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Partitioning evapotranspiration based on lysimeter water balance data and stable isotope profiles

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Zusammenfassung

In dieser Studie wurde ein wägbares Lysimeter für die Ermittlung von Evaporations- und Transpirationsraten von Sojabohne mittels einer Isotopen-Massenbilanz verwendet. Da die Methode ursprünglich für Laboranwendung konzipiert war, wurden die erforderlichen Änderungen für die Anwendung im Feld getestet und Verbesserungen in der Berechnung diskutiert.

Schlagwörter: Transpiration, Evaporation, Isotopenfraktionierung, Sojabohne, Bodenfeuchte

Summary

In this study a weighing lysimeter was used for a water and isotope mass balance method to determine evaporation and transpiration ratios of a soybean stand. As the method was originally used in a laboratory setup, the applicability of the adapted setup was tested and the results were discussed.

Keywords: transpiration, evaporation, isotopic fractionation, soybean, profile water content

Introduction

Weighing lysimeters are accurate and reliable instruments to measure water fluxes across its system boundaries such as evapotranspiration (ET). Therefore, they are suitable to evaluate and improve agronomic practices in regard to efficient use of water resources. One aspect of efficient water usage in plant production is the promotion of productive water loss (transpiration T) and the reduction of unproductive water loss (evaporation E). Knowledge of the components E and T is thus required to develop, adapt, and evaluate management practices with respect to efficient water use. Well-known approaches to distinguish between E and T refer to isotopic fractionation and mass conservation of isotopes and water.

Isotopic fractionation is based on the mass difference between naturally occurring stable water isotopes and the multitude of other water molecules. A basic principle is that the process of evaporation causes enrichment of heavier stable isotopes in soil water, since lighter isotopes evaporate more likely (Craig et al. 1965). In contrast, crop water uptake (representing T) does not cause accumulation of heavier isotopes. Hence, the isotopic composition of soil water can be determined and – in combination with the other water and isotope mass balance components – used for calculation of ET fractions.

Sutanto et al. (2012) developed a reliable isotope mass balance method establishing a small lysimeter setup in the laboratory. While the lysimeter allowed detailed determination of water balance components, soil water was extracted from within the lysimeter for isotopic analyses. However, the setup was restricted to small crops and well-watered conditions.

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The idea of this study was to adapt the method of Sutanto et al. (2012) for field application and to improve the calculation of balance components. This should allow investigating various commodity crops in combination with different tillage and irrigation practices even under water-scarce conditions. The adaption to field application was done by determination of isotopic soil water profiles from soil core samples instead of in-situ extraction of water samples, which failed under dry field conditions. Since lysimeters exclude destructive soil sampling, assessment of the isotopic profile was done in the adjacent area where properties and conditions did not deviate from the lysimeter. Therefore, one focus was placed on audit measures to prove the similarity of conditions at and adjacent to the lysimeter. A second focus was placed on the improved calculation of balance components.

Material and Methods

Study site

The adapted method was applied in 2019 to partition ET of a soybean stand in the agricultural area Marchfeld. The lysimeter plot was located in Groß-Enzersdorf, east of Vienna (48°12' N, 16°34' E; 157 m elevation a.s.l.). During the vegetation period (25.04. – 17.09.2019) the mean air temperature was 19.7°C, precipitation was 154 mm, and the lysimeter and its adjacent area were irrigated with 152 mm. Water from precipitation and irrigation was collected for isotopic signature analyses. Weather data was recorded with a local weather station as described in Nolz et al. (2013a). Plant parameters (e.g. plant height, phenological stages, and leaf area index) on the lysimeter and its adjacent area were determined weekly. Leaf area index (LAI) and was measured with an AccuPAR PAR/LAI Ceptometer Model LP-80 (Meter Group Inc., USA).

Lysimeter water balance

Actual ET of the soybean plant stand (66 plants/m^2) was determined with a weighing lysimeter (A = 2.9 m^2). Soil type was sandy loam (0-140 cm) over gravel (140-250 cm). Percolation at the free drainage outlet was collected and measured with a tipping bucket, stored with weighing data, and converted to mm as described in Nolz et al. (2013b). Furthermore, it was sampled weekly for isotope analysis. Mass changes of the lysimeter and the drainage tank were measured and logged in 10-minute intervals. The lysimeter and its adjacent area (approx. 60 m^2) were cultivated alike and were equipped with access tubes for monitoring soil water content (SWC).

