19. Gumpensteiner Lysimetertagung 2021, 17 – 24
ISBN: 978-3-902849-83-0

Estimating crop evapotranspiration of managed alpine grassland using remotely sensed LAI

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Zusammenfassung

Die Auswirkungen von Management und Pflanzenentwicklung auf die Verdunstung von Grünland (ET_C) können mithilfe von Blattflächenindexmessungen (LAI) und Wuchshöhe (h_{crop}) geschätzt werden. Die Verfügbarkeit von satellitenbasierten LAI-Produkten verringert dabei den Bedarf an In-situ-Messungen. In dieser Studie haben wir die geschätzte ET_C nach Penman-Monteith mit einer In-situ-LAI (AccuPAR-ET_{AP}) und einer Fernerkundungsmethode (Feldspektrometer-ET_{FS}) auf einem Dauergrünland der HBLFA Raumberg-Gumpenstein verglichen. Der Vergleich von ET_{FS} und ET_{AP} mit dem Lysimeter (ET_a) zeigt eine starke Korrelation und geringe Abweichungen zwischen den Ansätzen. Um unabhängig von In-situ-Messungen zu werden, haben wir eine Beziehung zwischen h_{crop} und LAI hergestellt. Auch diese Methode zeigt eine starke Übereinstimmung mit ET_a. Aufgrund der breiten Verfügbarkeit empfehlen wir die Verwendung eines Fernerkundungs-LAI, um die Schätzung der Grünland- ET_C auf Feldstücks- und regionaler Ebene zu verbessern.

Schlagwörter: Evapotranspiration, Leaf area index, Fernerkundung, Wirtschaftsgrünland

Summary

Impacts of management and crop development on crop evapotranspiration (ET_C) can be estimated using measurements of leaf area index (LAI) and crop height (h_{crop}). Recent progress in retrieving LAI from remote sensing platforms diminishes the need for in situ LAI measurements. In this study, we compared the estimated Penman-Monteith ET_C using LAI of an in situ (AccuPAR-ET_{AP}) and a remote sensing method (field spectrometer-ET_{FS}) on a managed grassland at AREC Raumberg-Gumpenstein. Comparing ET_{FS} and ET_{AP} with lysimeter (ET_a) showed a high correlation with little deviations between the two approaches. To become independent of in situ measurements, we established a relationship between h_{crop} and LAI to estimate $ET_{c\text{-}remote}$. We observed a much better agreement of $ET_{c\text{-}remote}$ with ET_a than that of the FAO reference ET_0. Because of the open access and the wide availability, we encourage the use of remotely sensed LAI to improve the estimation of managed grassland ET_C on a plot and regional scale.

Keywords: Evapotranspiration, Leaf area index, Remote sensing, Managed grassland

Introduction

Permanent grassland covers about 50% of the total agriculturally used area in Austria and is used either for livestock grazing, is sustainably managed, or is left abandoned (BMLRT 2020). As such, understanding water-related processes in mountain grassland is of high importance for the agricultural and energy sectors (Schaumberger et al. 2008).

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Crop evapotranspiration (ET_C) plays a significant role in grassland water budgets, especially in managed grassland, where the crop vegetation stage highly affects ET_C. The Penman-Monteith equation, recommended by the Food and Agriculture Organizations (FAO), includes the effect of crop development and management practices on ET, by including the leaf area index (LAI) and crop height (h_{crop}) in the calculation of the surface and aerodynamic resistances (Allen et al. 1998). As in-situ measurements of LAI are very scarce, laborious and expensive, remote sensing products are increasingly used) to monitor the changes of grassland development due to management activities or abiotic effects (droughts) (Darvishzadeh et al. 2008). Recent studies have shown a high correlation between direct respectively indirect in-situ methods and proximal and remotely sensed LAI-data (Klingler et al. 2020).

This study compares the LAI measurement method's influence on estimating ET_C of a managed permanent grassland. Estimated values of ET_C are compared with actual evapotranspiration (ET_a) values of a high precision lysimeter, managed according to the surrounding grassland (3-cut system).

Material and methods

Study area

The study was conducted at the test site at the Agricultural Research and Education Centre Raumberg-Gumpenstein in Austria (707 m above sea level) (Pötsch et al. 2019). The experiment is equipped with high precision weighable lysimeters, which offer a unique opportunity to study soil water fluxes of permanent grassland. The dominant species at the experimental site are *Arrhenatherum elatius, Dactylis glomerata, Taraxacum officinale* and *Lotus corniculatus*. The agricultural management of the grassland lysimeters corresponds to the regional management of the surrounding grassland at Gumpenstein, which includes three cuts per year and a fertilization intensity of 90 kg nitrogen, 65 kg phosphor and 170 kg potassium per year (Herndl et al. 2011).

