partitioning and data analysis based on $\Delta W$ (Schrader et al., 2013). Since noise in this type of data is not constant in time due to wind for example (Nolz et al., 2013), we apply a routine with adaptive averaging window widths ($\omega$) and adaptive $\Delta W$ thresholds ($\delta$) (AWAT) from Peters et al. (2014, 2016, 2017). As an intermediate result, the AWAT algorithm produces a step function of lysimeter weight. At last, a smoothing of the 1 min resolution time series is performed using a spline interpolation. We chose this routine because the authors included a processing step developed specifically for dew conditions (Peters et al., 2017). In our application, the parameter $\omega$ varied between 3 min to 31 min and $\delta$ between 0.01 mm to 0.05 mm. A detailed overview of the algorithm and an evaluation of the performance are compiled in Peters et al. (2017) and Hannes et al. (2015). If one out of all columns was measuring more than 16 h of water input during one day, the full day was excluded for the analysis for the respective column. Due to technical problems that became obvious after data processing, lysimeter column number 4 was completely excluded from further analysis. After the smoothing, the time series are aggregated to a 5-minute resolution to further decrease the remaining influence of noise for the subsequent step of flux partitioning, particularly for values close to zero.
Flux partitioning: the filtered time series of $\Delta W$ is divided into six different water fluxes, assuming that in 5-minute intervals, only one process prevails over the others. Negative $\Delta W$ is always classified as $ET$. Positive $\Delta W$ is separated into different flux categories in a decision tree structure considering additional meteorological data, as illustrated in figure 1. We use the convention that outgoing fluxes like $ET$ take negative values (related to negative $\Delta W$ as water is leaving the soil), and rain and NRWIs are positive (because associated with positive $\Delta W$). At the second decision node, we check if the rain gauge identifies a rain event during the period of weight increase. If true, all positive $\Delta W$ are classified as rain during 30 minutes before and after the event. This period was selected to match the measurement interval of rain gauges which is 30 minutes. If false, e.g., in the absence of rain, $rH$ is evaluated. If $rH$ exceeded a threshold identified as the 90th percentile of the $rH$ sensor records, $\Delta W$ is attributed to fog. In our case, this threshold value is at $rH_t = 97.8\%$ and measured by a sensor at 1 m height. We decided to set a $rH$ threshold that is based on the data distribution of the sensor because it accounts for the individual uncertainty which is particularly high when the air is nearly saturated (Feigenwinter et al., 2020), systematic biases, and drifts of $rH$ sensors.

If neither fog nor rain is detected, we compared $T_s$ with $T_{dew}$ at 1 m sensor height (equations in Appendix A2). Note that this is not necessarily representative of $T_{dew}$ within the grass canopy, which would be more suitable to infer dew formation. For example, through radiative cooling, the air cools faster closer to the surface than at 1 m height. To include the effect of the height difference, we compared sensors installed at 0.1 m and at 1 m height during a measurement campaign of two months in...
Spring 2021. The results show that the median temperature difference between the 0.1 m to 1 m sensor height is 1.4 °C with an IQR of 1.2 °C. Dew was therefore assigned when $T_s < (T_{dew} - T_{dew,t})$ where $T_{dew,t}$ is set to 1.4 °C.

If no dew was detected, $\Delta W$ could be potentially attributed to soil adsorption of atmospheric vapor (Zhang et al., 2019a). Adsorption occurs, however, at specific soil hydraulic and meteorological conditions given by a relation between $\Psi$ and atmospheric $rH$. Those have been observed in the laboratory (Camuffo, 1984; Arthur et al., 2016) and suggested from field observations (Kosmas et al., 2001; Uclés et al., 2015; Zhang et al., 2019b). For adsorption $\Psi$ falls below (or is less negative than) a given threshold. This threshold can also be expressed in terms of $SWC$, given the relationship between $\Psi$ and $SWC$ through the soil water retention curve. In order to integrate this knowledge into the classification of adsorption, measurements of $rH$ and $SWC$ were analyzed for the periods where adsorption conditions were identified based on modeling (see section 2.3.2). For these periods, we fit a nonlinear quantile regression (90th percentile) to measurements of $rH$ and $SWC$. This nonlinear relationship is depicted in Appendix Fig. A1. Although for the description of this relationship multiple empirical functions exist for samples measured in the laboratory under equilibrated conditions, they do not apply to our case due to the different observation ranges of $rH$ and $SWC$ at our site (see Fig. A1 for examples). When $rH \geq f(SWC)$, soil adsorption of atmospheric vapor is assigned to positive $\Delta W$. When $rH < f(SWC)$ we classify the flux as residual.

