Agricultural Water Management 213 (2019) 352–357

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

In-situ partitioning of evaporation and transpiration components using a portable evapotranspiration dome—A case study in Tall Fescue (*Festuca arundinacea*)

Muhammad Shahinur Alam[a,*], David W. Lamb[a,b], Muhammad Moshiur Rahman[a]

[a] *Precision Agriculture Research Group, University of New England, NSW, 2351, Australia*
[b] *Food Agility Cooperative Research Centre Ltd, University of New England, NSW, 2351, Australia*

ARTICLE INFO

Keywords:
Pasture evapotranspiration
Leaf Area Index (LAI)
Normalized Difference Vegetation Index (NDVI)
Crop coefficient (K_c)

ABSTRACT

Understanding the components of water consumption of a crop or pasture through evapotranspiration is important for improving water management. In this study the FAO dual crop coefficient methodology has been used in conjunction with a portable evapotranspiration chamber in-situ, to quantify the basal crop (K_{cb}) and soil evaporation (K_e) coefficients of a pasture as a function of leaf area index and a widely used spectro-optical reflectance index, NDVI. To facilitate the measurement of soil evaporation component, small segments of the green biomass of a target pasture canopy, Tall Fescue (*Festuca arundinacea* var. Dovey) were allowed to rapidly senesce by applying a commercial herbicide while preserving the soil moisture and canopy structure. The ratio between the transpiration and evapotranspiration components (K_{cb}/K_c) increased from 0.03 to 0.46 for zero to highest available vegetation cover (LAI from 0 to 4.22). A significant linear relationship was observed between K_{cb} and NDVI ($R^2 = 0.88$) suggesting the possibility of using the latter, for example through remote sensing technologies, to determine the former.

1. Introduction

Transpiration (T) by the canopy and Evaporation (E) from the soil, taken together as evapotranspiration (ET), accounts for up to 96% of the water loss depending on the types of vegetation cover and climatic condition of the region (Branson et al., 1976; Wilcox et al., 2003). While transpiration from plant canopies is associated with the production of biomass, evaporation is simply a loss mechanism that decreases water use efficiency (Kool et al., 2014); 30–80% of the water flux can be associated with evaporation (Wilcox et al., 2003). Both E and T are inextricably linked through environmental conditions such as atmospheric demand. Quantifying both E and T, each independent of the other, is useful because in irrigated systems, for example such information can inform strategies aimed at improving water use efficiencies (Kite, 2000; Zhao et al., 2013). Moreover, it is not necessarily just about maximizing water use efficiency because in some situations crops are grown under intentional water-limiting conditions, for example with a view to optimizing vigor and yield. Knowledge of E and T in this scenario is equally important to achieve the right water balance (Farahani et al., 2007; García García et al., 2012).

Considerable work involving various numerical and analytical methods to assess the components of evapotranspiration in crops have been reported. Measurement of the isotopic composition of the water mass released by the canopy (Brunel et al., 1997; Ferretti et al., 2003; Gibson and Edwards, 2002; Good et al., 2014; Lu et al., 2017; Rothfuss et al., 2010; Sutanto et al., 2012; Wang et al., 2013; Wen et al., 2016; Williams et al., 2004) or the recently developed correlation-based partitioning models, assuming that the transpiration and CO_2 intake occur simultaneously in plants (Scanlon and Kustas, 2010, 2012; Scanlon and Sahu, 2008), are the two most commonly used examples of directly estimating the components of evapotranspiration. Other methods such as the use of micro-lysimeters, soil heat pulse probes, enclosed chambers (to measure evaporation), eddy covariance, and sap flow measurements (to measure net transpiration) have also been used to separately quantify E and T (Ashktorab et al., 1994; Cammalleri et al., 2013; Er-Raki et al., 2010; Kang et al., 2003; Kool et al., 2016; Moran et al., 2009; Scanlon and Kustas, 2012; Wang and Yamanaka, 2014; Zhang et al., 2013; Zhao et al., 2013, 2015).

Using methods that involve directly measuring the property of individual leaves and stems is particularly challenging in grazing pastures, for example, owing to the small size of the plant parts. Traditional measurements that rely upon bulk properties of the soil or the plant

---

[*] Corresponding author.
E-mail address: malam3@myune.edu.au (M.S. Alam).

https://doi.org/10.1016/j.agwat.2018.10.042
Received 24 September 2018; Accepted 27 October 2018

canopy as a whole could bypass those challenges but they are not amenable for partitioning E and T, and certainly not in-situ.

The nature of the vegetation itself plays a key role in the partitioning of E and T, since T is the result of vegetation activity and E is also impacted through shading (Good et al., 2014; Schlesinger and Jasechko, 2014). To what extent the inter-relationship between E and T occurs in a given plant canopy remains highly dependent on the environmental conditions (e.g. evaporative demand), the canopy (cover) and the underlying soil conditions (Wang et al., 2014). Both the Leaf Area Index (LAI), which characterizes the canopy leaf area per unit ground area, and spectro-optical reflectance indices such as the often-used Normalized Difference Vegetation Index (NDVI), which is based on the scattering (reflectance) of incident red (wavelength ~650 nm) and near infrared (wavelength ~750 nm) radiation from plant canopies, have the potential to be linked with evapotranspiration coefficients (Alam et al., 2018; Er-Raki et al., 2007). This is an area of growing interest because of the rapid advances in remote sensing systems capable of imaging plant canopies in the required wavelength ranges (e.g. red and near infrared) offering unprecedented levels of spatial resolution and revisit frequencies. For example there are the obvious links with irrigation scheduling (D'Urso et al., 2013; Hornbuckle et al., 2009; Neale et al., 2003). In the case of pastures, these systems offer not only an insight into feed-base production and management (irrigated and rain fed) but also grazing management (Rahman et al., 2014a; Trotter et al., 2010).