Penman-Monteith equation

The Penman-Monteith equation is regarded as a standard method for estimating crop evapotranspiration (Monteith 1965) using measured meteorological (radiation, temperature, humidity, wind) and crop specific data (LAI and h_{crop}). Evapotranspiration of a reference crop can be estimated following the FAO-56 methodology (Allen et al. 1998), diminishing the need for crop phenological data. ET_C and ET_0 were calculated on a daily basis after recommendations by FAO (Food and Agriculture Organization) (Allen et al. 1998):

$$ET_C = \frac{\Delta(R_n - G) + \rho_a c_p (e_s - e_a)/r_a}{\lambda\left[\Delta + \gamma(1 + \frac{r_s}{r_a})\right]} \qquad 1$$

The ET_0 is derived from equation 1, assuming a constant grass height of 12 cm, LAI=h_{crop} · 24 and r_s of 70 (sm^{-1}):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \qquad 2$$

where ET_C, ET_0, R_n and G are in $MJm^{-2}\ d^{-1}$; Δ is the slope of the saturation vapor pressure temperature relationship ($kPa°C^{-1}$); ρ_a is the air density ($kg\ m^{-3}$), c_p is the specific heat of air ($MJkg^{-1}°C^{-1}$); γ is psychrometric constant ($kPa°C^{-1}$); r_a and r_s are the aerodynamic and surface resistances (ms^{-1}), respectively. r_a and r_s are calculated using linearly interpolated data of LAI and crop height (h_{crop}) measurements:

$$r_a = \frac{ln\left[\frac{z_m - 2/_3\, h_{crop}}{0.123\, h_{crop}}\right] ln\left[\frac{z_h - 2/_3\, h_{crop}}{0.1(0.123\, h_{crop})}\right]}{k^2 u_z} \quad (3)$$

where d is the zero plane displacement, z_m and z_h are heights of the wind and humidity measurements (m), respectively, u_z the wind speed ad height z (ms^{-1}) and k is the von Karman constant (0.41). Surface resistance is calculated (r_s) as:

$$r_s = \frac{r_l}{LAI_{act}} \quad (4)$$

where r_l is the bulk stomatal resistance of the vegetation (= 100 ms^{-1}), and LAI_{act} the active leaf-area index, which accounts for heat and vapor transfer occurring only in the upper half of the canopy (LAI_{act}=LAI · 0.5).

Field Data Collection of LAI

Indirect in-situ LAI measurements were performed in triplicate using the AccuPAR LP-80 Ceptometer (Decagon Devices Inc., Pullman, WA, USA). This linear quantum sensor measures the photosynthetically active radiation above and below the canopy and calculates the LAI using models that combine the radiation measurements with canopies-architecture related variables and sun position information (Meter 2018). The field spectrometer HandySpec Field VIS/NIR 1.7 field spectrometer (tec5 AG, Oberursel, Germany) was used to measure hyperspectral canopy reflectance in the range from 400 to 1690 nm. The measurements were carried out between 10 a.m. and 2 p.m. under as constant and cloudless conditions as possible, at four areas within the lysimeter. In addition to spectral reflectance measurements, the average crop height is collected on the plots using ultrasonic sensors. The measurements described above yielded the two independent estimates of the leaf area index LAI_{AP} and LAI_{FS}, respectively.

LAI Retrieval Algorithm

The ESA's Spectral Response Functions were used to convert the hyperspectral signature from the HandySpec into the corresponding S-2 bands (ESA, 2018). Subsequently, the LAI was calculated using a neural network algorithm that was trained with radiative transfer simulations and specifically tailored for Sentinel-2 data (Baret et al. 2010). The missing S-2 band 12 was calculated according to (Klingler et al. 2020). All transformations and calculations were performed using the SpectroAnalyst tool (Schaumberger and Adelwöhrer 2020).