The results of the partitioning algorithm, as well as the uncertainty of the NRWIs might be sensitive to the set of parameters and thresholds values used at each node. Therefore, the impact of the choice of threshold parameters on the flux uncertainty was tested. To do so, we defined a parameter set that describe the upper and lower limit of the parameter values, specifically $rH_t = [80, 100] \%$ and $T_{dew,t} = [0, 1.5] ^\circ C$. The parameter values tested cover the ranges of threshold values for $rH$ and $T_s$ which are currently used in similar studies to identify fog and dew conditions (e.g., Feigenwinter et al., 2020; Zhang et al., 2019b). We then ran forward the partitioning algorithm with all the combinations of the parameters. The uncertainty of the calculated fluxes was then characterized based on the interquartile range (IQR) of the resulting flux quantities as will be shown in Section 3.1.

### 2.3 Comparing rain and evapotranspiration against independent observations and derived NRWI against models predictions

We test the plausibility of inferred water fluxes by three different methods: 1) qualitative and quantitative comparison against direct measurements of rain and $ET$ and 2) comparison against model predictions of dew and adsorption in absence of respective direct measurements derived with alternative measured variables. Similar approaches were used successfully for the benchmarking of methods to simulate transpiration (Nelson et al., 2018) or carbon fluxes (Jung et al., 2020). Measured flux durations were compared to respective model estimates modeled flux using correlation, mean absolute error (MAE), and root mean squared error (RMSE) (full equations Appendix A2). 3) for periods classified as fog by the partitioning algorithm we cross check with images collected by a digital camera installed at the site (Luo et al., 2018). This was, however, only applicable for few events, since the first image per day was taken at 10 am.
2.3.1 Modelling dew

Dew is modeled as negative latent heat flux calculated based on models originally developed for determining evapotranspiration: (i) the Penman-Monteith (PM) (Monteith, 1965) equation which combines processes related to radiative energy and vapor pressure deficit (previously applied for dew in various forms by e.g. Jacobs et al., 2006; Aguirre-Gutiérrez et al., 2019; Groh et al., 2018), and (ii) equilibrium evaporation (previously applied for dew by Uclés et al., 2014).

We implemented the models as described in Ritter et al. (2019) and Jacobs et al. (2006) (Eq. (2.1)) and in Uclés et al. (2014) (Eq. (2.2)).

\[
\lambda E = \frac{s}{s + \gamma} \left( R_{\text{net}} - G \right) + \frac{\gamma}{s + \gamma} \frac{\rho_a \gamma \delta q}{\tau_{av}} \tag{2.1}
\]

\[
\lambda E = \frac{s \left( R_{\text{net}} - G \right)}{s + \gamma} \tag{2.2}
\]

where \(\lambda E\) (W m\(^{-2}\)) is the latent heat, \(s\) (Pa K\(^{-1}\)) is the slope of the specific saturation curve, \(\gamma\) (Pa K\(^{-1}\)) is the psychrometric constant, \(R_{\text{net}}\) is net radiation (W m\(^{-2}\)), \(G\) is the soil heat flux (W m\(^{-2}\)), \(\rho_a\) (kg m\(^{-3}\)) is the density of air, and \(\delta q\) is the deficit of specific humidity at reference level (kg kg\(^{-1}\)). \(\tau_{av}\) is the aerodynamic resistance to vapor transport between the surface and the air (s m\(^{-1}\)) and was derived with an empirical relationship based on \(u^*\) (Thom, 1972).

For both equations, dew occurs when \(\lambda E < 0\) and \(T_s \leq (T_{\text{dew}} - 1.4 \, ^\circ\text{C})\) (as explained in section 2.2.1). This approach has been reported to be suitable for detecting potential dew conditions and to analyze dew frequency and duration. But it is limited in reproducing dew yields (Ritter et al., 2019). Hence we focus on comparing condition lengths rather than yields since we aim to validate dew detection by the partitioning routine.

