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Multi-source characterisation of non-rainfall water inputs to a semi-arid ecosystem

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Zusammenfassung

Im Rahmen einer Langzeitstudie mit wägbaren Präzisionslysimetern konzentrieren wir uns auf die Unterscheidung und Quantifizierung unterschiedlicher Wasserflüsse aus der Atmosphäre in den Boden: Neben Regen zählen dazu Taubildung, Nebelniederschlag und Bodenwasseradsorption, wobei die drei letzteren als nicht-Regen Wassereintrag (NRWI) zusammengefasst werden. Um diese Prozesse in den Gewichtsänderungen der Lysimeter zu unterscheiden, wurden meteorologische, bodenhydrologische und radiometrische Daten genutzt. Unsere Ergebnisse zeigen, dass im Zeitraum 2018 - 2020 in 72.8 % der Nächte Wasser als NRWI auf der Oberfläche und im Boden kondensiert ist. Der Gesamteintrag beträgt im Mittel 43.5 mm, was 8.1% des mittleren jährlichen Inputs darstellt. Während zwischen Oktober und April Wasser hauptsächlich als Tau kondensiert, ist Bodenwasseradsorption im Mediterranen Hochsommer zwischen Juli und September der einzige NRWI Wassereintrag.

Schlagwörter: Lysimeter, Savanne, NRWI, Kondensation - Evaporation, Tau

Summary

As part of a long-term study with weighable precision lysimeters, we focus on distinguishing and quantifying the different water fluxes. These were classified as evapotranspiration, rainfall, and non-rainfall precipitation (NRWI): dew formation, fog precipitation, and soil water adsorption. Meteorological, soil hydrological and radiometric data were used to partition the underlying lysimeter weight changes. Our results show that in 2018 - 2020, water condensed as NRWI on the surface and in the soil in 72.8 % of the nights. The total input amounts to 43.5 mm, which represents 8.1 % of the mean annual input. While water condenses mainly as dew between October and April, soil water adsorption is the only NRWI water input during the Mediterranean midsummer between July and September.

Keywords: lysimeter, savannah, NRWI, condensation-evaporation, dew

Introduction

Climate predictions project changes in frequency of precipitation, causing prolonged periods without rainfall. Therefore, there is a rising interest in the role of non-rainfall water input (NRWI) for semi-arid ecosystems. The term NRWI summarizes processes of condensation deposition from the near-surface atmosphere, that are distinguished by different meteorological and soil hydraulical conditions involved (Agam and Berliner 2004). Fog is defined as aerosols of water droplets that are suspended in the air near the Earth's surface, which adhere after contact. Dew forms on surfaces when their temperature decreases below the saturation point of the adjacent air. Under the influence of capillarity and mineral surface charge, soil water interface phenomena deviate from

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free water, provoking condensation of vapor already at values of relative humidity (rH) < 100% if soil water potential is low. The most widely used term in the lysimeter literature for this mechanism is soil vapor adsorption (SVA).

These processes have all been observed in arid and Mediterranean ecosystems (Agam and Berliner 2004, Verhoef et al. 2006). However, most studies were focused on individual NRWI processes and short observational records. New technical developments of large weighing lysimeters with controlled lower boundary conditions facilitate to measure water fluxes at high precision and temporal resolution. Particularly, in combination with additional measurements they enable to trace NRWI over time periods of several years. Such data allows to study intra- and inter-annual contributions of NRWI to local water balances and to reveal if they support vegetation or microbial activity during water limited periods.

In this study we i) characterize the different types of NRWI from a time series of lysimeter weight in a Mediterranean tree-grass ecosystem and ii) analyze the contribution of the different components to the water balance over a time period of three years.

Material and Methods

Field site and instrumentation

The field site is a Mediterranean savannah type tree-grass ecosystem close to Majadas de Tietar in central Spain (*Figure 1*). Mean annual air temperature (T_a) is 16.7 °C and annual precipitation is ca. 650 mm. The herbaceous layer consists of native annual species with seasonally varying fractional cover, that is mainly driven by moisture availability. The site is extensively grazed by cows. The soil is formed of alluvial deposits and classified as Abruptic Luvisol (IUSS Working Group WRB 2015) with a sandy topsoil of 80 % sand, 11 % silt and 9 % clay (Perez-Priego et al. 2017). The site is equipped with three high precision weighing lysimeter stations (UGT) installed in the open areas, each containing two soil cylinders of 1 m^2 surface area and 1.20 m length. All lysimeters (L1-L6) were equipped with soil moisture and temperature probes (UMP-1, Umwelt-Geräte-Technik GmbH, Müncheberg, Germany) at 10, 20, 40 cm depth. More details can be found in Perez-Priego et al. (2017).