Lysimeter data

Measurements of the C0T0 high precision weighable lysimeter, representing the untreated reference plot in the Lysi-T-FACE experiment (Herndl et al. 2011), were used for this study. The lysimeter has a surface area of 1 m^2 and a depth of 1.5 m. It is equipped with time-domain reflectometry probes that measure the soil water content at different soil depths. Soil water contents at 30 cm depth were standardized using the Soil Moisture Anomaly Index SMAI as defined by Jiménez-Donaire et al. (2020) and employed to identify severe drought periods, during which actual evapotranspiration is expected to be lower than potential crop evapotranspiration. The raw lysimeter data underwent manual and automated plausibility checks and were post-processed using the adaptive window and threshold filter AWAT (Peters et al. 2017). The actual evapotranspiration ET_a is calculated from the water balance equation on a 10 min resolution following Schrader et al. (2013).

Results

Comparing crop ET with Lysimeter ET

The crop evapotranspiration (ET_c) is according to Allen et al. (1998) „the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions". To compare the lysimeter-obtained evapotranspiration with the estimated ET_c, days with potential water stress were excluded from the analysis. *Figure 1* shows the effect of water stress on ET_a. (An apparent effect of water stress is observed over the summer of 2019, with low SMAI values and a higher (<-1) difference between ET_a, ET_c.) A threshold value of SMAI<-1.42 was employed to identify water stress following the drought classification by McKee (1993). Daily SMAI values smaller than 1.42 indicate the occurrence of severe drought events. (The scatter plot in *figure 1* shows a good agreement between the defined threshold and the difference in ET_a, ET_c. In the period over 2016-2019, potential water stress was identified on 42 days).

Comparison of ET_c estimated with LAI measured with AccuPAR vs Field spectrometer

Table 1 summarizes the estimated crop evapotranspiration for the whole vegetation period over 2016-2019 when LAI data was available. Additionally, the mean values, root-mean-square errors and correlations are reported for each cut. Regarding the LAI values, the AccuPAR and FieldSpec values showed a high correlation of 0.87 and 0.91 for the first and second cut. Higher deviances of LAI were observed in the third cut, with a mean LAI of 2.50 and 3.39, for the field-spectrometer and AccuPAR, respectively. Estimated ET_C using LAI_{FS} data showed a better correlation and lower RMSE, compared to the LAI_{AP}. Observing the LAI values on *figure 2* and the RMSE for each cut, the overestimation of LAI_{AP} in the second and third cut seems to affect the estimation of ET_C negatively.

Table 1. Mean values, the correlation coefficient (r) of LAI and root-mean-square Error (RMSE) for the estimated crop evapotranspiration for each cut.

	1st cut	2nd cut	3rd cut	Whole period
LAI_{FS}	3.32	2.19	2.50	2.60
LAI_{AP}	3.32	2.22	3.39	2.99
r (LAI)	0.87	0.91	0.81	0.81
RMSE ET_{FS}	0.62	0.78	0.50	0.62
RMSE ET_{AP}	0.59	0.87	0.54	0.67
RMSE $ET_{c\text{-}remote}$	0.68	0.78	0.46	0.62
RMSE ET_0	1.00	1.21	0.69	0.95

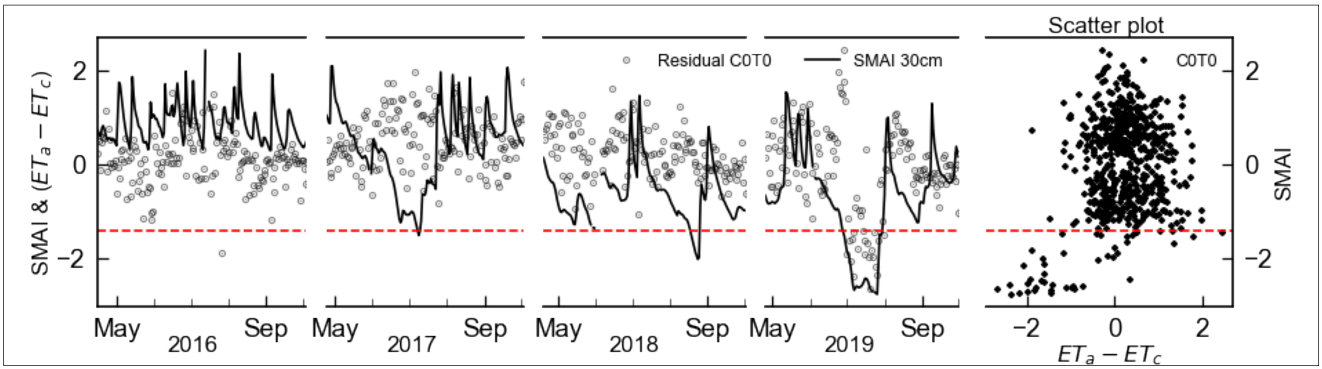

Figure 1: Difference between ET_a and ET_c, the Soil Moisture Anomaly Index and the scatter plot between these two variables for the period 2016-2019.