Limited research has investigated the relationship between the individual components of ET using metrics such as NDVI or LAI in agricultural systems (Brun et al., 1972; Kang et al., 2003; Kristensen, 1974; Wang et al., 2014). Kang et al. (2003) investigated the relationship between LAI and the ratio of T and ET for winter wheat and maize based on lysimeter data. The whole-season result indicated a saturation of T/ET for both these crops at approximately LAI = 3 and this saturation continued into higher values of LAI (R^2 = 0.968 and 0.981 for wheat and maize respectively). The experiment was conducted with a lysimeter to measure actual evapotranspiration and a microlysimeter was used to measure the soil evaporation component. The data were accumulated over an entire growing season where it would be expected that soil moisture variations would occur. The impact of soil moisture variations and the wetting frequency on instantaneous evapotranspiration and on soil evaporation were separately investigated by Zhang et al. (2013) and Alam et al. (2017), for a winter wheat-summer maize crop sequence and for pasture respectively. In these studies the influence of wetting frequency and soil moisture variation on soil evaporation and evapotranspiration were apparent.

The FAO dual crop coefficient approach is well-suited for calculating the evapotranspiration coefficient (K_c) of a plant canopy; the ratio to the actual evapotranspiration of a canopy to the reference value based on the application of the FAO Penman-Monteith (FAO-PM) method to the local environmental conditions for a 'standard canopy' (Allen et al., 1998). In this way, the impact of weather variability (namely evaporative demand) on actual evapotranspiration can be normalised by introducing the relevant coefficients (K_e for E and K_{cb} for T) in the calculation. The value of K_c can subsequently be partitioned into coefficients for soil evaporation (K_e i.e. soil evaporation coefficient) and canopy transpiration (K_{cb} i.e. basal crop coefficient) where $K_c = K_{cb} + K_e$. In order to partition the evaporation and transpiration using the relevant coefficients, any two of the three variables (ET, E and T) must be known, together with the reference crop evapotranspiration value (ET_o) from which the crop coefficients can be derived (Allen et al., 1998). Er-Raki et al. (2010) evaluated the dual crop coefficient approach and compared the standard method with the data obtained from a combination of eddy covariance based actual evapotranspiration measurements and scaled-up sap flow measurements of transpiration in an olive orchard. Ultimately they sought to measure the ET components. They demonstrated that because of inadequate distribution of irrigated water, most of the applied water was removed from the system in the form of soil evaporation and they observed that the crops could be still facing water stress even when doubling the actual crop water application. They concluded that applying the FAO model to separately estimate the ET components could provide valuable information to improve operational irrigation scheduling. In an earlier study, Er-Raki et al. (2007) investigated the relationship between the K_{cb} of wheat crops, and the corresponding vegetation coverage and NDVI values derived from a hemispherical canopy imaging system and a hand-held MSR87 multispectral radiometer, respectively. Based on the strength of the relationship they recommended the use of the NDVI for estimating crop water requirements. Duchemin et al. (2006) studied the feasibility of Landsat 7 ETM + derived NDVI to estimate the K_{cb} on a large scale for an irrigated area dominated by wheat. They reported an exponential relationship between LAI and K_{cb} (R^2 = 0.79) and a linear relationship between NDVI and K_{cb} (R^2 = 0.79).

In the case of grazing pastures, Rothfuss et al. (2010) partitioned water fluxes of Tall Fescue (*Festuca arundinacea* var. Dovey) in a controlled chamber environment containing a soil monolith by using water stable isotopes. They were able to generate time series data of evapotranspiration components and the corresponding LAI (acquired by destructive sampling and subsequent leaf scanning/image analysis). The authors reported a T:ET ratio progressing from zero to 0.30 at approximately 36 days post sowing (LAI ≈ 2), beyond which the soil evaporation dropped to only 5% of the total evapotranspiration. The authors were unable to rule out a constant level of soil evaporation occurring, or even a slight increase with increasing LAI, when factoring in the measurement uncertainties with the challenges of maintaining a constant soil moisture availability throughout the trial.

In addition, to avoid the challenges of attempting in-vivo measurements on small pasture plants using techniques such as sap flow measurements, another advantage of bulk measurements such as the dual crop coefficient approach is the fact that local environmental conditions are factored in to the observed values as a matter of course. The consequences of changing weather parameters are incorporated through the reference crop evapotranspiration value (ET_o).

The specific objective of this study is to develop a method of separately estimating pasture evapotranspiration components; namely soil evaporation and canopy transpiration in-situ (under field conditions) and at a scale commensurate with collecting (again in-situ) optical vegetation indices of the pasture canopy to allow and exploration of the index-ET relationships.