Soil water monitoring

SWC was monitored using EnviroSCAN® and DIVINER 2000® soil moisture probes (Sentek Pty Ltd., Stepney, Australia). The probes contained sixteen sensors on a mounting rail measuring SWC from 10 to 160 cm down the soil profile. *SWC monitoring for determining mass balance:* Half-hourly SWC data from EnviroSCAN from the lysimeter were the basis for the water component of the water and isotope mass balance. *SWC monitoring for comparing lysimeter and adjacent area:* Regular Diviner measurements were the basis to check similarity of SWC distribution in and next to the lysimeter. SWC values of each depth were compared to prove the hypothesis of equal water content distribution down the profiles using a two sample t-test with Bonferroni correction for independent samples of each sensor depth.

Isotope analysis and mass balance

Soil cores were sampled weekly with an auger down to 85 cm (composite samples within ± 5 cm of each sensor depth). Isotope ratios were analyzed with a laser-based isotope analyzer (Picarro L2140-I for water samples and Picarro L2130-I for vapor analysis from soil core pore water samples). Analysis of vapor samples was done with a water-vapor equilibration method based on Wassenaar et al. (2008). Measured values were normalized and reported in delta notation δ referenced to the Vienna Standard Mean Ocean Water-Standard (Craig 1961). The isotope mass balance can be constituted as

$$m_{total} = m_i + m_p = m_e + m_f + m_t + m_l \quad (1)$$

where m is the mass of water. The components are the initial (i) and final (f) soil moisture, precipitation and irrigation (p), evaporation (e), transpiration (t), and percolation (l). Each component can also be described as product of the stable isotope concentration δ (e.g. $\delta^{18}O$) and the fraction of water in that component x (as $x_j = m_j/m_{total}$). The components can be directly measured (δ_i, x_i, δ_p, x_p, δ_f, x_f), derived from theoretic assumption (δ_t, δ_l, x_l), calculated from atmospheric conditions and fractionation factors (δ_e), and finally determined as a residue of the balance calculation (x_t, x_e). For evaporation, an isotopic fractionation factor was summing equilibrium (ε_{eq}) and kinetic (ε_k) fractionation.

Improvement of mass balance evaluation

The modifications of the balance component calculation comprised three altered approaches compared to the original evaluation (Sutanto et al. 2012). First, the calculation of δ_e was not derived from averaged atmospheric parameters within the evaluation period, but weighed with high-resolution actual ET values from lysimeter evaluation. Secondly, δ_e was calculated based on the isotopic signature in the surface layer instead considering the whole lysimeter vessel depth. The third modification affected the root water uptake. δ_t was derived from actual root density and water distribution instead of an averaged value across the lysimeter depth.

Results

Comparing lysimeter and adjacent area

Similarity of conditions in and next to the lysimeter were confirmed with several control measurements. *Figure 1a* shows SWCs in and next to the lysimeter for selected dates during the vegetation period, *Figure 1b* displays similarity of plant development for the lysimeter and its adjacent area.

Improvement of mass balance evaluation

The determination of fractionation factors based on 10-minute lysimeter data and 15-minute weather data increased the average of the weekly total isotope fractionation factor ε_{total} from 14.0 to 16.2 ‰. For the entire vegetation period this means a higher estimation of the transpiration fraction compared to an averaged calculation of appro-

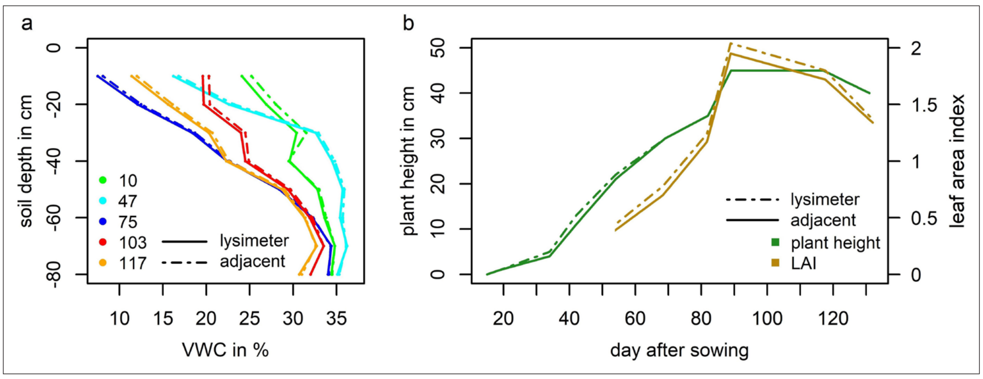

Figure 1: a) Comparison of SWC distributions at the lysimeter and its adjacent area: measurements at different crop development stages for given days after seeding (DAS). Averaged SWC in %. b) Plant height and averaged leaf area index (LAI) values on the lysimeter and its adjacent area. Plant height is given in cm, LAI is dimensionless. Each displayed LAI value constitutes the mean of six single measurements. Dates given as DAS.