Estimation of ET_c using an LAI/h_{crop} relationship

A relationship between LAI and h_{crop} was obtained by fitting a simple linear function y = k*x to the ultrasonic crop height data from the lysimeter plot. As the ET_{FS} data showed a better agreement with the lysimeter ET_a, we only used LAI_{FS} data for the fitting process.

$$h_{crop} = 0.12\ LAI \tag{5}$$

where h_{crop} is obtained crop height in m. Using LAI_{FS} and the above-derived relationship, $ET_{C\text{-}remote}$ was estimated. Over the entire observed period results similar to ET_{FS} were obtained, thus showing that $ET_{C\text{-}remote}$ of managed grassland can be successfully estimated without the need for crop height data. In *Figure 4*, which shows the relationship between LAI_{FS} and h_{crop}, we can observe that the derived h_{crop} relationship underestimated higher h_{crop} values in the first cut, which lead to higher RMSE values of ET_C remote in the first cut (*Table 1*).

Conclusions and outlook

This study used LAI measurements of the AccuPAR indirect optical method and the proximal (field spectrometer) remote sensing approach to estimate crop evapotranspiration observed at a field weighable lysimeter. Estimated ET_c values were compared to lysimeter-obtained *ET* over the period 2016-2019. Comparing the estimated ET_{AP} and ET_{FS} with ET_a, showed a high agreement with both methods, considering r and RMSE. A high correlation (r>0.85) was observed between the LAI values for the first and second cut, whereas the LAI slightly deviated on the third. No larger deviations of ET_{FS} and ET_a were observed in the first cut, whereas a higher RMSE of the ET_{AP} was observed in the second and third cut. To estimate ET_C independently of in situ measurements, a relationship was established between LAI and h_{crop}. The estimated $ET_{c\text{-}remote}$ exhibited similar values to ET_{FS} and outperformed ET_0, thus providing an accurate method to estimate ET_c using remotely sensed crop data. Recent studies showed a good agreement between proximal (field-spectrometer) and satellite remote sensing data (Sentinel-2), thus providing an opportunity to expand these findings on a regional scale.