2.3.2 Modelling adsorption

Adsorption conditions were identified based on the vertical humidity gradient near the surface. We implemented the re-arranged aerodynamic diffusion equation originally used by Milly (1984) and previously applied for modeling adsorption by Verhoef et al. (2006):

\[
e_{s,0} = \frac{\gamma \tau_{av} \lambda E}{\rho_a C_p} + e_a \tag{2.3}
\]

The target value \(e_{s,0}\) (kPa) is vapor pressure of soil air at the surface. \(e_a\) (kPa) is vapor pressure of the atmosphere and \(C_p\) (J kg\(^{-1}\) K\(^{-1}\)) is the specific heat of air at constant pressure. The other parameters are the same as in Eq. (2.1). When \(e_{s,0} < e_a\), gradient driven vapor flow is towards the soil surface. This is assumed to be indicative of the adsorption of vapor from the atmosphere. Different from the dew models, we used high-quality filtered measurements from EC for \(\lambda E\) in Eq. (2.3). Again, we only compared the simulated daily duration of suitable conditions of atmospheric adsorption against the results obtained with the lysimeter weights partitioning and we constrained the comparison to moments when \(T_s \leq (T_{\text{dew}} - 1.4 \, ^\circ\text{C})\).
3 Results

3.1 Diurnal and seasonal changes of water fluxes

Figure 2. Diel and seasonal dynamics of a) lysimeter weight changes, b) assigned flux types, both from lysimeter 6, c) $rH$ measured at 1 m height. Solid vertical lines mark sunrise and sunset, respectively, determined with the geographic coordinates of the field site. Mean $SWC$ at 0.05 m depth and maximum diel difference of $T_s$ are displayed as diel measurements in panels d) and e).

Figure 2 shows the fingerprint of lysimeter $\Delta W$ induced by ET, rain, and NRWI, assigned water flux types (exemplarily shown for lysimeter column 6) and $rH$, respectively, together with mean diel $SWC$ at 0.05 m depth and maximum diel $T_s$ range.

Lysimeter $\Delta W$ are mainly negative between sunrise and sunset (Fig. 2a), e.g., water is lost from the column due to $ET$. After sunset, however, they are zero or positive during most of the year, indicating water input. This diel pattern is consistent across seasons, following the seasonal daylight variability. The flux classification reveals seasonal differences in the prevailing NRWI (Fig. 2b). At the beginning of June, atmospheric adsorption mainly occurs during the early morning, before sunrise. From July to September the length of the adsorption period increases, and the onset shifts towards earlier in the night. In this
period, the diel variability of $rH$ is relatively low (Fig. 2c), $SWC$ at 5 cm depth is below 10% and $T_s$ oscillates up to an amplitude of 35 °C day$^{-1}$ (Fig. 2d & e). A rain event, in late July increases $SWC$ and is followed by some days of increased $ET$ which also prevails during night-time.

A rain event in late September leads to longer-lasting increases in $SWC$ and $rH$. Such conditions are typically associated with vegetation re-greening. $ET$ and dew alternate during night-time. Frequent rain events in November and December are accompanied by dew and fog becoming the dominant NRWIs until the end of the measurement period in April.

NRWI occur for at least 3 h during 297 days (81% of the year) with a mean duration of 6 hours per day of occurrence.

The weekly sums in Fig. 3 illustrate that the seasonal dynamics are consistent across lysimeters. The ecosystem receives atmospheric water at any time of the year but with shifting relative relevance of the water flux types over the year. Rain is the dominant liquid water input (i.e. it contributes more than 50% of the weekly water input) during 29 weeks since it’s total amount is usually much greater than NRWI, whereas NRWI is dominant in 24 weeks. They are even the only water input during 15 weeks with adsorption as exclusive water input in 10 weeks of the year. Dew and fog occurrence is synchronized with rain with regard to the seasonal occurrence, and therefore their relative contribution is small. The median contribution of adsorption until September 2019 is 0.9 mm week$^{-1}$. With $ET$ amounting to $-5.7$ mm week$^{-1}$, thus adsorption compensates for 19% of the weekly water loss during summer.

**Figure 3.** Means of weekly sums across lysimeter columns for (a) ET and rain, (b) adsorption and noise, (c) dew and fog, and (d) relative contributions of rain and NRWIs to total water input per week, respectively. Shading indicates the variability across lysimeter columns expressed as an inter-quartile range (IQR).
3.2 Water flux sums and their consistency with measurements and theory

The cumulative measured rain is $565.0 \pm 11\,\text{mm}$ as an average across the six lysimeters. Thereby, the difference between the maximum and minimum across the lysimeters is $30.7\,\text{mm}$, which is an absolute deviation of $5\%$ between columns. For comparison, the rain gauge recorded $597\,\text{mm}$ of rain during the same time period. The underestimation of the estimates from lysimeters compared to the rain gauge, as well as the deviation between columns, is mainly caused by a few large rain events in January 2020 (Fig. 4a). The cumulative measured ET across lysimeters is $-570.7 \pm 20\,\text{mm}$. The annual cumulated difference between lysimeters is $46.7\,\text{mm}$. Annual cumulative ET determined through EC measurements is $-619\,\text{mm}$. As in the case of rain, the ET estimates deviate strongest in winter which indicates a technical problem during days with rain at this time of the year, while estimates are more consistent during the rest of the study period (Fig. 4d).

