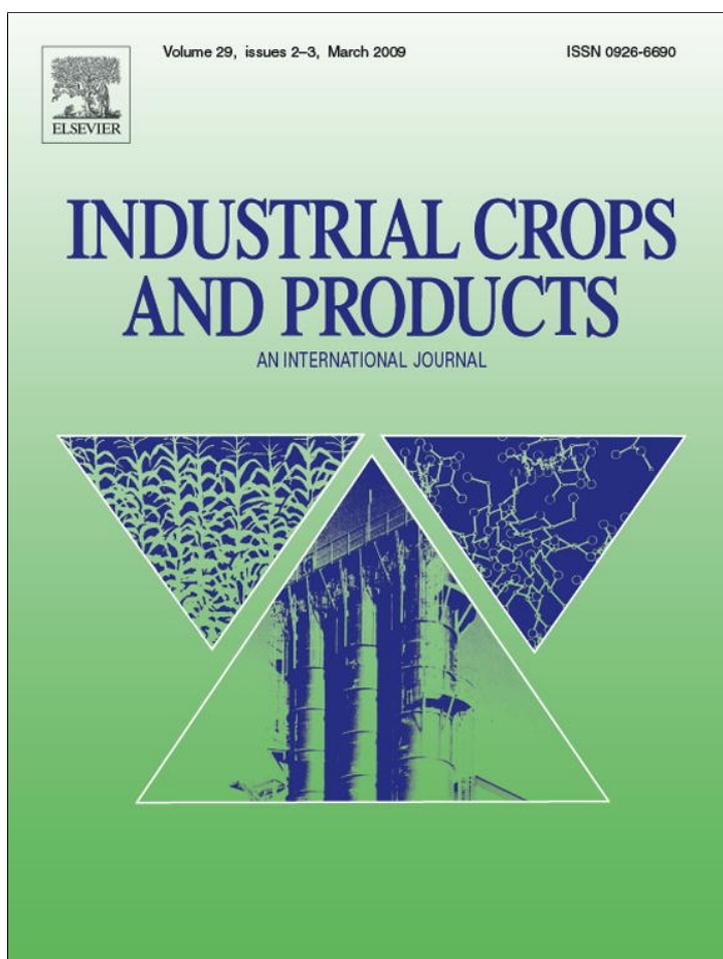


Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

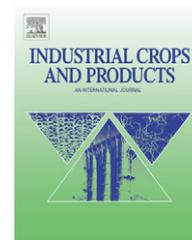
Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

<http://www.elsevier.com/copyright>



ELSEVIER

available at www.sciencedirect.comjournal homepage: www.elsevier.com/locate/indcrop

Evapotranspiration over a camelina crop at Maricopa, Arizona[☆]

A.N. French*, D. Hunsaker, K. Thorp, T. Clarke

U.S. Arid Land Agricultural Research Center, USDA/ARS, 21881 N. Cardon Lane, Maricopa, AZ 85238, USA

ARTICLE INFO

Article history:

Received 12 February 2008

Received in revised form

30 May 2008

Accepted 2 June 2008

Keywords:

Camelina

Evapotranspiration

Remote sensing

Thermal infrared

Irrigation

ABSTRACT

Evapotranspiration (ET) over an oilseed crop, *Camelina sativa*, was evaluated for an experimental plot in Maricopa, Arizona between December 2006 and April 2007. Camelina (cv. Robinson) was grown in a 1.3-ha field in a randomized design containing 32 plots replicated for four levels of water depletion: 40, 55, 65, and 75%. Six supplemental plots evaluated water stress with 85% soil water depletion. A surface energy balance model, utilizing meteorological and radiometric observations within the plots, was implemented to estimate latent heat fluxes from the camelina canopy at 15-min intervals during most of the growing season. The latent heat fluxes were then summed to produce daily estimates of ET. A distinct aspect of the model was the incorporation of canopy thermal infrared observations at 15 different locations, which allow plant water stress detection. The resulting ET values were compared with independent observations of soil water depletion, obtained from soil neutron probe profiles. Agreement on a plot-by-plot basis between modeled and observed ET values was very good, where root mean squared errors (RMSE) were usually less than 0.8 mm d^{-1} , $R^2 > 0.78$, and bias $< 0.76 \text{ mm d}^{-1}$. Average yield for the camelina crop was $1000 \pm 310 \text{ kg ha}^{-1}$. Average total oil content was $41.4 \pm 3.8\%$ by weight. Oil content was predicted by yield with fair accuracy where R^2 was 0.425 and RMSE was 2.36%. Correlation between resultant camelina yield and total ET was weak; the four main water depletion treatment plots showed no dependence of yield upon cumulative ET. The secondary water stress treatment plots, however, did show dependence, where a 20% reduction in cumulative ET resulted in a corresponding 24% reduction in yield. Hence seasonal camelina water minimally required 333–423 mm. The ET results showed that the surface energy balance is a feasible and valuable technique for monitoring crop water requirement over this potential oil seed crop. Further work is needed to characterize the relation between camelina yield and ET, including tests of different varieties and levels of fertilization.

Published by Elsevier B.V.

1. Introduction

Camelina sativa (L.) Crantz is an oil seed crop with thousands of years of cultivation (Schultze-Motel, 1979; Henriksen and Robinson, 1996) that is undergoing resurgent interest due to

its attractive oil characteristics and relatively low agronomic requirements. Camelina seeds have about 40% oil content and are high in unsaturated oils such as Omega 3 fatty acids (Putnam et al., 1993; Budin et al., 1995; Bonjean and Goffic, 1999; Zubr, 2003), offering a variety of culinary and

[☆] Mention of trade names or proprietary products in this article does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that may also be suitable.

* Corresponding author. Tel.: +1 520 316 6371; fax: +1 520 316 6330.

E-mail address: Andrew.French@ARS.USDA.GOV (A.N. French).

0926-6690/\$ – see front matter. Published by Elsevier B.V.

doi:10.1016/j.indcrop.2008.06.001

industrial applications (Putnam et al., 1993; Shukla et al., 2002; Fröhlich and Rice, 2005; Vollmann et al., 2007). Camelina has a short growing season (~80 days to maturity), has lower nitrogen requirements than the competitor crops canola and sunflower (Putnam et al., 1993), and can be used in mixed cropping systems for weed management (Saucke and Ackermann, 2006; Paulsen, 2007). Geographic effects upon yield have been reported by (Zubr, 2003; Gugel and Falk, 2006). Budin et al. (1995), Angelini et al. (1997), and Vollmann et al. (2007) discuss camelina oil yield and content.