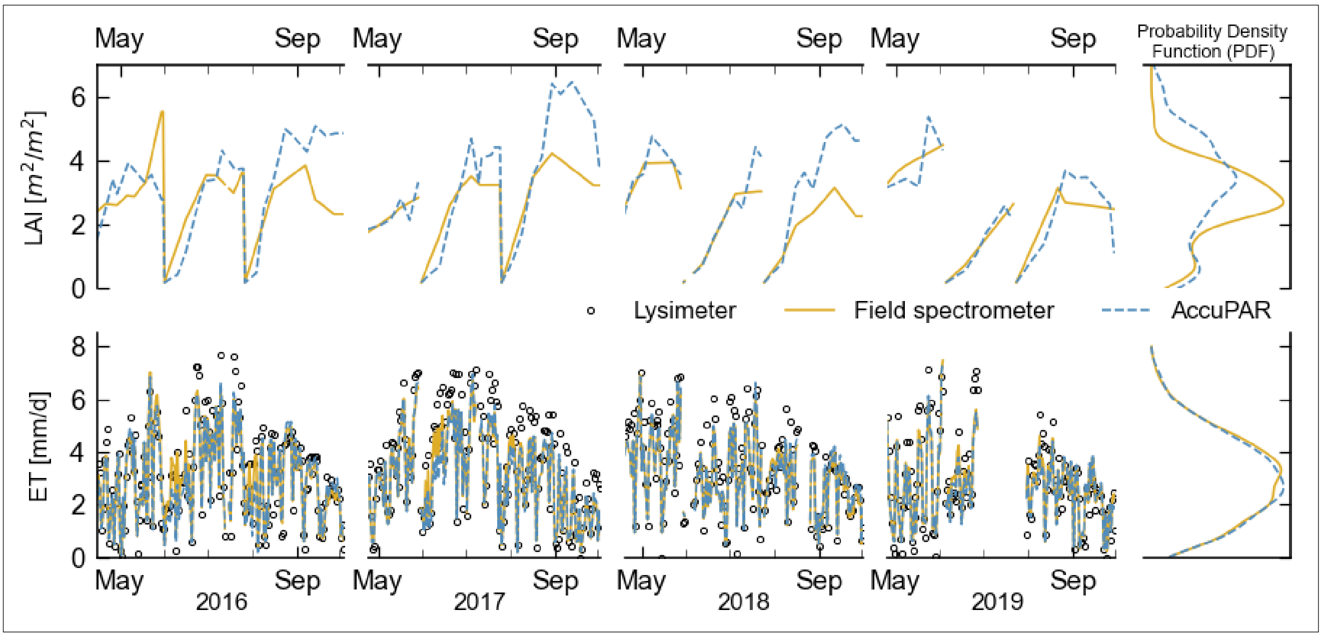

Figure 2: LAI values and estimated crop evapotranspiration with a corresponding probability density function.

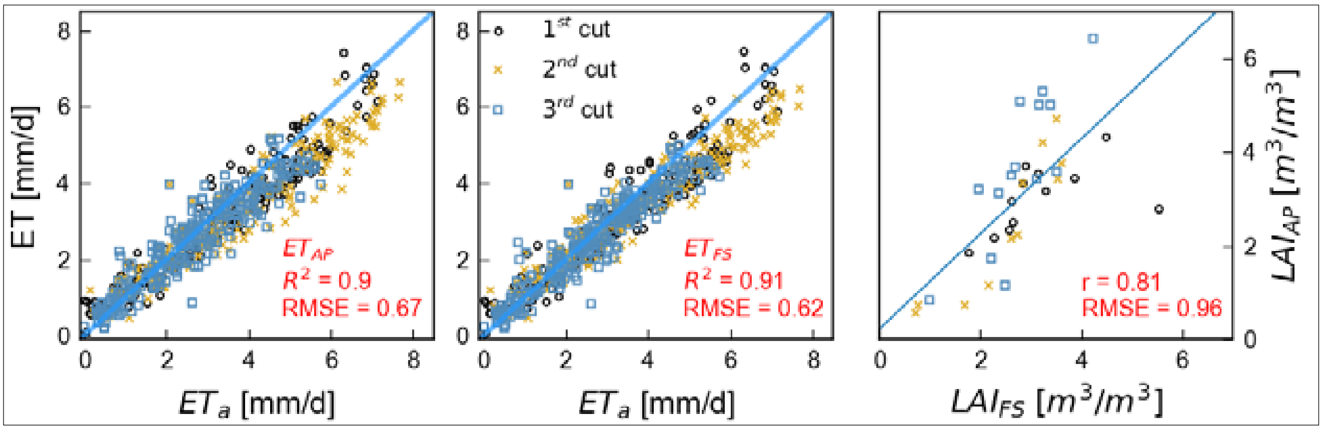

Figure 3: Crop evapotranspiration of ET_{AP} and ET_{FS} compared to lysimeter ET_a and the correlation between LAI_{FS} and LAI_{AP}.

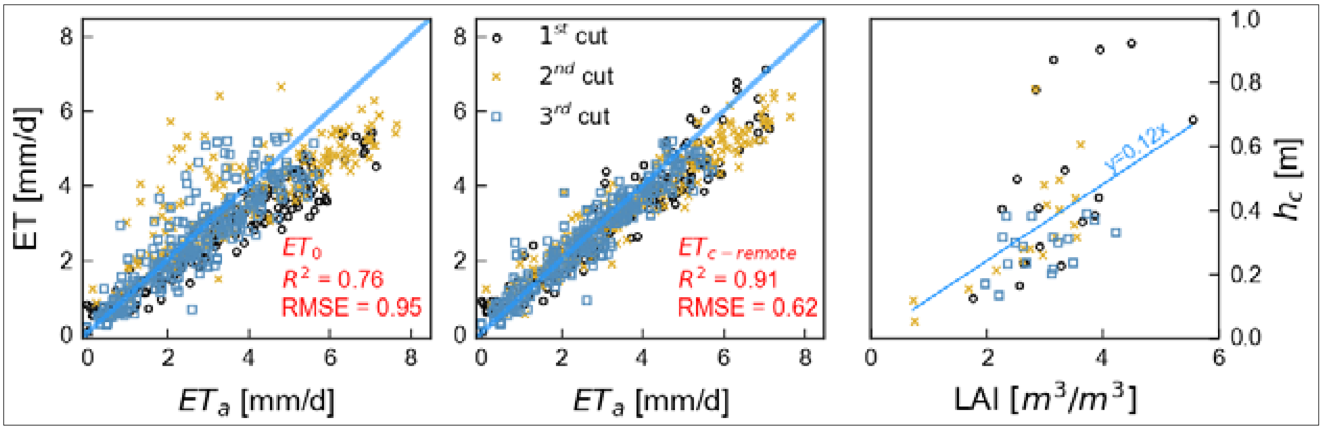

Figure 4: Estimated FAO reference ET_0, $ET_{c\text{-}remote}$ and the relationship between LAI_{FS} and h_{crop}.