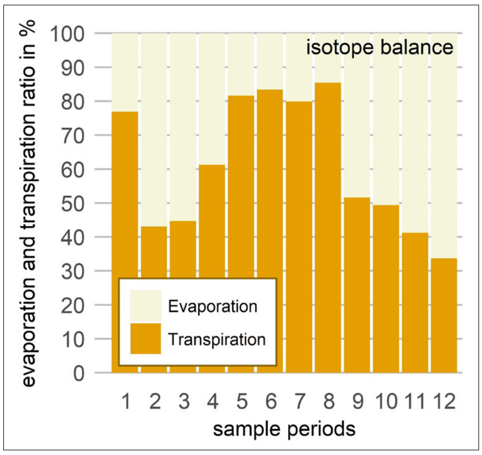

Figure 2. T and E ratios for the sample periods.

ximately 5 %. The calculation of δ_e based on $\delta_{surface}$ instead of δ_t showed the opposite effect with a similar extent: It lowered the estimation of the transpiration fraction during the vegetation period by approximately 5 %. For considering root water uptake more accurately, root density distribution was described linearly from its maximum at the surface layer down to the lowest observed root depth. Compared to averaged δ values from the entire surveyed soil column, δ_t values shifted from a range of -8.2 to -5.7 to a range of -4.9 to -2.5.

Determination of E and T ratios

Figure 2 shows E and T fractions determined with the isotope mass balance.

Discussion

Comparing lysimeter and adjacent area

Control measurements proved equal moisture conditions in and next to the lysimeter during the entire measuring period (*Figure 1a*). Only the comparisons at day 10 after seeding indicated rejection of the hypothesis of similar moisture distributions (for α of 0.05 and Bonferroni adjusted p-values). Also plant heights and LAI values demonstrated concurrent plant development in and next to the lysimeter (comparison of equal means, α of 0.05).

Improvement of mass balance evaluation

The weighted determination of fractionation factors had little influence on equilibrium fractionation, but considerable effect on kinetic fractionation. For this factor, it better weights factors by excluding or reducing phases of low evaporation and transpiration such as night times and rain events. The effect of the weighted determination on δ_e (T fraction + 5 %) is canceled out by the calculation of δ_e based on $\delta_{surface}$ instead of δ_t (T fraction - 5 %), though. Therefore, these two improvements merely shifted the E and T ratios between the sampling periods, but had no effect throughout the entire period.

The more precise calculation of the isotopic signature of water taken up by roots (δ_t) based on regularly monitored root length and shape – had a substantial impact on ET fractions. It caused an increase of the evaporation fraction of about 20 %. As the root water uptake potential strongly depends on root length density and root distribution across the soil profile, isotopic composition of transpired water δ_t may in general be determined weighted on actual root density distribution.

Determination of E and T ratios

The remarkably large T fraction of the first period in the isotope mass balance may be attributed to the preceding long dry phase and dry soil surface. With increasingly frequent rain events, surface layer wetness also increased and the evaporation fraction rose. Nonetheless, transpiration was dominant during times of maximum soil coverage. At the end stage of crop development, measured transpiration fraction remained higher than the simulated transpiration fraction. This is accounted to the remaining foliage and ground covering weeds.

Conclusions

The adaption of the water and stable mass balance for field application showed to be permissible. All considered parameters (water content distribution, LAI, and plant height) suggested similar conditions at the lysimeter and the adjacent area for this particular trial. Therefore, the experimental setup as well as the applied audit measures allow investigation of commodity crops and agronomic practices under the wide range of field conditions.

The results from the water and isotope mass balance show that T and E rates strongly depend on water distribution across the soil profile and its plant availability and that the supposed dependency on canopy cover is overestimated. Consequently, the setup is apparently appropriate for investigation of irrigation strategies.

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