Camelina also appears to be heat and drought tolerant (Putnam et al., 1993; Angelini et al., 1997), characteristics that have strong appeal for growers in arid lands. For the southwestern U.S.A. in particular, camelina may be a valuable alternative crop to wheat or cotton in the face of long-standing drought, urbanization and strong competition for tight water supplies. However, camelina has been commonly grown in rain fed environments, and guidance for irrigation schedules is sparse. In the face of this lack of knowledge, arid-land growers would likely have to rely upon irrigation experience gained from related oilseed crops such as rapeseed or lesquerella (Hunsaker et al., 1998). Clearly, in order for camelina to become economically viable in irrigated semi-arid environments that reliance needs to be replaced with knowledge specific to camelina.

One way to gain that knowledge is to grow camelina in experimental plots with variable irrigation levels and then to observe and estimate resulting evapotranspiration (ET) and yield values. Estimates for ET can be made from frequent observations of soil water throughout the growing season (Evet and Steiner, 1995; Hunsaker et al., 1998, 2005) and can establish irrigation needs for a specific location and soil type. By accounting for water depletions in the soil root zone, water losses from deep percolation, and water gains from irrigation and rainfall, ET over the crop can be estimated to better than 1 mm over daily to weekly time intervals. With some loss of accuracy, it is also possible to estimate ET by using crop coefficient/ET models such as FAO-56 (Allen et al., 1998) or by monitoring temporal changes in vegetation canopy densities (Hunsaker et al., 2007).

An alternative ET estimation approach that is generally applicable and has the potential to further reduce demanding field acquisition procedures is to estimate the surface energy balance using the equation:

$$LE = R_n - G - H \quad (1)$$

where the energy flux analog for ET, is LE the latent heat. LE is equivalent to net radiation at the surface (R_n) minus soil heat flux (G) and sensible heat flux (H). The assumed sign convention is for all values to be positive for incoming R_n and outgoing for G , H , and LE . Additional fluxes such as photosynthesis and canopy heat storage are usually small ($<10 \text{ W m}^{-2}$) at daily time steps and thus are neglected (Brutsaert, 1982). Benefits of the ET-energy balance approach include the ability to monitor crop ET at hourly, rather than daily, time steps and the ability to detect crop water stress (Jackson, 1981).

The objective of this report is to assess camelina ET from an energy balance perspective and to determine relationships between modeled and observed crop ET. Accordingly, results

from a 2006–2007-camelina crop planted in central Arizona are presented. First, the experimental plan is described, followed by a description of the energy balance methodology. Next, observations and modeled inputs and outcomes are reported. Lastly, ET retrievals from the energy balance approach are discussed with respect to ET observations based on soil water depletions.

2. The camelina 2007 Maricopa, AZ experiment

The camelina 2007 experiment, part of a 2-year project to investigate effective irrigation scheduling methodologies for camelina, was planted in November 2006 on a leveled 1.3-ha site (field 111) at the University of Arizona Maricopa Agricultural Center (MAC) (33°04'N, 111°58'W, 361 m MSL) in central Arizona, USA. Experimental objectives included establishment of camelina crop coefficients compatible with the ET/FAO-56 (Allen et al., 1998) guidelines, refinement of irrigation scheduling techniques utilizing observations of fractional crop cover (Hunsaker et al., 2005, 2007), and monitoring ET using surface energy balance estimates. The camelina cultivar 'Robinson', was broadcast planted at 8.2 kg ha^{-1} . The field soil was Casa Grande series (Typic Natrargids, fine-loamy, mixed, hyperthermic). Volumetric soil water at field capacity and wilting point for the uppermost 1 m are respectively 0.24 ± 0.04 and $0.12 \pm 0.01 \text{ m}^3 \text{ m}^{-3}$ (Post et al., 1988).

The 1.3-ha site, MAC field 111 (Fig. 1) contained 40 plots, where each plot measured 10.0 m east to west, and 17 m north to south. Flood irrigation was used for the camelina experiment with water supplied by 152-mm gated pipe (indicated by three east–west heavy lines in Fig. 1). Irrigation amounts were measured with an inline propeller-type flow meter. Field layout was similar to related ET experiments over cotton (Hunsaker et al., 2005) and wheat (French et al., 2007; Hunsaker et al., 2007) and included raised mid-field boardwalks (dashed lines in Fig. 1). The field design was based on the need to test ET effects due to different levels of maximum soil water depletion, need for bare soil end-member reference plots, and the need to evaluate ET over severely water stressed plants. Hence 32 plots (plots 11–18, 21–28, 31–38, and 41–48) were allocated for water depletion treatment tests, 2 plots were maintained as dry bare soil (plot 1) and wet bare soil (plot 3), and 6 plots were designated as water stress treatment plots (plots 2, 4, 5, 6, 7, and 8). The main irrigation treatments, designated by labels T1, T2, T3, T4, were assigned to plots in a randomized block design and were replicated eight times. The allowable maximum water depletions for these treatments respectively were 40, 55, 65, and 75%, allowing testing ET under a wide range of irrigation schedules. A fifth treatment, T5, was designed for severe water stress (maximum depletion of 85%), and was replicated six times and was not part of the block design. Layout size and field logistics did not allow testing ET effects due to fertilization, and consequently all planted plots received 50 kg N ha^{-1} . Additional nitrogen inputs were likely low, although nitrogen carryover from previous crops at the site was unknown. Average irrigation water nitrates were 12.0 ppm.