Acknowledgements

This work is partly funded by the Earth System Sciences programme of the Austrian Academy of Sciences (project ClimGrassHydro).

References

Allen R.G., Pereira L.S., Raes D., Smith M., others, (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao Rome 300, D05109.

Baret F., Weiss M., Bicheron P., Berthelot B. (2010) Sentinel-2 msi products wp1152 algorithm theoretical basis document for product group b. INRA-EMMAH Avignon Fr.

BMLRT (2020) Grüner Bericht 2020 - Bericht über die Situation der österreichischen Land- und Forstwirtschaft. Bundesminist. Für Nachhalt. Tour. Wien 297 S.

Darvishzadeh R., Skidmore A., Schlerf M., Atzberger C., Corsi F., Cho M. (2008) LAI and chlorophyll estimation for a heterogeneous grassland using hyperspectral measurements. ISPRS J. Photogramm. Remote Sens. 63, 409-426.

ESA (2018) Sentinel-2 spectral response functions (S2-SRF).5 [https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi/document-library/-/asset_publisher/Wk0TKajiISaR/content/sentinel-2a-spectral-responses] (15.1.2020).

Herndl M., Pötsch E.M., Bohner A., Kandolf M. (2011) Lysimeter als Bestandteil eines technischen Versuchskonzeptes zur Simulation der Erderwärmung im Grünland.

Jiménez-Donaire M. del P., Tarquis A., Giráldez J.V. (2020) Evaluation of a combined drought indicator and its potential for agricultural drought prediction in southern Spain. Nat. Hazards Earth Syst. Sci. 20.

Klingler A., Schaumberger A., Vuolo F., Kalmár L.B., Pötsch E.M. (2020) Comparison of Direct and Indirect Determination of Leaf Area Index in Permanent Grassland. PFG–Journal Photogrammetry Remote Sensing Geoinformation Science 88 (5), 369-378.

McKee T.B., Doesken N.J., Kleist J., others, (1993) The relationship of drought frequency and duration to time scales, in: Proceedings of the 8th Conference on Applied Climatology. Boston, 179-183.

Meter (2018) AccuPAR PAR/LAI Ceptometer model LP-80: operator's manual. Pullman, WA, 81 S.

Monteith J.L. (1965) Evaporation and environment, in: Symposia of the Society for Experimental Biology. Cambridge University Press (CUP) Cambridge, 205-234.

Peters A., Groh J., Schrader F., Durner W., Vereecken H., Pütz T. (2017) Towards an unbiased filter routine to determine precipitation and evapotranspiration from high precision lysimeter measurements. J. Hydrol. 549, 731-740.

Pötsch E., Herndl M., Bahn M., Schaumberger A., Schweiger M., Kandolf M., Reinthaler D., Schink M., Adelwöhrer M. (2019) Climgrass-ein innovatives Freilandexperiment zur Klimafolgenforschung im Grünland. 21. Alpenländisches Expertenforum „Klimawandel im Alpenraum-Auswirkungen auf Ökosystem Grünl. Dessen Bewirtsch. HBLFA Raumberg-Gumpenstein Irdning-Donnersbachtal.

Schaumberger A., Adelwöhrer M. (2020) SpectroAnalyst – Management von Hyperspektraldaten für die Grünlandforschung. Presented at the 40. Wissenschaftlich-Technische Jahrestagung der DGPF, Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V.,Band 29, Stuttgart, 184-196.

Schaumberger A., Eitzinger J., Formayer H. (2008) Räumliche Modellierung der potenziellen Evapotranspiration, in: Paper Presented at the AGIT-Symposium, Salzburg.

Schrader F., Durner W., Fank J., Gebler S., Pütz T., Hannes M., Wollschläger U. (2013) Estimating precipitation and actual evapotranspiration from precision lysimeter measurements. Procedia Environ. Sci. 19, 543-552.