T_a and relative humidity (rH) are measured at 1 m height above the surface (CPK1–5, MELA Sensortechnik, Germany). Short- and longwave incoming and outgoing radiation is observed with a net radiometer (CNR4, Kipp and Zonen, Delft, Netherlands) at ~3 m height above the surface. Surface temperature (T_s) is calculated from the longwave outgoing radiation using the Stefan-Boltzmann's law.

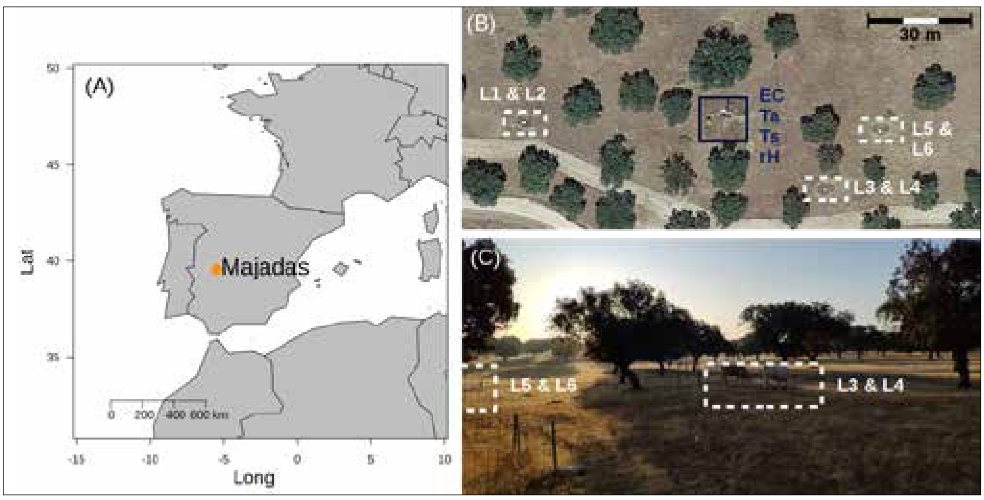

Figure 1: (A) Location and (B) aerial view of Majadas de Tietar field site with lysimeter (L1:L6) and atmospheric measurement locations (adapted from Google (nd)) and (C) L5 & L6 and L3 & L4 on 26.09.2019 at 8:30 during scattered light conditions and grazing.

An eddy covariance (EC) system is operated at 1.8 m height. A detailed description of the system and data processing can be found in Perez-Priego et al. (2017). The time series considered in this study is 01.01.2018 – 31.12.2020.

Lysimeter data processing

Lysimeter weights are determined every minute. We analyze the resulting changes (ΔW_{lys}) as a time series. Outlier value and maintenance periods are filtered out. Then, data smoothing was done by using the adaptive window and adaptive threshold (AWAT) filter routine described by Peters et al. (2014, 2017). Changes of the water tank at the lower boundary were accounted for. ΔW_{lys} were further compared across all six lysimeter columns in order to filter ΔW_{lys} caused by animals: we calculated the mean ΔW_{lys} for one minute interval (*i*). This value was then subtracted from the individual ΔWl_{ys} at *i*. In a second step, the average standard deviation (sd) from *i* - 3 to *i* + 3 minutes was calculated. Any value > 1.5 σ was not accounted for. All remaining weight changes ΔW were associated to the exchange of water at the soil-atmosphere boundary.

ΔW was classified based on the assumption that only one flux is dominant each minute. We differentiated between **evapotranspiration** (ΔET when ΔW < 0) versus water input of different origin (when ΔW > 0). The latter was separated based on prevailing atmospheric, surface and soil hydraulic conditions. **Rainfall** was attributed when the rain gauge registered a rain event (ΔW > 0 and $rain_{gauge} > 0$). **Fog** was defined for rH at saturation (ΔW > 0 and rH = 100). When T_s fell below atmospheric dewpoint temperature we assigned **dew** (ΔW > 0 and $T_s \geq T_d$). For the remaining ΔW > 0, we modeled SVA of atmopspheric humidity based on LE fluxes from EC measurements with equations (2), (3) and (4) in Verhoef et al. (2006). We used modeled SVA, and measured SWC and rH data to build a plot scale adsorption isotherm (Paulus et al. 2021 *manuscript in preparation*). Based on this equation we defined **SVA from the atmosphere** at (ΔW > 0 and $SWC \leq SWC_{ads\ thres}$). When (ΔW > 0 and $SWC \geq SWC_{ads\ thres}$) we labeled ΔW > 0 as **transient SVA** assuming it to be rather related to interrupted vapor transport from deeper layers. Positive fluxes in this study indicate fluxes from the atmosphere to the soil, while negative fluxes describe the opposite.