2. Materials and methods

2.1. Site location and preparation

A 50 m × 20 m plot of established Tall Fescue (*Festuca arundinacea* var. Dovey), located on the University of New England SMART Farm, NSW, Australia (Latitude −30.481088 °S, Longitude 151.644757 °E) was selected for collection of transpiration and evaporation data together with an appropriate vegetation index and LAI. Several automatic weather stations (AWS) were installed in the vicinity of the plot to provide a value for reference crop evapotranspiration (ET_o) data during the data collection period from November 2017 to March 2018 coinciding with the peak summer growing season. In order to promote a range of LAI, the entire site was first mown to a height of approximately 2 cm, and then divided into smaller plots of 4 m × 2 m; each treated with different rates of nitrogen fertilizer (0 to a maximum of 100 kg N/ha). Each plot was regularly irrigated to achieve non-water-limited growth.

2.2. Instrumentation

A portable, hemispherical evaporation chamber (0.18 m^3; Alam et al. (2018)) was utilized to measure the field evapotranspiration (ET_c) directly from the target canopy. The 'dome' chamber was fitted with sensors and a data logger and calibrated beforehand to precisely measure the vapor accumulation from transpiration and/or evaporation following the protocol of Alam et al. (2018). Temperature and relative humidity data related to the calculation of evaporation and transpiration inside the chamber were recorded with the help of a data logger (LSM1E904, ICT International, Armidale, Australia) and a laptop computer.

Prior to collecting each ET_c measurement, a handheld, active, optical sensor (GreenSeeker®, Trimble, Sunnyvale, California, USA) was used to measure the nadir-viewed NDVI at a height of 100 cm above the canopy surface. This limited the sensor coverage of the target canopy to a diameter of 68 cm. The canopy LAI was measured using an AccuPAR ceptometer (LP – 80; Decagon Devices, Pullman, USA). The approximately 1 m long, linear sensor probe comprises of 80 sensors spaced 1 cm apart and is divided into 8 segments. Only 4 of the 8 segments were kept activated during the measurement to ensure a similar target canopy area was interrogated as with the nadir-viewing NDVI measurements. The volumetric soil moisture content at each sampling location was recorded to a depth of 6 cm using a MP306 soil moisture probe (ICT International, Armidale, Australia). All data were processed in MS Excel.

2.3. Data collection sequence and calculation of crop coefficients

The first set of evapotranspiration (ET_c) data was collected at 21 days post-mowing from 6 locations. The volumetric soil moisture content (6 cm) was also recorded at this time. Immediately following the evapotranspiration measurements, a herbicide (Active Ingredient: 16 g/L Glyphosate as ammonium salt and 20.5 g/L Nonanoic acid) was applied to stop leaf transpiration. Within two days of application (i.e. day 23) the canopies were completely senescenced and a second dome evapotranspiration measurement was conducted over the same canopy segments. As with the previous green canopy dome measurement, the pasture was irrigated the evening prior (i.e. day 22) and the intervening night period used to allow the canopy surface to dry and the absorption of any surface water into the soil. The volumetric soil moisture content at 6 cm depth was again recorded prior to this second measurement.

The same protocol was applied to a second set of 10 locations within the trial site at 30/32 days post-mowing in order to provide locations with higher values of LAI. Fig. 1 (a) and (b) shows the aerial view of the experimental site and a closer view of a selected measurement location 2 days after the application of the herbicide.

The field sampling sequence for all measurements is summarized in Fig. 2.

Reference crop evapotranspiration (ET_o) data were collected from the nearby SMART Farm AWS (Taylor et al., 2013) in order to calculate the relevant crop coefficients, K_c and K_e, from the evapotranspiration measurements. The nearby AWS was configured to measure ET_o every 10 min using an array of environmental sensors and the Penman-Monteith equation (Allen et al., 1998; Penman, 1948). The maximum time interval between any field measurements of ET_c and the AWS-derived ET_o values used to calculate K_c (or K_e) was 5 min.

Day 20	Irrigate 6 sites selected
Day 21	NDVI, LAI, VWC and ET_C measurements
	Application of herbicide
Day 22	Irrigate
Day 23	VWC, ET_C measurements
Day 29	Irrigate Additional 10 sites selected
Day 30	NDVI, LAI, VWC and ET_C measurements
	Application of herbicide
Day 31	Irrigate
Day 32	VWC, ET_C measurements

Fig. 2. Field measurement sequence spanning two successive sets of green/senescence measurements and the final surface drying measurement.

For each evapotranspiration measurement the K_{cb} was calculated from the difference of the derived K_c and K_e values.

A diagram summarizing the measurement/calculation sequence for the green/senescence combination trials is given in Fig. 3.

All ET_c measurements conducted throughout the trial were conducted within a short window of time (12.00–13.00 hr) on any given day and under clear sky conditions.

3. Results and discussions

During the green/senescence measurements of evapotranspiration throughout the trial the volumetric soil water content at 6 cm depth (root zone) was observed to remain within a range considered as field capacity, and certainly above the wilting point given the predominantly clay soil at the sites (Zotarelli et al., 2010) (Fig. 4). Moreover, the difference in VWC between the green (Day x) and senescence (post herbicide application; Day x + 2) measurements did not exceed 10%. Only one sample site (site No. 7) exhibited a VWC approaching the wilting point range for the clay soil.