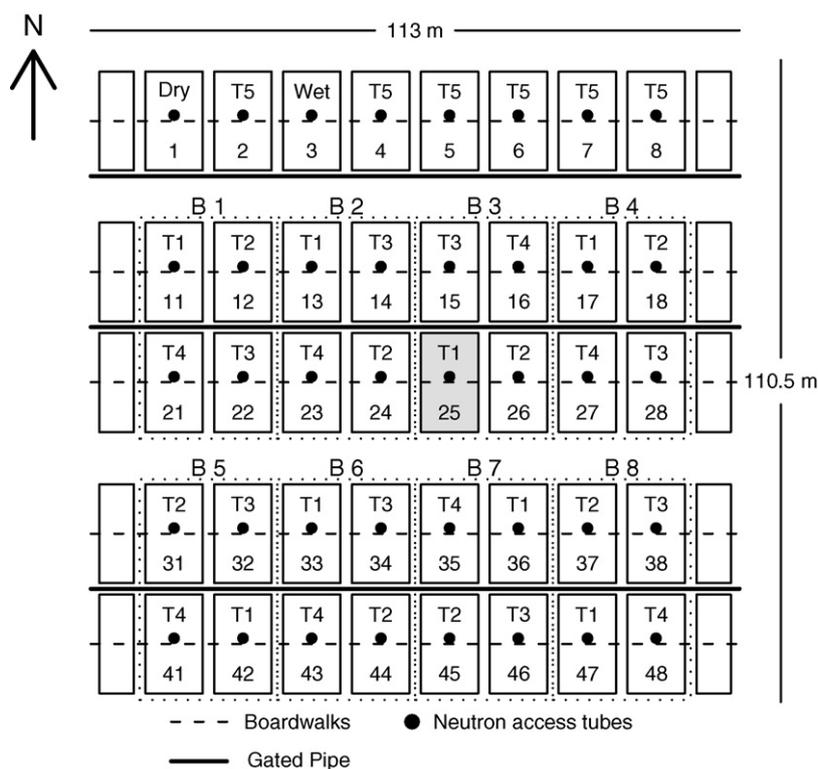


Fig. 1 – Plot design for the camelina experiment at Maricopa, Arizona. Each 10-m × 17-m plot is labeled by number at the bottom. Treatment identifiers (at the top of each plot) correspond to different water depletions: T1 at 40%, T2 at 55%, T3 at 65%, T4 at 75%, and T5 at 85%. Neutron access tube locations are indicated by solid circles. Mid-field boardwalks are shown by dashed lines. Block design is indicated by dotted lines with identifiers (B1–B8) at the top of each block. Water stress plots with 85% depletion (2, 4, 5, 6, 7, and 8) were not blocked. The gray shading locates the plot (25 in the 40% depletion treatment) with meteorological observations. Heavy lines indicate irrigation pipe locations.

Soil water data were collected by neutron probes for depths between 0.3 and 1.9 m. Near-surface soil water could have also been measured with the neutron probes by implementing depth control stands (Evelt et al., 2003), but for this experiment time-domain-reflectometry (TDR, Soil-Moisture Equipment Corp., Santa Barbara, CA) data was used instead for the soil water between the surface and 0.3 m. The neutron probe (Campbell Pacific Nuclear, Concord, CA) was calibrated to soils within MAC field 111. Volumetric retrieval accuracies were approximately $\pm 0.1 \text{ m}^3 \text{ m}^{-3}$ root mean squared error (RMSE). Combining neutron probe data with TDR data results in $\sim 7\%$ errors relative to lysimeter data (Evelt et al., 1993), meaning that plant water consumption, hence ET, could be accurately monitored.

Irrigation frequency was determined by measured soil water depletions and occurred at intervals between 9 days (T1, 40% depletion) and 88 days (T5, 85% depletion). ET estimates followed methods described in (Hunsaker et al., 2007) and (French et al., 2007), wherein soil water depletions for each plot were calculated by frequent monitoring of change in soil water. Based on seasonal soil water data, depletions up to 1.3-m depths occurred and were used to compute ET. However, a shallower effective rooting depth of 0.7 m (empirically selected during the early season) was used for irrigation scheduling computations to ensure plant growth.

Ground-based meteorological, thermal infrared (TIR), and photographic data were collected to help estimate the surface sensible heat fluxes and vegetative cover for selected plots. Meteorological and TIR data were continuously collected and block-averaged to 15-min intervals. Digital photographs were collected weekly at mid-field locations for each plot.

Meteorological data were collected at one central location (plot 25, T1, 40% depletion), with ancillary data collected at seven additional sites: three T1 (40% depletion) plots, 13, 36, and 42, and four T2 (55% depletion) plots, 12, 26, 37, and 44. These sites were used for surface energy balance computations. Instruments deployed were a solar radiometer (Eppley 8-48, The Eppley Laboratory, Inc. Newport, RI), eight net radiometers (Q7, REBS, Seattle, WA), 16 soil heat flux plates, two for each net radiometer site (HFT-3, REBS, Seattle, WA), two anemometers at 2-m height (12102D 3-cup photochopper, R.M. Young Co., Traverse City, MI), two wet-bulb/dry-bulb air temperatures (aspirated ceramic wick humidity gauges of US-ALARC design), and a TR525M tipping-bucket rain gauge (Texas Electronics, Dallas, TX).

The TIR data were collected from 15 locations at ~ 1 -m height and obliquely oriented to minimize soil radiation, maximize coverage of camelina canopy, but avoid viewing the sky. Since the camelina crop was broadcast planted, view angle and plant isotropy effects upon observed temperatures due to row structure were not a concern (Fuchs et al., 1967). Two types

of thermal infrared (IRT) thermometers were used: 15° field of view Everest 4000 infrared thermometers (Everest Inter-science, Inc., Tucson, AZ) and 36° field of view IRR-PN IRT's (Apogee Instruments, Inc., Logan, UT). All IRT instruments were calibrated against a reference blackbody in a constant-temperature room to accuracies better than 0.5°.

Weekly photographic data were collected on 13 occasions to document camelina canopy cover fractions. A Canon Powershot G2 camera was mounted at the end of a 2.6-m hand-carried aluminum pole, allowing nadir-views for all test plots with a field of view of ~1.6 m × 1.2 m. Pixel resolution was better than 1 mm at mid-season canopy heights (~0.5 m). Image data were originally collected in raw mode, then converted to three-band (red, green, and blue) TIFF format.