Results

Generally, we find lysimeter weight losses during daytime and increases at night-time (exemplary shown with L6 in *Figure 2 A*). Disentangling the multiple water exchange processes in *Figure 2 B* we find similar seasonal variations across years. ET patterns

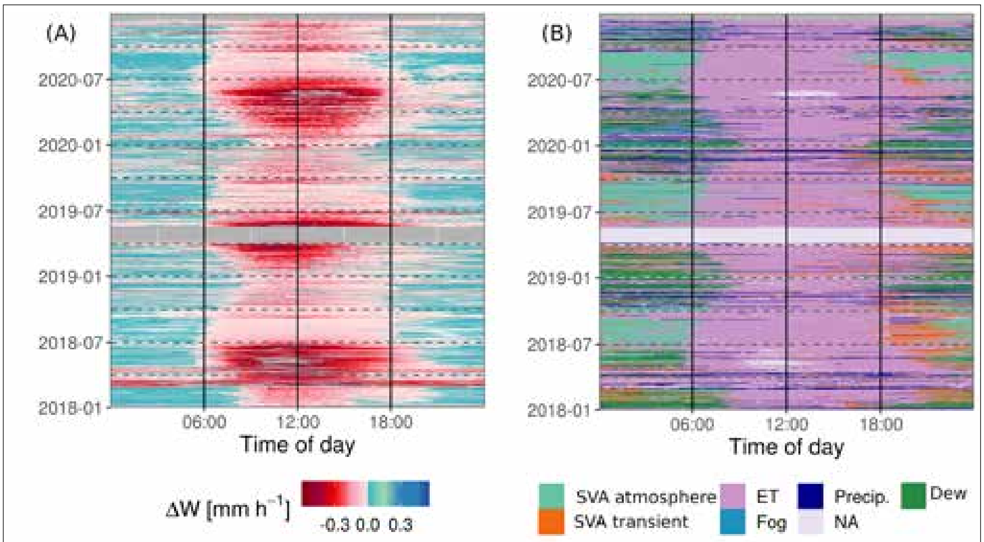

Figure 2: Intra- and inter-annual patterns of daily (A) lysimeter 6 weight changes ΔW (A) and (B) decomposed water fluxes (atmospheric - and transient adsorption, evapotranspiration (ET), precipitation, dew and fog) based on meteorological and soil hydraulic conditions between 2018 - 2020.

Table 1. Yearly mean sums and standard deviation (in brackets) of water fluxes in Majadas. All values are reported in mm.

Year	ET	Precipitation	Dew	Fog	SVA (atm)	total Σ in
2018	- 531.1 (72)	665.4 (63.6)	13.1 (0.9)	0.04 (0.1)	10.1 (7.5)	688,6
2019	- 479.6 (37.6)	441.4 (17.8)	33.7 (8.0)	0.2 (0.1)	25.5 (6.4)	500,5
2020	- 580.4 (31.4)	672.4 (161.4)	15.8 (11.8)	5.3 (3.2)	16 (9.6)	709,1

clearly follow the annual cycle of solar radiation. Between January and March nights and mornings are dominated by dew. Rain and fog events are also frequent in this period. From March onwards, ET is higher in absolute amount and daily occurrence duration, with daily mean fluxes of -2.8 ± 1.08 mm d^{-1} (max -6.5 mm d^{-1}). In this period, dew still develops during the second half of the night and rain events occur until May. In summer, evaporation during the day is reduced to a seasonal mean of -0.9 ± 0.6 mm d^{-1}. Between midnight and sunrise, SVA of water from the atmosphere is the dominant water flux with mean 0.16 ± 0.2 mm d^{-1}. Before midnight, SVA weight gains stem likely from deeper layers. Both fluxes reduce the daily losses by 26 ± 24 % (atmospheric SVA 22 %, transient SVA 6 %). The beginning of atmospheric SVA starts earlier in the evening along the dry season. Around October, these conditions end abruptly with the onset of rain.

The mean annual contribution of NRWI to the local water balance is 43.5 mm, which is 8.1 % of incoming water (see *Table 1*). Thereby, dew accounts for 22.1 mm, SVA contributes 17.6 mm and fog amounts to 3.9 mm. All fluxes vary largely between lysimeters and years. The fraction of nights with detected NRWI is 73 %, equalling 273 days per year.

The mean diurnal cycles of T_s, T_a, and rH in January and July are shown in *Figure 3 A* and *B*. T_s amplitudes in summer are 19.0 °C in early morning and peaking at 49 °C at midday. T_a is warmer in the morning (20 °C) and has a daily maximum of 40 °C. In winter, the amplitude is between 2 and 14 °C for T_a and T_s, respectively. rH is inversely following T_a with wider ranges in July (18 - 65 %) and slightly smaller ranges in January (60 - 95 %). Mean ΔW of L1 and L3 (*Figure 3 C*) show marked differences in the diurnal cycles. In summer, midday ET and night-time SVA are stronger in L1. In winter, the ΔW deviations are persistent although less pronounced.