Descriptive statistics of the annual sums of NRWIs across lysimeter columns are summarised in Table 1. The average annual NRWI sum amounted to $42.0\,\text{mm}$ with individual contributions of $6.6\,\text{mm}$ from fog, $14.1\,\text{mm}$ from dew, and $21.2\,\text{mm}$ from
Table 1. Mean, median, inter quartile range (IQR) and minimum, and maximum annual sum of individual NRWI fluxes across lysimeter columns. All values are reported in mm year$^{-1}$.

| Flux     | Mean | Median | IQR  | min  | max  |
|----------|------|--------|------|------|------|
| Fog      | 6.6  | 7.6    | 3.9  | 3.1  | 9.5  |
| Dew      | 14.1 | 11.8   | 8.6  | 9.5  | 20.2 |
| Adsorption | 21.2 | 16.6   | 8.3  | 14.4 | 34.5 |
| Residuals | 23.7 | 21.2   | 7.6  | 12.8 | 37.3 |

Table 2. Uncertainty related to the flux partitioning parameters. The table summarises the annual mean and median fluxes of all lysimeters across all combinations of parameters in the given ranges. Additionally, their interquartile range (IQR) is provided.

| Flux     | Parameter range | Mean [mm] | Median [mm] | IQR [mm] |
|----------|-----------------|-----------|-------------|----------|
| Fog      | [95, 100] %     | 6.7       | 6.7         | 10.4     |
| Dew      | [-2, 0] °C      | 9.4       | 8.0         | 7.1      |
| Adsorption | no perturbation | 24.2     | 22.8        | 5.3      |
| Residuals | -               | 25.3      | 25.2        | 3.6      |

adsorption. The differences in flux sums across lysimeters for all NRWI are relatively larger than for rain and $ET$, with coefficients of variation around 40%. The largest relative annual deviation between columns was found for adsorption with a difference of 20.0 mm. But the flux which is most affected by the threshold parameter in the lysimeter flux partitioning is fog, which can be seen in Table 2. The IQR for the fluxes decreases the later in the partitioning scheme the respective flux is estimated (Fig. 1). Thereby, for dew and adsorption, the spatial variability between lysimeter columns (IQR in Table 1) exceeds the range of uncertainty related to the partitioning parameters (IQR in Table 2).

To assess whether the thermodynamic requirements for dew and adsorption are met at our site we compare the lysimeter-inferred observations of dew and adsorption with their potential occurrence determined with the models from PM, equilibrium evaporation, and the aerodynamic diffusion equation (Fig. 5). Our results show that the measured fluxes are temporally consistent with model results, both concerning diurnal and seasonal dynamics.

In general, the Majadas site has suitable conditions for dew between October 2019 and end of May 2020, from sunset to sunrise. The statistical metrics for the comparison of daily dew duration between lysimeters and models are summarized in Table A2. They show that overall, the models suggest a longer duration of dew conditions by 3 h day$^{-1}$ to 5 h day$^{-1}$. Model statistics from PM and the evaporation model are not deviating from each other indicating that in our application, no difference between the simplified and full PM model is detectable. In the case of adsorption the lysimeter-based estimates agree better with the model predictions (Table A2). When comparing only measurements where at least two out of the five lysimeters show weight increases assigned to adsorption, evaluation statistics improve by one hour. In addition, the agreement of lysimeters is overall stronger during adsorption than during dew conditions (Fig. 5). Single lysimeters, however, frequently also measured adsorption until midday and before sunset.
Discussion