To compute fractional cover, various techniques were investigated, including supervised maximum likelihood classification, unsupervised isocluster classification, and green index classification. Based on qualitative comparisons, the best and most consistent results were obtained from a green/red ratio (VI_G):

$$VI_G = \frac{DN_G}{DN_R} \quad (2)$$

where DN_G and DN_R were the unadjusted digital numbers for the green and red bands, respectively. Because of the very fine spatial resolution of the camera, pixels were considered unmixed. This meant that fractional cover could be computed by empirically setting a threshold that best discriminates between soil and vegetation, and then summing pixel counts for each respective class. Smaller values of VI_G represent bare soil, while larger values represent camelina canopy. For the camelina experiment threshold values between 0.9 and 1.05 allowed good soil/camelina discrimination when the soil surface was dry and skies were clear. For simplicity a threshold of 1.0 was used. An example of that discrimination can be seen for Plot 32 (T3, 65% depletion) on January 23, when fractional cover was 50% (Fig. 2). The bimodal distribution for this example is strong, with small ambiguity between soil and camelina cover.

After camelina harvest on 19 April 2007, collected seeds were weighed and oven-dried to obtain dry matter yield. Yields were based only on samples taken from an ~6 m × 4 m area within the southern half of each plot since this portion closely corresponded to photographic cover surveys and was undisturbed by meteorological equipment. Each harvest area was individually marked and measured for total area. Due to loss of seed while harvesting, measurements from plot 28 were excluded from further analysis.

3. ET estimation and measurement

Although ET can be observed directly with aerodynamic measurements using the eddy covariance technique (Lenschow, 1986), such measurements are costly, complex to acquire, and because of variable wind directions, are sometimes not representative of fields of interest. Less complex ways to estimate ET at field scales using the energy balance approach do exist, however, and have been shown feasible using readily available meteorological observations. Methods, based upon the

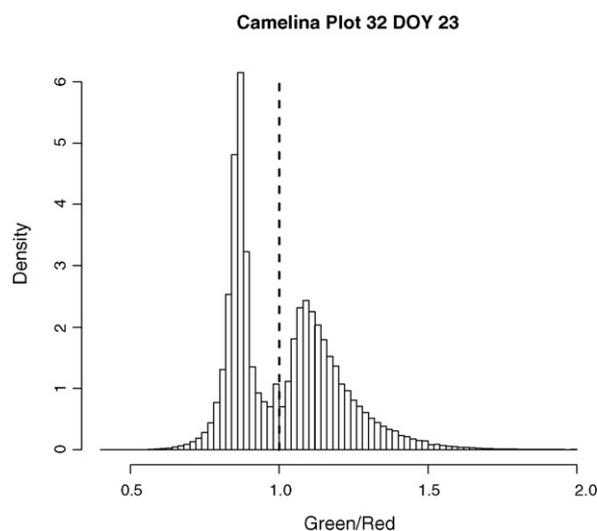


Fig. 2 – Histogram of green/red ratio for a nadir-view photograph of camelina plot 32 (65% depletion) on 23 January 2007. Estimated cover fraction was 50% using a classification threshold of 1.0 (dashed line). The bimodal distribution characterizes bare soil pixels with values less than the threshold and camelina pixels with greater values.

reference ET-crop coefficient approach have been described by Jensen (1968), Wright (1982), Doorenbos and Pruitt (1984), Allen et al. (1998), and Allen et al. (2005); these can provide effective ET estimates for standard conditions. For non-standard conditions, specifically for sparse or water stressed conditions, alternatives may be preferable. In addition to meteorological data, these use radiometric data in visible, near infrared, and thermal infrared bands. Early reports on these methods include those by Bartholic et al. (1970); Brown and Rosenberg (1973); Jackson et al. (1977); Soer (1980); Seguin and Itier (1983); Hatfield et al. (1984). More recent research extensively using remote sensing image data include Norman et al. (1995), Anderson et al. (1997), Bastiaanssen et al. (1998), Su (2002), French et al. (2003), and Colaizzi et al. (2006).

For the 2007 camelina experiment, an energy balance approach that considered standard and non-standard conditions was used and was based on the Two-Source Energy Balance model (TSEB) (Norman et al., 1995). TSEB incorporates observations of canopy cover, canopy height and composite surface temperatures to estimate soil evaporation separate from plant transpiration. Some implementations of TSEB utilize remote sensing image data, either from single-time-of-day observations (Anderson et al., 1997; Kustas et al., 2002; French et al., 2003) or for multiple times throughout the day (Mecikalski et al., 1999). Following Eq. (1), TSEB provides separate estimates for net radiation supplied to the soil and the vegetation using a multiscattering formulation described in Norman et al. (1995) and in Campbell and Norman (1998). Soil heat flux, G , is computed as constant fraction of net radiation at the soil surface. G could be more accurately modeled by considering modeled time of day and changing fractional cover, but considering that it is typically small at daily time steps this refinement was not included.

In the usual TSEB approach, the source of soil latent heat (LE_s) in TSEB was computed from:

$$LE_s = R_{n,s} - G - \rho c_p \left[\frac{T_s - T_a}{r_s + r_a} \right] \quad (3)$$

where $R_{n,s}$ is net radiation at the soil surface, ρ the moist air density, c_p the heat capacity at constant pressure, T_s and T_a the soil surface and air temperatures, respectively, and r_s and r_a are soil and aerodynamic heat flux resistances. TSEB estimates T_s from fractional weighting of observed composite temperatures, T_{surf} , (i.e., data containing both soil and vegetation contributions):

$$T_s = \left[\frac{T_{surf}^4 - fT_c^4}{1 - f} \right]^{1/4} \quad (4)$$

where f is fractional camelina cover and T_c is an assumed canopy temperature. For canopy latent heat (LE_c), TSEB relies upon fractional cover estimates and a Priestley–Taylor (Priestley and Taylor, 1972) constraint:

$$LE_c = f_g \alpha \left[\frac{\Delta}{\Delta + \gamma} \right] R_{n,c} \quad (5)$$

where f_g is fractional green vegetation, α the Priestley–Taylor parameter (nominally 1.26 for unstressed conditions), Δ the slope of the water vapor saturation curve, γ the psychrometric constant, and $R_{n,c}$ is net radiation intercepted by the canopy. Note that cover in Eq. (5), f_g , is a different specification from cover in Eq. (4), f , because non-green vegetation does not transpire. The practical effect of this distinction, however, was unimportant since non-green fractions only became significant after maturity, when irrigations had ceased.