Fig. 5 (a) and (b) demonstrate the relationship between the crop coefficients K_c, K_e and K_{cb} and LAI and NDVI, respectively, under assumed non-limiting soil moisture conditions. The vertical error bar for each data point represents the compound error in calculating the respective coefficient from the parameters measured inside the evapotranspiration dome (Alam et al., 2018). Noteworthy is the fact that the Site no. 7 data point described above (LAI = 0) does not appear to be an

Fig. 1. (a) An aerial view of the trial site showing the 16 specific measurement locations, and (b) an example of a measurement location 2 days after application of the herbicide in preparation for its second ET measurement.

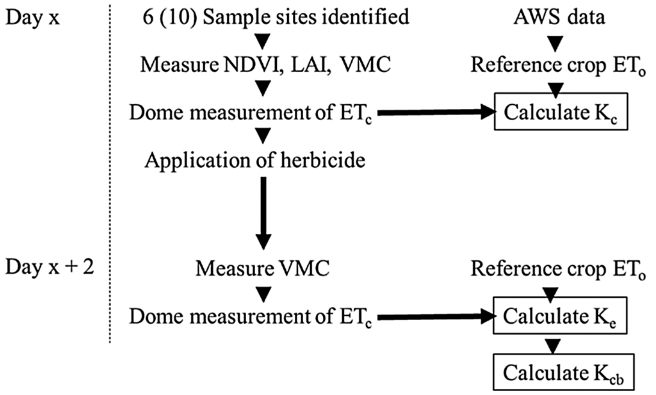

Fig. 3. Flow diagram of the measurement and associated calculations.

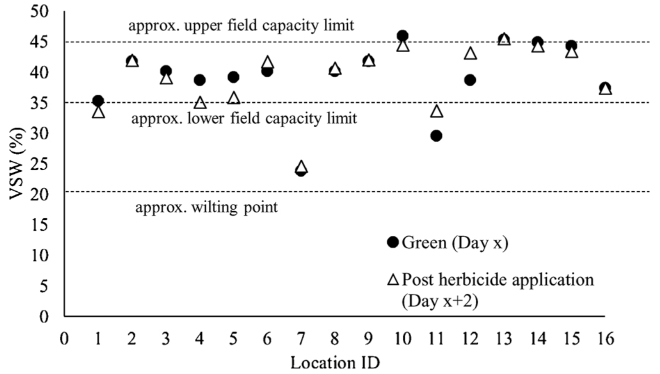

Fig. 4. Volumetric soil moisture content values at each location during the measurement.

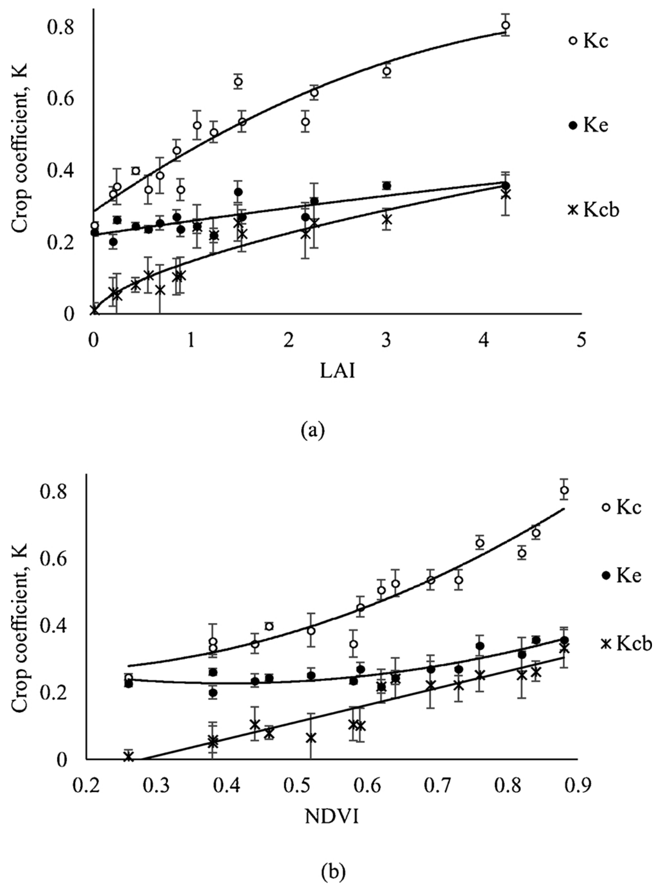

Fig. 5. Relationship between crop coefficients K_c, K_e, K_{cb} and (a) LAI and (b) NDVI under assumed non-limiting soil moisture conditions.

outlier in comparison to the graphed trend curves.

The relationship between K_c and LAI (Fig. 5 (a)) is non-linear ($R^2 = 0.93$) and at the upper value of LAI (≈ 4) the trend curve suggests a tendency towards saturation. The shape of the K_c - LAI response curve is consistent with the previous findings (Alam et al., 2018; Rothfuss et al., 2010) and the tendency towards a saturation value is based on the notion that the upper leaves are primarily contributing to the plant water loss (Pons and Bergkotte, 1996; Pons et al., 2001) with the diminishing transpiration capability of individual leaves at varying positions down the vertical plant canopy (Silcock and Wilson, 1982). The same applies to the K_{cb}. As expected, in Fig. 5 (a) $K_e \approx K_c$ at LAI ≈ 0, rendering the value of the K_{cb} zero at LAI ≈ 0.