In this study, we showed that large weighing lysimeters and a few ancillary measurements can be used to efficiently disentangle and therefore quantify all types of surface water fluxes, particularly NRWI. Our data from a semi-arid Mediterranean savanna site shows that the climatic conditions fulfill the thermodynamic requirements to induce diel cycles of evaporation and condensation at almost all times of the year. The routine proposed to detect and distinguish NRWI is successfully validated against models based on energy balance and moisture gradients, regarding the occurrence of the process.
We found that NRWIs occur frequently at our site, in line with previous research in such a climate regime. The occurrence of both adsorption and dew was shown by Zhang et al. (2019b). We support their observation that dew formation and adsorption dominate at different times of the year. Regular dew formation (120 nights year$^{-1}$ to 200 nights year$^{-1}$) has been reported across sites (Tomaszkiewicz et al., 2015). In a similar semi-arid steppe ecosystem in Spain, the mean number of days per year with suitable conditions for dew formation was 285 days (Uclés et al., 2014), however, their ecosystem is close to the Mediterranean sea and likely, therefore, receives more humidity than Majadas. Our observation that especially nights are prone to the formation of NRWI is also documented in the literature. Dew formation length has often been reported to correlate with the length of the night (Tomaszkiewicz et al., 2015) and was in another Spanish site reported to last on average 9.3 ± 3.2 hours night$^{-1}$ (Uclés et al., 2014). In contrast, for adsorption, reported observation times differ. Kosmas et al. (1998) observed the flux to occur mainly between 0:00 and 6:00 h and also Saaltink et al. (2020) found suitable night-time conditions for adsorption through a reversed gradient of vapor concentration between soil and atmosphere from lysimeter observations and confirmed it with a fully coupled numerical model. Yet, Verhoef et al. (2006) found adsorption occurring during the afternoon and ceasing at night. Since changes in $T_s$ and their effects on the phase equilibrium of water are one of the main controlling factors of adsorption, the different findings between studies could be related to site-specific timing of surface exposure to radiation.

Next to the diagnosed occurrences, also the NRWI amounts we determined are within the range of previously reported estimates for similar climate regimes. At our study site Majadas, the largest annual NRWI contribution is adsorption with 21.2 mm year$^{-1}$. This value is relatively low, compared to sites close to the sea, where values of 81 mm year$^{-1}$ (Saaltink et al., 2020), and 26 mm to 110 mm between April and October have been reported (Kosmas et al., 2001). But it matches well with observations from Qubaja et al. (2020) that measured annual adsorption of 14 mm year$^{-1}$ using flux chambers in a semi-arid pine forest in Israel. Furthermore, dew and fog quantified here at 14.4 mm year$^{-1}$ and 6.6 mm year$^{-1}$, respectively, are within the range reported from other sites which are depending on site 4 mm year$^{-1}$ to 39 mm year$^{-1}$ for dew (Tomaszkiewicz et al., 2015) and 1.3 mm year$^{-1}$ to 50 mm year$^{-1}$ for fog (Zhang et al., 2019b; Kidron and Starinsky, 2019). It is important to remark, however, that part of the large variability concerning the length of occurrence and condensation rates for NRWI could be related to biases of the measurement devices. Micro lysimeters, until now one of the most widely used instruments, were reported by Kidron and Kronenfeld (2020b) to overestimate NRWI likely due to greater heat loss through the walls, compared to the surrounding unperturbed soil.

We found differences in the absolute annual NRWI sums between individual lysimeters that can be attributed either to (i) spatial variability (heterogeneity) in the soil and vegetation characteristics affecting the energy balance, or (ii) instrumental and methodological uncertainty. Particularly for the latter, external disturbances by wind or animals and internal disturbances such as data gaps, and data processing have been shown to alter results significantly (Schrader et al., 2013; Nolz et al., 2013).

Developing processing routines for raw data from large weighing lysimeters has challenged researchers during the last decade (Schrader et al., 2013; Peters et al., 2014, 2016, 2017; Hannes et al., 2015). To assess the robustness of the processing we compared rain across lysimeters as rain is expected to be similar across nearby lysimeters and heterogeneous soils and vegetation. The variation of rain across lysimeters is only 5%, which is of a similar magnitude reported in other studies (Hannes,
et al., 2015; Schneider et al., 2021). Model simulations independently confirmed, that the conditions at night are suitable for NRWI, although especially for dew the simulations showed that the potential for dew formation is generally longer than actual occurrence, measured with lysimeters.

A focus of this study was partitioning the lysimeter $\Delta W$ into water flux classes. This approach includes the simplified assumption that one flux is always dominating over the others at each time step. In reality, the fluxes can occur simultaneously with their relative importance shifting gradually over time (Li et al., 2021b), but postulate to be minimal at the time scale we are looking at. Ideally, we would account for a statistical probability ratio between different NRWI per time interval. But current research that is quantifying such ratios is too scarce for generalization (Li et al., 2021b).