The oblique IRT viewing configuration used for the camelina experiment, however, did not allow use of Eq. (3) when the fraction of visible soil was small (~20–30%) because radiometric temperature partitioning became unreliable. This unreliability is evident from inspection of Eq. (4); when f approaches 1, the denominator approaches 0 and makes the temperature partitioning error sensitive. Although such inaccuracies do not affect Eq. (5), they do affect total estimated ET and required model adjustment for cases where soil radiometric temperatures could not be observed. The chosen adjustment replaced Eqs. (3) and (5) when cover exceeded 70% by following a single-source latent heat estimation approach similar to those used for many years (Reginato et al., 1985). For dense camelina cover, only net radiation at the canopy level was considered and LE_c was computed using radiometric temperature observations as equivalent to canopy temperatures (T_c):

$$LE_c = R_{n,c} - \rho c_p \left[\frac{T_c - T_a}{r_a} \right] \quad (6)$$

Eq. (6) presumes small values of $R_{n,s}$, and no sensible heat flux from the soil, both of which seem reasonable given small gap fractions. Eq. (6) also removes objections to the use of the Priestley–Taylor parameter, although in doing so it presumes near equivalence between the radiometric temperature and

the theoretical aerodynamic temperature. Error encountered for their non-equivalence was discussed by Sun and Mahrt (1995), where a common outcome is an overestimation of sensible heat flux and a consequent underestimation of latent heat.

A critical component for energy balance modeling is fractional vegetation cover, which is used for partitioning radiometric temperature and net radiation between soil and vegetation components. Cover data are also important for sparse canopy while using Eq. (5). In previous work for wheat (French et al., 2007), this was most effectively done with airborne remote sensing imagery using visible and near infrared bands since this returned synoptic views under identical lighting conditions. Unfortunately for this study, airborne data were not available, meaning that it was not possible to consider plant density variability within each plot. However, nadir-view photographs were regularly collected along mid-field transect positions and provided unambiguous discrimination between sunlit camelina cover and soil background. Assuming close to uniform planting densities, these photographs were representative of conditions throughout each plot. Undoubtedly near infrared photography, rather than strictly visible photography, would have been preferable since spectral contrast between red and near infrared bands is large and much greater than seen between red and green bands. But in this instance, the photographic quality was very good and all observations were collected above the canopy, meaning that there was ample spectral contrast between dry background soil and camelina cover.

Having obtained LE estimates at discrete times throughout the day using either Eq. (5) for sparse cover or Eq. (6) for dense cover, daily ET (ET_{daily}), as water depth, was computed by summation:

$$ET_{daily} = \frac{1}{\lambda \rho} \sum_t LE_t \Delta t \quad (7)$$

where λ is the latent heat of vaporization of water, ρ density of liquid water, t the estimation time over a course of one day, and Δt is the estimation time interval. Note that in contrast to single-time-of-day estimates from remote sensing imagery, LE values in this method were derived from IRT data collected throughout the day, meaning that ET_{daily} estimates were obtained directly without resort to an evaporative fraction assumption used for previous studies (French et al., 2003, 2007).

4. Results

The 2007 camelina experiment was conducted from December 2006 to March 2007 where the crop was broadcast planted 6 November, initially irrigated 5 December, reached maturity by early March 2007 and harvested 18 April 2007. Camelina yields, unadjusted for moisture content, ranged between 1716 and 564 kg ha⁻¹ for non-water-stressed plots T1–T4.

Most meteorological and IRT instruments were installed by 26 January and collecting data until 15 March; this resulted in 49 days suitable for ET modeling. Soil water profiles from

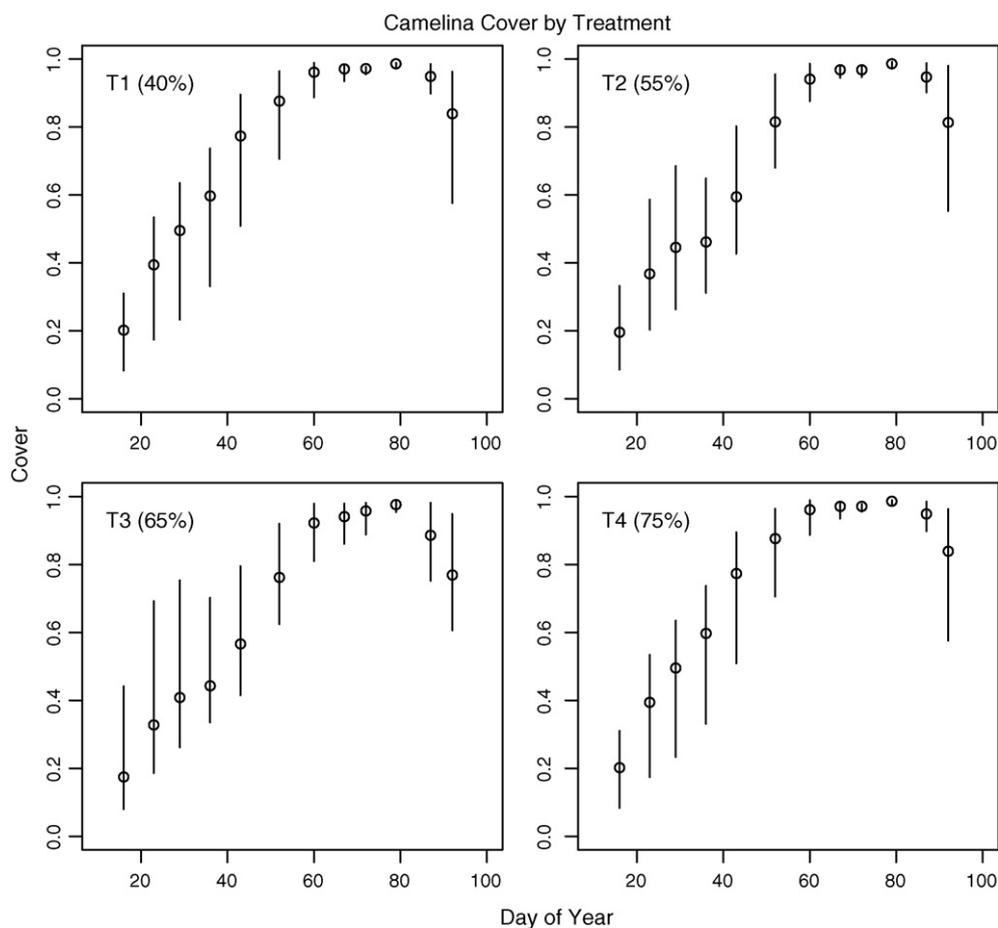


Fig. 3 – Camelina fractional cover as a function of time and treatment.

neutron profiling were collected at 3–18 day intervals with an average 6 day frequency, until 5 April when the camelina crop was sprayed with 3.4-l desiccant (Gramoxine, 378.6 ml ha⁻¹) prior to harvest.