The K_e derived from the subsequently senesced canopies at each site exhibits a statistically significant ($p < 0.0001$) albeit small (slope ≈ 0.003) linear increase with increasing LAI. This trend is ascribed to the irrigation/drying cycle used in this trial. Following the transition of each plot from green to senescence the plots were briefly irrigated and allowed to dry overnight before the dome ET and VMC measurements. It is likely that the higher-LAI canopies have reduced the amount of overnight surface drying (e.g. via restricting air flow or reducing solar illumination during the preceding – approximately 6 h- daylight hours) resulting in more moisture available for surface evaporation (« 6 cm depth) during the subsequent dome measurements. In other words, under the conditions applied in this trial we have created a direct (inverse) relationship between canopy cover and resistance to surface evaporation (Choudhury and Monteith, 1988; Oke, 1987). Thus the increasing amount of the K_e observed with increasing LAI in this work, while small and nonetheless significant, is an artefact of the residual moisture left during the drying process following irrigation, rather than a canopy-driven process. Increasing K_e with increasing LAI in Tall Fescue was also observed by Rothfuss et al. (2010) up until LAI $\approx$ 1.6. In this particular work, beyond this value there are no data points until LAI 3.9 where the value has collapsed to almost zero, whereas in this present work the evaporation coefficient increases monotonically up to the upper limit of LAI 4. Rothfuss et al. (2010) concede that "Given the lack of data between LAI 1.6 and 3.9, it is difficult to infer with reasonable precision from these results a partition value for a LAI greater than 1.6. The main limitation of the Monolith experiment was the volume of the RUBIC I chamber, which could not physically allow the experiment to be run with more than 0.15 m of soil depth for our soil surface and under the magnitude of the volumetric water content values encountered all along the study. Therefore, the time required for the root system to partially extract water directly from the reservoir and bypass water in the soil was rather small. In the latest stage, transpiration isotopic composition converged to that of soil evaporation, making accurate partition difficult". Consequently the result of this work in Fig. 5 (a), and especially for LAI > 2, suggests a persistence in the soil evaporation component for larger (LAI) Tall fescue canopies, at least up to the upper limit (LAI 4) investigated in this work. Irrespective of the artificial cause of the observed significant relationship between E and LAI in this present work, the results nevertheless highlight the ability of the technique used here to divine a response, albeit small.

Corresponding to LAI = 0 in Fig. 5 (a) is the NDVI value of 0.26 (lowest x-axis value in Fig. 5 (b)) which is that associated with the bare soil. Of note in Fig. 5 (b) is the significant linear increase in K_{cb} with increasing NDVI. This is unsurprising given both K_{cb} and NDVI are both derived from the interaction of incoming radiation and the canopy leaves which declines at lower reaches of the canopy (for example Deckmyn and Impens (1998); Jovanovic and Annandale (1998)). The NDVI certainly increases asymptotically with increasing LAI (Fig. 6) as the PAR, a driver of photosynthetic activity including transpiration within the canopy decreases at lower reaches on the canopy (Silcock

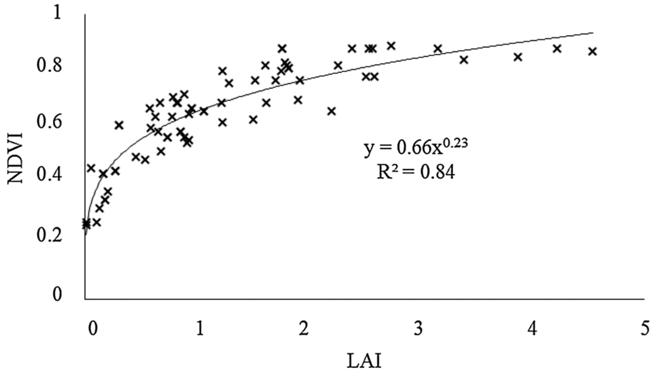

Fig. 6. Relationship between LAI and NDVI.

and Wilson, 1982). The observed linearity is also consistent with the observations of Rahman et al. (2014b) who observed a linear relationship between fAPAR and NDVI resulting from increases in LAI in Tall fescue.

The ratio of transpiration and evapotranspiration coefficients (K_{cb}/K_c) changes from 0 at LAI = 0 up to ≈ 0.40 for an LAI of 4.2. Rothfuss et al. (2010) also described a T/ET ratio ranging from 0 up to 0.30 at 36 days post sowing when LAI value reached approximately 2. In the following days their soil evaporation dropped significantly, to only 5% of the total evapotranspiration and accounting for uncertainties they observed that the ratio could be lower.

In corn and winter wheat, transpiration/evapotranspiration ratios of 0.63 (Zegada-Lizarazu and Berliner, 2010) and 0.83 (Zhang et al., 2011), respectively; the former under furrow and the latter under flood irrigation were stated. It has been reported that rangeland and pasture grasses can have the lowest T/ET ratio of vegetation cover (Kool et al., 2014); for native shrubs and grasses the ratio could be as low as 0.42 (Cavanaugh et al., 2011) and 0.64 (Sutanto et al., 2012), respectively.