Disentangling individual NRWI fluxes is nevertheless important because of different respective i) controlling factors and ii) implications for the ecosystem. Better knowledge on controlling factors can help to identify potential NRWI occurrence also in ecosystems without specialized measurement devices. The role of dew has often been reported as moistening plant surfaces with direct leaf water uptake (Tomaszkiewicz et al., 2015). Soil vapor adsorption, however, occurs at low $\Psi$ where grasses in Majadas have already senesced. Nevertheless, due to it’s continuous occurrence in periods of low $SWC$, it would be a beneficial ecological strategy for organisms to use this diel water input. So far, it is recognized that microbial and lichen respiration is triggered by adsorption (Evans et al., 2019; McHugh et al., 2015; Dirks et al., 2010; Li et al., 2021a; Gliksman et al., 2017) but more research is necessary to understand the impact of this flux on different organisms. The approach applied most frequently in the literature as well as in this study is based on a discontinuous tree-based classification system which was implemented similarly as suggested by Zhang et al. (2019a). As an extension of their system one node was added to account for prior knowledge on the controls of adsorption. The prior knowledge for soil adsorption stems, however, from smaller samples at equilibrium conditions in the laboratory (Arthur et al., 2016). Our application to point measurements of $rH$ and $SWC$ from above and below the soil surface assumes that by choosing the statistical upper envelope we can distinguish equilibrium conditions from remaining noise in the time series as best as possible. Although uncertainty remains about the real shape of this relationship, this approach gives a more conservative estimate of the adsorption amount and helps prevent overestimation. The validity of this relationship is further confirmed by having a similar shape independently whether it was derived from the periods when lysimeter measurements unanimously were classified as adsorption (before including residuals as a final node) or deduced from negative EC derived $\lambda E$.

The advantage of the discontinuous tree-based classification is that it is applicable widely because the necessary data is commonly measured. The disadvantage is that selection of the parameters and thresholds in the classification algorithm is critical, especially at the upper nodes, where choices propagate into the estimates of flux classes of deeper nodes. Our test on different parameter combinations found that the strongest impact on flux quantity was for fog, followed by adsorption. Nevertheless, the ranking was not affected by choice of parameters and thresholds, e.g. in all tested cases adsorption had the largest contribution to annual flux sums.

Apart from instrumental and methodological uncertainty, the spatial heterogeneity of soil and vegetation characteristics of the field site (Nair et al., 2019) can affect our results. In fact, dew and adsorption amounts are both reported to vary substantially with the surface cover type (Uclés et al., 2016), soil exposure (Kosmas et al., 2001), shading hours (Uclés et al., 2015), distance
from trees (Verhoef et al., 2006; Qubaja et al., 2020) and soil texture, particularly clay and sand content (Kosmas et al., 2001; Orchiston, 1952; Yamanaka and Yonetani, 1999). Verhoef et al. (2006) showed in a measurement campaign with eight lysimeters concentrically arranged around a single oak tree that at the most exposed spots adsorption was doubled compared to the shaded spot. At our site, there are also individual sparse trees (Bogdanovich et al., 2021) which cause small-scale differences in shading. Since some lysimeter columns are more exposed than others, part of the deviation in NRWI could be explained by spatial heterogeneity. This is supported by measurements of soil Ψ within the individual columns, which showed that one column had an overall greater mean $T_{soil}$ in summer and the threshold of potential adsorption conditions was reached nearly a full month earlier than in other columns. Micrometeorological variables were however not measured individually at each column and therefore we have no insight into the exact causes of spatial heterogeneity in dew formation. The applied models both only suggest times of dew formation potential based on measurements at the central facility, while the quantity is derived from weight changes. For the same reason, spatial differences are robust and follow-up investigations can be targeted towards understanding their causes.

Notably, the current study also provides an opportunity to propose a way forward in adsorption research based on the observed similar temporal pattern between negative EC derived $\lambda E$ and lysimeter vapor adsorption occurrence. EC instruments are currently one of the most popular instruments to estimate $\lambda E$ at an ecosystem scale (Baldocchi, 2014, 2020). But measurements are frequently discarded when the underlying micrometeorological assumptions of the technology are not met (Göckede et al., 2004). This often affects night-time EC measurements (Massman and Lee, 2002). Previous research in a pine forest in Israel also indicated that EC-derived $\lambda E$ tends to be negative at night during adsorption (Qubaja et al., 2020). At our site, this pattern is obvious and indicates that night-time EC measurements could serve to detect adsorption (Fig. 6).