4.1. Estimation of camelina canopy cover

Photographic cover estimates (Fig. 3) showed that the camelina canopy developed at similar rates regardless of irrigation treatment. On 16 January (DOY 16), mean cover was close to 20% in all cases, while full cover was achieved approximately by DOY 65. Closed canopies were maintained for 30 days, followed by rapid senescence by DOY 88. While some differences were observed between cover development for the different irrigation treatments – where T1 (40% depletion) cover increased most rapidly and T3 (65% depletion) least rapidly – the differences were small (~10%). Cover variations more significant than those imposed by irrigation treatments occurred within treatments themselves, evidenced by the wide cover range, ~20–40%, displayed during vegetative growth. These observations suggest that expansion of camelina canopy could have been controlled by factors other than soil water status. Another explanation, though unverifiable, is that despite uniform irrigation, near-surface soil water within plots were highly variable causing variable germination.

4.2. Estimation of ET

Applying a point-based energy balance estimation routine over 15 camelina plots provided daily energy balance estimates from 22 January to 9 March (DOY 22 to 68) and spanning most of the camelina growing season. The energy balance components R_n and ET_{daily} could be verified with field observations to have good accuracy and modest bias.

Consistency of R_n estimates was demonstrated from data collected over plot 12 (T2, 55% depletion) for DOY 40–60 (Fig. 4), where a collection of 971 samples of 15-min modeled net radiation values were compared with observations. In this instance the TSEB energy balance model predicted observations with RMSE of 23.3 W m⁻², a small overestimation bias of 6.0 W m⁻² and an R^2 value of 0.98. The illustrated pattern was repeated elsewhere for T1 (40% depletion) plots 13, 25, 36, and 42, and for T2 (55% depletion) plots 26 and 37, where higher R_n modeled values (>400 W m⁻²) tended to overestimate observations by ~30 W m⁻², but were also compensated by similar underestimations for lower R_n values (<100 W m⁻²).

Energy balance model results and observations also showed ET_{daily} values typically ranged from 2.0 to 6.5 mm d⁻¹ over most of the camelina growing season. Summary plots of ET_{daily} , grouped by irrigation treatment, are shown in Fig. 5, where energy balance estimates are indicated by solid lines and comparable reference ET_{daily} values obtained from the

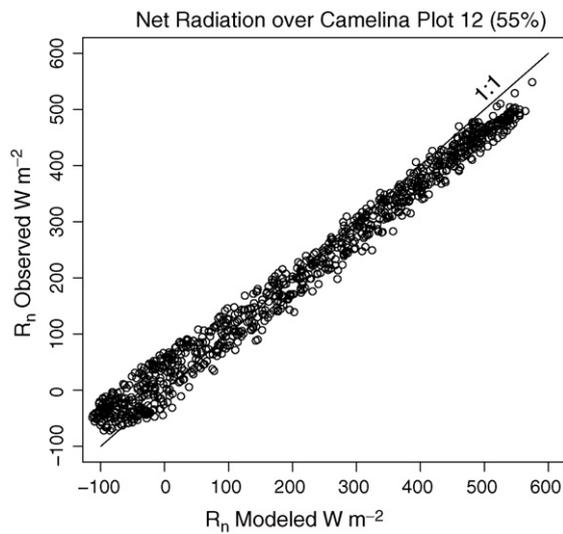


Fig. 4 – Observed vs. modeled daytime net radiation, R_n ($W m^{-2}$), over plot 12 (55% depletion) for the period 10 February to 2 March 2007. For 971 samples, RMSE was 22.5, and bias 4.1 ($W m^{-2}$).

FAO-56 Penman-Monteith equation are indicated by dashed lines. Filled squares indicate ET_{daily} derived from soil water depletion observations from the neutron probe surveys and not otherwise confounded by precipitation events. The open

circles are irrigation depths (referenced to the labels on the right hand side of each graph). The gray shading around the ET_{daily} lines for treatments T1 (40% depletion) and T2 (55% depletion) indicates the range of modeled estimates for each day. Only one IRT each was installed for treatments T3 (65% depletion) and T4 (75% depletion), hence the lack of shading for these graphs.

Qualitative assessment of Fig. 5 shows good seasonal agreement between ET estimates from the energy balance approach and those observed from soil water depletions. Energy balance estimates also show large day-to-day variations, otherwise undetected by the multi-day depletion data. In some instances (DOY 32, 41, and 52), these variations depart from the seasonal average by over $1 mm d^{-1}$. They are not associated with irrigation events but are associated with recent precipitation. In one instance (DOY 32), modeled ET indicated an unrealistic condensation event on the canopy. This outcome resulted from over-estimated canopy sensible heat and could have been avoided by setting a constraint to minimum allowable LE values. This was not done, however, in order to reveal model behavior under the widest range of meteorological and surface temperature conditions.

Quantitative assessment of modeled ET_{daily} values confirmed the good agreement, where values can be compared with soil water depletions in Tables 1-4, each of which summarizes ET estimates by plot and by day interval. Energy balance estimates were well correlated with observed soil