4. Conclusion

It was possible to separate soil evaporation and plant transpiration components by using the portable evaporation chamber and a method of applying a rapid-acting herbicide to terminate photosynthetic activity while preserving soil moisture and plant canopy structure conditions. Both parameters were measured in response to varying LAI. At the same time the relative contributions of soil evaporation and plant transpiration in relation to the vegetation coverage (LAI) and a spectro-optical reflectance index- the NDVI were quantified. A significant relationship between the K_{cb} and the reflectance index (NDVI) was identified which suggests that the latter could be used in a non-water limiting condition to predict the former. The system proved capable of quantifying the soil evaporation over the range of LAI investigated (0–4), which in this present work exhibited a small, but significant increase with increasing LAI.

Acknowledgements

The authors wish to acknowledge the technical assistance of Derek Schneider in preparing the field sites, and Dr Malem McLeod (NSW Department of Primary Industries, Australia) for loan of the ET dome. One of us (MSA) wish to acknowledge receipt of a Strategic International Postgraduate Research Scholarship from the University of New England, Australia.

References

Alam, M.S., Lamb, D.W., Rahman, M.M., 2018. A refined method for rapidly determining the relationship between canopy NDVI and the pasture evapotranspiration coefficient. Comput. Electron. Agric. 147, 12–17. https://doi.org/10.1016/j.compag.2018.02.008.

Alam, M.S., Lamb, D.W., Rahman, M.M., Bradbury, R., McCarthy, C., 2017. Determining pasture evapotranspiration using active optical sensor derived normalized difference vegetation index. Paper Presented at the 1st Asian-Australasian Conference on Precision Pasture and Livestock Farming, Claudelands Conference and Exhibition Centre. https://doi.org/10.5281/zenodo.897037.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. FAO, Rome 300 (9) D05109.

Ashktorab, H., Pruitt, W.O., Paw, U.K.T., 1994. Partitioning of evapotranspiration using Lysimeter and micro-bowen-Ratio system. J. Irrig. Drain. Eng. 120 (2), 450–464. https://doi.org/10.1061/(ASCE)0733-9437(1994)120:2(450.

Branson, F., Miller, R.F., McQueen, I., 1976. Moisture relationships in twelve northern desert shrub communities near Grand Junction, Colorado. Ecology 57 (6), 1104–1124.

Brun, L.J., Kanemasu, E.T., Powers, W.L., 1972. Evapotranspiration from soybean and Sorghum fileds 1. Agron. J. 64 (2), 145–148.

Brunel, J.P., Walker, G.R., Dighton, J.C., Monteny, B., 1997. Use of stable isotopes of water to determine the origin of water used by the vegetation and to partition evapotranspiration. A case study from HAPEX-Sahel. J. Hydrol. 188–189, 466–481. https://doi.org/10.1016/S0022-1694(96)03188-5.

Cammalleri, C., Rallo, G., Agnese, C., Ciraolo, G., Minacapilli, M., Provenzano, G., 2013. Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard. Agric. Water Manag. 120, 89–97. https://doi.org/10.1016/j.agwat.2012.10.003.

Cavanaugh, M.L., Kurc, S.A., Scott, R.L., 2011. Evapotranspiration partitioning in semi-arid shrubland ecosystems: a two-site evaluation of soil moisture control on transpiration. Ecohydrology 4 (5), 671–681.

Choudhury, B.J., Monteith, J.L., 1988. A four-layer model for the heat budget of homogeneous land surfaces. Q. J. R. Meteorol. Soc. 114 (480), 373–398. https://doi.org/10.1002/qj.49711448006.

D'Urso, G., De Michele, C., Bolognesi, S.F., 2013. IRRISAT: the italian on-line satellite irrigation advisory service. Paper Presented at the EFITA-WCCA-CIGR Conference "Sustainable Agriculture Through ICT Innovation.", June 24–27.

Deckmyn, G., Impens, I., 1998. UV-B and PAR in a grass (Lolium perenne L.) canopy. Plant Ecol. 137 (1), 13–19.

Duchemin, B., Hadria, R., Erraki, S., Boulet, G., Maisongrande, P., Chehbouni, A., Escadafal, R., Ezzahar, J., Hoedjes, J., Kharrou, M., 2006. Monitoring wheat phenology and irrigation in Central Morocco: on the use of relationships between evapotranspiration, crops coefficients, leaf area index and remotely-sensed vegetation indices. Agric. Water Manag. 79 (1), 1–27.

Er-Raki, S., Chehbouni, A., Boulet, G., Williams, D.G., 2010. Using the dual approach of FAO-56 for partitioning ET into soil and plant components for olive orchards in a semi-arid region. Agric. Water Manag. 97 (11), 1769–1778. https://doi.org/10.1016/j.agwat.2010.06.009.

Er-Raki, S., Chehbouni, A., Guemouria, N., Duchemin, B.ı., Ezzahar, J., Hadria, R., 2007. Combining FAO-56 model and ground-based remote sensing to estimate water consumptions of wheat crops in a semi-arid region. Agric. Water Manag. 87 (1), 41–54.

Farahani, H.J., Howell, T.A., Shuttleworth, W.J., Bausch, W.C., 2007. Evapotranspiration: progress in measurement and modeling in agriculture. Trans. Asabe 50 (5), 1627–1638.