To help assess the relevance of adsorption, we suggest revaluing night-time $\lambda E$ fluxes of EC instruments. This could also help to up scaling and in doing so overcoming the problems with clarifying the role of NRWI across research communities (Gerlein-Safdi, 2021), for example concerning energy balance closure of EC (de Roode et al., 2010), ecological significance of foliar water uptake (Berry et al., 2019) and impacts on remote sensing products (Xu et al., 2021). Irrespectively, our findings underline the necessity for methods on processes of the water cycle during the night to avoid biased measurements towards evaporation while missing condensation.

5 Conclusions and outlook

In this manuscript, we derive NRWI from time series of automated weighted lysimeters and compare their length of occurrence with established model estimations. In summary, our data suggest that this semi-arid savanna ecosystem switches between evaporation and condensation almost daily. Attributing the condensation pattern into different NRWI sheds light on the distinct mechanisms that are each dominant in a different season. In summer, adsorption of atmospheric vapor on soil particles is facilitated by large diel temperature differences and dry soils lead to steep gradients of atmospheric vapor pressure between the atmosphere and the soil air driving vapor diffusion. In winter and spring, high $rH$ leads to frequent fog deposition and surface cooling to dew condensation. Spatial heterogeneity of vegetation, soil characteristics, and radiation regimes, together with
measurement uncertainties are stronger reflected in NRWI than in other fluxes of surface water exchange. Although between 01.06.2019 and 31.05.2020, the total NRWI sum comprises only 7.4\% of the local water input, the relative contribution strongly varies weekly. Rain frequency is unevenly distributed within the year and especially atmospheric adsorption stands out as the only water input during 11 weeks in the dry season. The ecological relevance of this flux has yet to be scrutinized.

Our analysis focuses on lysimeters, that cover only a spatial area of $1\, m^2$, each. We show that the temporal variability of the NRWI derived from the instruments is coherent with negative LE fluxes at dry conditions. Based on this observation, future work could focus on revalue night-time $\lambda E$ fluxes from EC instruments to improve the spatial representativeness and assess the relevance of NRWI at the larger scale and across seasonally dry ecosystems.

**Figure 6.** Diel and seasonal variation of a) quality filtered $\lambda E$ fluxes from EC and b) assigned lysimeter fluxes. Solid curved vertical lines mark sunrise and sunset, respectively, determined with the geographic coordinates of the field site.
Code and data availability. The raw and processed lysimeter data used in this study, as well as the meteorological and radiometric variables necessary for partitioning the water fluxes will be made publicly available after the manuscript is accepted in a Zenodo repository together with the full code for the lysimeter raw weight processing and partitioning in R statistical programming language. The code and data for the modeling can be provided on request.

Author contributions. MM, RO, MR, OPP, SP designed the setup and planned the study. OK, GM, AC, TEM, MM, and OPP were maintaining the site and instrumentation and conducted the measurements. SP, TEM, and TW processed the data. SP analyzed the data and prepared the original draft, both under the supervision of MM, RO, TEM, and AH. All authors discussed, reviewed and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. SP acknowledge the support for this research through the International Max Planck Research School for Global Biogeochemical Cycles (IMPRS-gBGC) at the University of Jena. The authors acknowledge the Alexander von Humboldt Foundation for supporting this research through the Max Planck Research Prize 2013 to Markus Reichstein. RO was supported by funding from the German Research Foundation (Emmy Noether Grant 391059971). We thank the city council of Majadas de Tietar for support. Our thanks go to Martin Strube, Ramón López-Jimenez, Martin Hertel, and the Freiland group at the MPI-BGC for great technical and scientific assistance during fieldwork. SP would further like to thank Andre Peters and Johanna Blöcher for their helpful comments and suggestions.
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## Symbolslist