Discussion

The detected frequent occurrence of dew at our site is in line with findings from Ritter et al. (2019), who have shown that dew frequency across grasslands in the US is linearly related to rH when rH > 70%. Their data implies that grasslands like the Majadas site, with mean night-time rH close to saturation have a dew occurrence in > 90% of the nights. A recent study from another Spanish site by Saaltink et al. (2020) also measured frequent nightly inward fluxes in summer due to SVA and were also able to simulate their observations with a thermo-hydraulic numerical model for unsaturated flow. The model showed that large sub-diurnal temperature gradients were driving SVA. Under such conditions, several authors reported SVA occurrence during afternoons and early mornings (Kosmas et al. 2001, Agam and Berliner 2004, Verhoef et al. 2006).

The different components of NRWI feature a high spatial and inter-annual variability. For dew, this aspect has been addressed in the literature. A study from a continental grassland in Mexico, reports reports annual dewfall varying between 16-69 mm mm $year^{-1}$ (Aguirre-Gutiérrez et al. 2019). But to our knowledge, there are no studies yet assessing the inter-annual variability of SVA. Studies focusing on shorter time periods reported contrasting SVA magnitudes. Kosmas et al. (2001) measured over a surface cover gradient 46.8 mm at the vegetated spot and 88.7 mm below bare soil during the same time period. Verhoef et al. (2006) reported flux differences from 0.2 mm d^{-1}, at an area below trees, to 0.7 mm d^{-1}, at the most exposed lysimeter side in a Spanish Olive Orchard. Their results illustrate the small-scale heterogeneity of water and energy fluxes created by the non-homogeneous partial canopy cover in Savannah ecosystems. In this context, probably spatial heterogeneities and the resulting differences in micro-climates

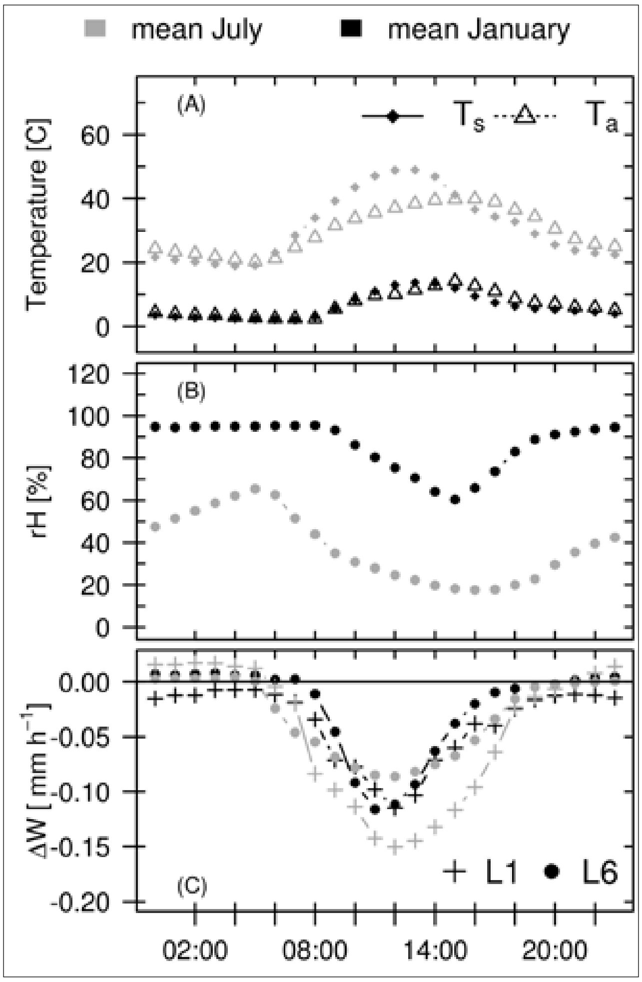

Figure 3: Mean diurnal cycles in July (grey) and January (black) of (A) surface (T_s) and air temperature (T_a) (B) relative humidity and (C) mean diurnal weight changes (Δ*W*) of lysimeter 1 (L1) and lysimeter 3 (L3).

can explain the deviations between the mean diurnal cycles of ΔW between lysimeters (*Figure 3C*).

Conclusions

Our results show that that nighttime water fluxes in a semi-arid tree-grass ecosystem are dominated by NRWI. These findings are consistent across years, reflecting the strong seasonality of the ecosystem. Fog and dew events happen predominantly in winter and atmospheric SVA occurs exclusively in summer. NRWI contribute 8.1 % to the yearly water input. Our approach to distinguish and quantity NRWI fluxes can contribute to further analyses investigating the role of NRWI for vegetation functioning and soil characteristics.

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