Ferretti, D., Pendall, E., Morgan, J., Nelson, J., Lecain, D., Mosier, A., 2003. Partitioning evapotranspiration fluxes from a Colorado grassland using stable isotopes: seasonal variations and ecosystem implications of elevated atmospheric CO 2. Plant Soil 254 (2), 291–303.

García García, J., Martínez-Cutillas, A., Romero, P., 2012. Financial analysis of wine grape production using regulated deficit irrigation and partial-root zone drying strategies. Irrig. Sci. 30 (3), 179–188. https://doi.org/10.1007/s00271-011-0274-4.

Gibson, J., Edwards, T., 2002. Regional water balance trends and evaporation--transpiration partitioning from a stable isotope survey of lakes in northern Canada. Global Biogeochem. Cycles 16 (2).

Good, S.P., Soderberg, K., Guan, K., King, E.G., Scanlon, T.M., Caylor, K.K., 2014. δ2H isotopic flux partitioning of evapotranspiration over a grass field following a water pulse and subsequent dry down. Water Resour. Res. 50 (2), 1410–1432.

Hornbuckle, J., Car, N., Christen, E., Stein, T., Williamson, B., 2009. Irrigation water management by satellite and SMS: a utilisation framework. Cooperative Research Centre for Irrigation Futures.

Jovanovic, N., Annandale, J., 1998. Measurement of radiant interception of crop canopies with the LAI-2000 plant canopy analyzer. South Afr. J. Plant Soil 15 (1), 6–13.

Kang, S., Gu, B., Du, T., Zhang, J., 2003. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. Agric. Water Manag. 59 (3), 239–254. https://doi.org/10.1016/S0378-3774(02)00150-6.

Kite, G., 2000. Using a basin-scale hydrological model to estimate crop transpiration and soil evaporation. J. Hydrol. 229 (1), 59–69. https://doi.org/10.1016/S0022-1694(99)00199-7.

Kool, D., Agam, N., Lazarovitch, N., Heitman, J.L., Sauer, T.J., Ben-Gal, A., 2014. A review of approaches for evapotranspiration partitioning. Agric. For. Meteorol. 184, 56–70. https://doi.org/10.1016/j.agrformet.2013.09.003.

Kool, D., Kustas, W., Ben-Gal, A., Lazarovitch, N., Heitman, J., Sauer, T., Agam, N., 2016. Energy and evapotranspiration partitioning in a desert vineyard. Agric. For. Meteorol. 218, 277–287.

Kristensen, K., 1974. Actual evapotranspiration in relation to leaf area. Nord. Hydrol. 5 (3), 173–182.

Lu, X., Liang, L.L., Wang, L., Jenerette, G.D., McCabe, M.F., Grantz, D.A., 2017. Partitioning of evapotranspiration using a stable isotope technique in an arid and high temperature agricultural production system. Agric. Water Manag. 179, 103–109.

https://doi.org/10.1016/j.agwat.2016.08.012.

Moran, M., Scott, R., Keefer, T., Emmerich, W., Hernandez, M., Nearing, G., Paige, G., Cosh, M., O'Neill, P., 2009. Partitioning evapotranspiration in semiarid grassland and shrubland ecosystems using time series of soil surface temperature. Agric. For. Meteorol. 149 (1), 59–72.

Neale, C., Jayanahi, H., Wright, J.L., 2003. Crop and irrigation water management using high resolution airborne remote sensing. Paper Presented at the 54th IES Meeting of the Internation Commission on Irrigation and Drainage (ICID) Workshop on Remote Sensing of ET for Large Regions.

Oke, T., 1987. Boundary Layer Climates. 1987. Methuen, London.

Penman, H.L., 1948. Natural evaporation from open water, bare soil and grass. Proc. R. Soc. Lond. A 193 (1032), 120–145.

Pons, T.L., Bergkotte, M., 1996. Nitrogen allocation in response to partial shading of a plant: possible mechanisms. Physiol. Plant. 98 (3), 571–577.

Pons, T.L., Jordi, W., Kuiper, D., 2001. Acclimation of plants to light gradients in leaf canopies: evidence for a possible role for cytokinins transported in the transpiration stream. J. Exp. Bot. 52 (360), 1563–1574.

Rahman, M., Lamb, D., Stanley, J., Trotter, M., 2014a. Use of proximal sensors to evaluate at the sub-paddock scale a pasture growth-rate model based on light-use efficiency. Crop Pasture Sci. 65 (4), 400–409.

Rahman, M., Stanley, J., Lamb, D., Trotter, M., 2014b. Methodology for measuring fAPAR in crops using a combination of active optical and linear irradiance sensors: a case study in Triticale (X Triticosecale wittmack). Precis. Agric. 15 (5), 532–542.

Rothfuss, Y., Biron, P., Braud, I., Canale, L., Durand, J.L., Gaudet, J.P., Richard, P., Vauclin, M., Bariac, T., 2010. Partitioning evapotranspiration fluxes into soil evaporation and plant transpiration using water stable isotopes under controlled conditions. Hydrol. Process. 24 (22), 3177–3194. https://doi.org/10.1002/hyp.7743.