| Symbol | Full form | Unit |
|--------|-----------|------|
| $C_p$  | Specific heat capacity of dry air = 1004 | $m^2 m^{-2} K^{-1}$ |
| $G$    | Soil heat flux | $W m^{-2}$ |
| $R_{net}$ | Net radiation | $W m^{-2}$ |
| $SWC$  | Volumetric soil water content | $m^3 m^{-3}$ |
| $T_a$  | Air temperature | $^\circ C$ |
| $T_s$  | Surface temperature | $^\circ C$ |
| $T_{dew}$ | Atmospheric dewpoint temperature | $^\circ C$ |
| $T_{soil}$ | Soil temperature | $^\circ C$ |
| $\gamma$ | Psychrometric constant | $K^{-1}$ |
| $\rho_a$ | Density of air | $kg m^{-3}$ |
| $s$    | Slope of the saturation specific humidity curve | $kPa K^{-1}$ |
| $ET$   | Evapotranspiration | $mm$ |
| $G$    | Ground heat flux | $W m^{-2}$ |
| $LW$   | Long wave radiation | $W m^2$ |
| $SW$   | Short wave radiation | $W m^2$ |
| $\Delta W$ | Lysimeter weight change | $kg$ |
| $\Psi$ | Soil matric potential | $hPa$ |
| $\delta q$ | Deficit in specific humidity at reference level | $kg kg^{-1}$ |
| $\lambda E$ | Latent heat flux | $W m^{-2}$ |
| $\sigma$ | Boltzmann’s constant = $5.67 \times 10^{-8}$ | $W K^{-4} m^{-2}$ |
| $\varepsilon$ | Emissivity of grass cover = 0.99 | NA |
| $e_a$  | Actual vapor pressure of the atmosphere | $hPa$ |
| $e_{s,0}$ | Vapor pressure of soil air at the soil surface | $kPa$ |
| $rH$   | Relative humidity | $\%$ |
| $r_{av}$ | Aerodynamic resistance to vapor transport between the surface and air | $sm^{-1}$ |
| $u^*$  | Friction velocity | $m s^{-1}$ |
| $u$    | Wind speed | $m s^{-1}$ |
A2 Additional equations

Surface temperature \((T_s, ^\circ C)\) was calculated from measurements of the radiometric tower

\[
T_s = 4 \sqrt{\frac{LW \downarrow}{\sigma} - \frac{LW \downarrow}{\sigma \times \varepsilon} + \frac{LW \uparrow}{\sigma \times \varepsilon} - 273.15}
\]  \hspace{1cm} (A1)

where \(LW\) is long wave radiation up (\(\uparrow\)) and down (\(\downarrow\)) (W m\(^{-2}\) s\(^{-1}\)), \(\sigma\) is Boltzmann’s constant (W K\(^{-1}\) m\(^{-2}\)) and \(\varepsilon\) is emissivity of grass (NA).

Dewpoint temperature \((T_{dew}, ^\circ C)\) was calculated from \(rH\) and \(T_a\) based on the Magnus equation (\(\lambda = 17.62, \beta = 243.12\)) (Sonntag, 1990):

\[
T_{dew} = \frac{\lambda \times \left( \ln \left( \frac{rH}{100} \right) + \frac{\beta \times T_a}{\lambda + T_a} \right)}{\beta - \ln \left( \frac{rH}{100} + \frac{\beta \times T_a}{\lambda + T_a} \right)}
\]  \hspace{1cm} (A2)

where \(rH\) is relative humidity (\%) and \(T_a\) is air temperature (\(^\circ C\)).

Evaluation statistics the comparison of the occurrence duration between lysimeter measurements and modeling

| Evaluation Statistics | Formula |
|-----------------------|---------|
| Mean absolute error   | \[\text{mae} = \frac{1}{n} \sum_{i=1}^{n} |\hat{y}_i - y_i|\] |
| Mean squared error    | \[\text{mse} = \frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2\] |
| Root mean squared error | \[\text{rmse} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\hat{y}_i - y_i)^2}\] |
Table A2. Evaluation statistics for the comparison of the occurrence duration between lysimeter measurements and modeling. Dew was modeled based on Penman-Monteith (PM) and the equilibrium evaporation model and adsorption based on the aerodynamic diffusion equation. Statistics are shown for the options i) more than one and ii) more than two lysimeters measuring dew or adsorption, respectively. The units of all values are hours day$^{-1}$.

| Flux          | Model                  | #n lysimeters | Length [hour] |
|---------------|------------------------|---------------|---------------|
|              |                        | cor | mae | rmse |
| Dew          | PM                     | >1  | 0.44 | 3.32 | 4.76 |
|              |                        | >2  | 0.36 | 3.78 | 5.30 |
|              | Equilibrium evaporation | >1  | 0.44 | 3.32 | 4.76 |
|              |                        | >2  | 0.36 | 3.78 | 5.30 |
| Adsorption   | Aerodynamic diffusion equation | >1  | 0.76 | 4.90 | 5.8 |
|              |                        | >2  | 0.76 | 4.00 | 4.70 |
Figure A1. Relationship of SWC and rH during modeled adsorption (gradient driven vapor diffusion towards the soil surface) between April to October. The full formula with the parameters for the 90th quantile from non-linear quantile regression is given in the upper left. The lines additionally illustrate the 50th, 85th, and 95th quantile. Empirical relationships from the literature for equilibrated conditions are shown in orange and purple (Arthur et al., 2016).