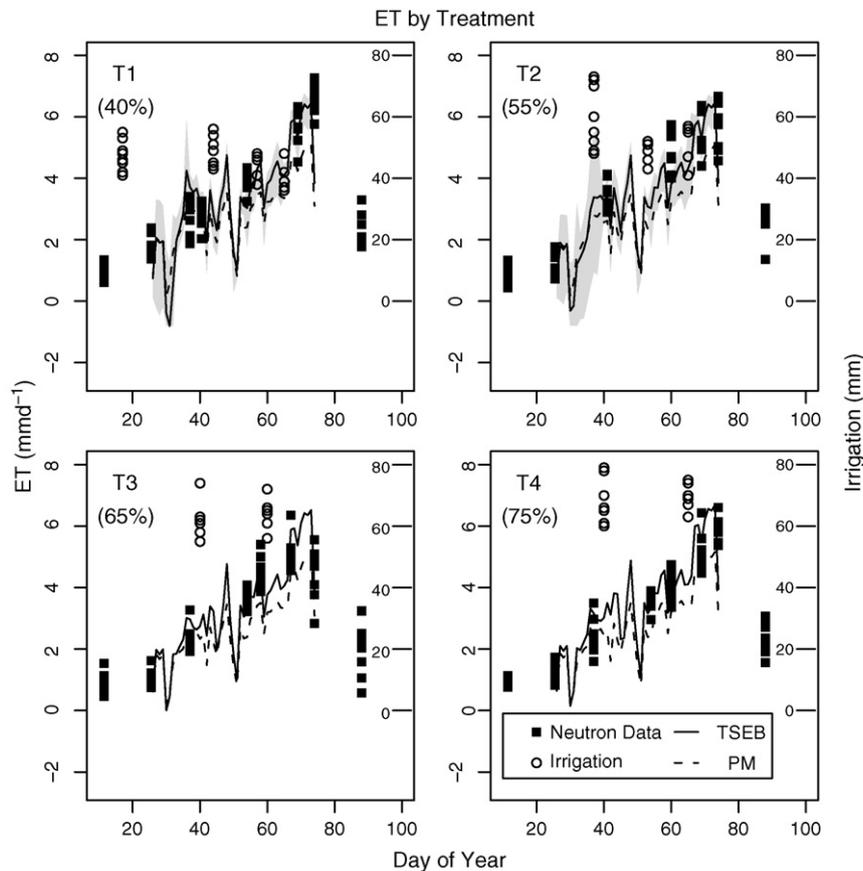


Fig. 5 – Evapotranspiration and irrigation over camelina treatments T1 (40%), T2 (55%), T3 (65%) and T4 (75%). Box symbols indicate ET ($mm d^{-1}$) derived from neutron data. Open circles indicate irrigation depths (mm).

Table 1 – ET estimation over T1 (40% depletion) treatment plots

DOY	Plot 13 (40%)		Plot 25 (40%)		Plot 36 (40%)		Plot 42 (40%)		Bias
	EB	SWD	EB	SWD	EB	SWD	EB	SWD	
23–28	1.32	1.68	1.80	1.82	1.94	1.37	2.19	2.38	0.00
36–38	4.06	2.97	4.13	3.10	4.57	2.63	4.55	3.30	1.33
39–42	3.18	2.83	3.42	2.70	3.57	2.78	3.64	2.88	0.65
52–56	4.31	3.88	4.59	4.08	4.70	3.24	4.73	3.72	0.85
68–70	5.89	5.60	6.29	6.33	6.39	5.23	6.43	6.10	0.43
71–77	5.83	6.46	6.18	7.26	6.24	6.21	6.25	5.76	–0.30
R ²	0.86		0.88		0.82		0.87		
RMSE	0.68		0.75		0.76		0.55		
Bias	0.19		0.18		0.99		0.61		

ET values are listed as water depths in mm d⁻¹ for each day of year (DOY) observation interval. Energy balance (EB) ET modeled values for plots within the treatment type are listed next to ET values derived from soil water depletion (SWD) values.

Table 2 – ET estimation over T2 (55% depletion) treatment plots

DOY	Plot 12 (55%)		Plot 26 (55%)		Plot 37 (75%)		Plot 44 (85%)		Bias
	EB	SWD	EB	SWD	EB	SWD	EB	SWD	
23–28	1.30	1.55	1.60	0.78	1.61	1.08	2.03	1.42	0.43
40–42	2.81	3.21	3.07	2.90	3.28	3.53	3.29	4.07	–0.31
57–63	5.16	5.67	5.51	4.63	5.58	4.10	5.66	5.46	0.51
68–70	5.90	6.37	6.29	5.07	6.34	5.10	6.39	6.20	0.55
71–77	5.83	6.67	6.19	5.97	6.21	4.91	6.27	6.44	0.13
R ²	0.99		0.94		0.88		0.92		
RMSE	0.16		0.51		0.55		0.60		
Bias	–0.49		0.66		0.86		0.01		

Energy balance (EB) ET modeled values in mm d⁻¹ over plots 12, 26, 37, and 44 for day of year (DOY) intervals are listed next to ET values derived from soil water depletion (SWD) values.

water depletions, with RMSE usually better than 0.8 mm d⁻¹. R² values were high (0.78 or better) with high significance ($p < 0.07$) for all treatments. Relative to SWD values, modeled ET data mostly had small positive bias (<0.76 mm d⁻¹) when compared plot-by-plot. Bias by day, was also small, typically 0.5 mm d⁻¹ and with no systematic change through the growing season.

4.3. Camelina yield

Camelina seeds, harvested on 19 April 2007, were collected plot-by-plot, then weighed prior to and after oven-drying. Average moisture content, estimated from 25 g seed samples from 31 plots (where plot 28 (T3, 65% depletion) had to be excluded due to seed loss during harvest), was 4.15 ±

Table 3 – ET estimation over a T3 (65% depletion) treatment plot

DOY	Plot 15 (65%)		Bias
	EB	SWD	
23–28	1.55	1.15	0.40
36–38	3.53	1.97	1.56
52–56	4.52	3.94	0.58
57–59	5.14	4.67	0.47
64–70	5.56	5.14	0.42
71–77	6.12	4.09	2.03
R ²	0.78		
RMSE	0.75		
Bias	0.91		

Energy balance (EB) ET modeled values in mm d⁻¹ over plot 15 for day of year (DOY) intervals are listed next to ET values derived from soil water depletion (SWD) values.

Table 4 – ET estimation over a T4 (75% depletion) treatment plot

DOY	Plot 16 (75%)		Bias
	EB	SWD	
23–28	1.60	0.82	0.78
36–38	3.72	2.07	1.65
52–56	4.61	3.62	0.99
57–59	5.50	4.46	1.04
64–70	6.32	4.93	1.39
71–77	6.21	5.47	0.74
R ²	0.95		
RMSE	0.39		
Bias	1.10		

Energy balance (EB) ET modeled values in mm d⁻¹ over plot 16 for day of year (DOY) intervals are listed next to ET values derived from soil water depletion (SWD) values.