Scanlon, T.M., Kustas, W.P., 2010. Partitioning carbon dioxide and water vapor fluxes using correlation analysis. Agric. For. Meteorol. 150 (1), 89–99. https://doi.org/10.1016/j.agrformet.2009.09.005.

Scanlon, T.M., Kustas, W.P., 2012. Partitioning evapotranspiration using an eddy covariance-based technique: improved assessment of soil moisture and land–atmosphere exchange dynamics. Vadose Zone J. 11 (3).

Scanlon, T.M., Sahu, P., 2008. On the correlation structure of water vapor and carbon dioxide in the atmospheric surface layer: a basis for flux partitioning. Water Resour. Res. 44 (10).

Schlesinger, W.H., Jasechko, S., 2014. Transpiration in the global water cycle. Agric. For. Meteorol. 189, 115–117.

Silcock, R., Wilson, D., 1982. The effects of leaf orientation on photosynthesis, transpiration and diffusive conductance of leaves of contrasting Festuca species. New Phytol. 90 (1), 27–36.

Sutanto, S., Wenninger, J., Coenders-Gerrits, A., Uhlenbrook, S., 2012. Partitioning of evaporation into transpiration, soil evaporation and interception: a comparison between isotope measurements and a HYDRUS-1D model. Hydrol. Earth Syst. Sci. 16 (8), 2605–2616.

Taylor, K., Griffith, C., Lefort, L., Gaire, R., Compton, M., Wark, T., Lamb, D., Falzon, G., Trotter, M., 2013. Farming the web of things. IEEE Intell. Syst. 28 (6), 12–19.

Trotter, M.G., Lamb, D.W., Donald, G.E., Schneider, D.A., 2010. Evaluating an active optical sensor for quantifying and mapping green herbage mass and growth in a perennial grass pasture. Crop Pasture Sci. 61 (5), 389–398. https://doi.org/10.1071/CP10019.

Wang, L., Good, S.P., Caylor, K.K., 2014. Global synthesis of vegetation control on evapotranspiration partitioning. Geophys. Res. Lett. 41 (19), 6753–6757.

Wang, L., Niu, S., Good, S.P., Soderberg, K., McCabe, M.F., Sherry, R.A., Luo, Y., Zhou, X., Xia, J., Caylor, K.K., 2013. The effect of warming on grassland evapotranspiration partitioning using laser-based isotope monitoring techniques. Geochim. Cosmochim. Acta 111, 28–38.

Wang, P., Yamanaka, T., 2014. Application of a two-source model for partitioning evapotranspiration and assessing its controls in temperate grasslands in central Japan. Ecohydrology 7 (2), 345–353.

Wen, X., Yang, B., Sun, X., Lee, X., 2016. Evapotranspiration partitioning through in-situ oxygen isotope measurements in an oasis cropland. Agric. For. Meteorol. 230, 89–96.

Wilcox, B., Seyfried, M., Breshears, D., Stewart, B., Howell, T., 2003. The water balance on rangelands. Encyclopedia of Water Science 791–794.

Williams, D.G., Cable, W., Hultine, K., Hoedjes, J.C.B., Yepez, E.A., Simonneaux, V., Er-Raki, S., Boulet, G., de Bruin, H.A.R., Chehbouni, A., Hartogensis, O.K., Timouk, F., 2004. Evapotranspiration components determined by stable isotope, sap flow and eddy covariance techniques. Agric. For. Meteorol. 125 (3), 241–258. https://doi.org/10.1016/j.agrformet.2004.04.008.

Zegada-Lizarazu, W., Berliner, P.R., 2010. Inter-row mulch increase the water use efficiency of furrow-irrigated maize in an arid environment. J. Agron. Crop. Sci. 197 (3), 237–248. https://doi.org/10.1111/j.1439-037X.2010.00451.x.

Zhang, B., Liu, Y., Xu, D., Zhao, N., Lei, B., Rosa, R.D., Paredes, P., Paço, T.A., Pereira, L.S., 2013. The dual crop coefficient approach to estimate and partitioning evapotranspiration of the winter wheat–summer maize crop sequence in North China Plain. Irrig. Sci. 31 (6), 1303–1316. https://doi.org/10.1007/s00271-013-0405-1.

Zhang, Y., Shen, Y., Sun, H., Gates, J.B., 2011. Evapotranspiration and its partitioning in an irrigated winter wheat field: a combined isotopic and micrometeorologic approach. J. Hydrol. 408 (3-4), 203–211.

Zhao, N., Liu, Y., Cai, J., Paredes, P., Rosa, R.D., Pereira, L.S., 2013. Dual crop coefficient modelling applied to the winter wheat–summer maize crop sequence in North China Plain: basal crop coefficients and soil evaporation component. Agric. Water Manag. 117, 93–105. https://doi.org/10.1016/j.agwat.2012.11.008.

Zhao, P., Li, S., Li, F., Du, T., Tong, L., Kang, S., 2015. Comparison of dual crop coefficient method and Shuttleworth–Wallace model in evapotranspiration partitioning in a vineyard of northwest China. Agric. Water Manag. 160, 41–56.

Zotarelli, L., Dukes, M., Morgan, K., 2010. Interpretation Of Soil Moisture Content To Determine Soil Field Capacity And Avoid Over-Irrigating Sandy Soils Using Soil Moisture Sensors. University of Florida Cooperation Extension Services AE460.