0.22% after 5 days of drying at 70.0°C. Average dry seed yield was $1004 \pm 310 \text{ kg ha}^{-1}$, consistent with results reported by (Putnam et al., 1993), but considerably lower than mentioned elsewhere. For example, Vollmann et al. (2007) report yields ranging between 1574 and 2248 kg ha^{-1} . Contrary to expectation, no significant yield response to irrigation treatments was found other than for water stress test T5 (85% depletion) plots 2, 4, 5, 6, 7, and 8. Yield response was tested for two factors and one covariant: water depletion treatment effects [T1 (40%), T2 (55%), T3 (65%), and T4 (75%)], block design (four plots per block), and plant stand density. Plant densities, measured one time on 10 January 2007, for field 111 were $106 \pm 23 \text{ plants m}^{-2}$. Reasons for lower yields at Maricopa are unknown but could be due to the selected variety, or due to lower nitrogen levels. In the latter case, 50 kg ha^{-1} was supplied, whereas levels up to 100 kg ha^{-1} have been proposed as optimal (Zubr, 1997). Total oil content, measured with a Bruker Mini-spec NMR Analyzer MQ20, was $41.4 \pm 3.8\%$ by weight. Average total oil was comparable to values mentioned by Budin et al. (1995); Zubr (2003); Vollmann et al. (2007) and substantially greater than the 27–33% reported by Angelini et al. (1997) for drought-stressed plantings.

The relationship between oil content and yield showed moderate correlation (Fig. 6). Using results from plots within irrigation treatments T1 (40%)–T4 (75%), and excluding plot 28 (T3, 65%) due to seed loss, oil content could be predicted from dry matter yield with an R^2 of 0.425 and RMSE of 2.36%. This correlation exists despite the poor relationship between yield and irrigation treatment, meaning that forecast of crop productivity could be made prior to harvest if mid-season seed estimates were available.

5. Discussion

Outcomes from a 2007 Maricopa experiment showed that ET from the oil-seed crop camelina can be estimated within

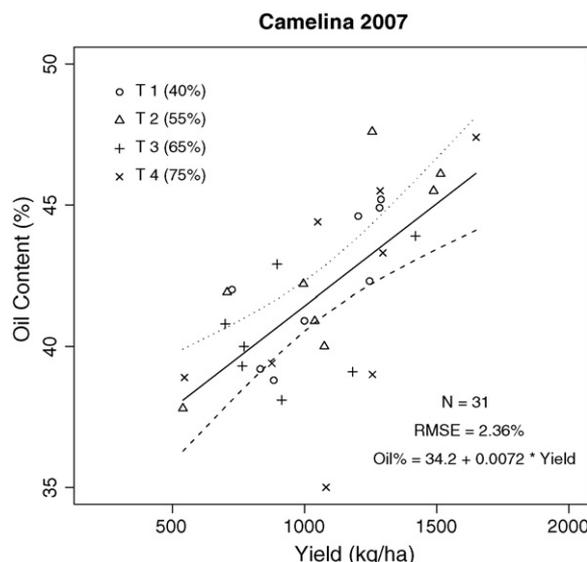


Fig. 6 – Camelina oil content (%) vs. dry matter yield (kg ha^{-1}).

1.1 mm d^{-1} accuracy for most cover conditions using an energy balance approach. The chosen method, TSEB, assessed the four main energy flux components, R_n , G, H, and LE in 15-min intervals and summed the results to daily time steps. Net radiation was estimated with 4% bias, meaning that subsequent modeling of sensible and latent heat fluxes could be meaningfully estimated. Considering both day and night energy fluxes meant that G estimation accuracy was not important. Consequently, remaining errors were apportioned between the turbulent flux components H and LE.

For most of the growing season, surface temperature data represented only camelina canopy surfaces meaning that the energy balance model provided little or no information about

Table 5 – Total camelina ET, organized by treatment, between 23 January and 18 March 2007

									Mean	SD
T1 (40% depletion)										
Plot	11	13	17	25	33	36	42	47		
Depth	267	285	284	308	319	265	275	323	291	23
T2 (55% depletion)										
Plot	12	18	24	26	31	37	44	45		
Depth	309	253	265	258	239	245	293	309	271	28
T3 (65% depletion)										
Plot	14	15	22	28	32	34	38	46		
Depth	240	234	261	NA	268	242	233	279	251	18
T4 (75% depletion)										
Plot	16	21	23	27	35	41	43	48		
Depth	236	264	255	233	247	276	256	244	251	14
T5 (85% depletion)										
Plot	2	4	5	6	7	8				
Depth	229	204	213	193	197	168			201	21

Depth values shown are cumulative soil water depletions (mm) in each plot. Mean and standard deviation (SD) ET values are shown for the five treatment types.

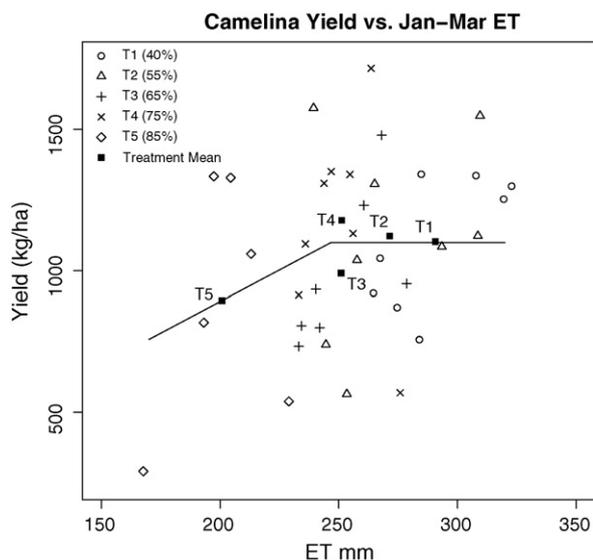


Fig. 7 – Camelina yield (kg ha^{-1}) vs. cumulative ET (mm) for the period 23 January to 18 March 2007.

soil-sourced energy fluxes. Hence subsequent modeling over full canopy cover neglected soil evaporation; based on ET comparisons with soil water depletions, this neglect appeared to be non-consequential. An associated benefit of estimating ET using canopy temperatures only was the avoidance of the Priestley–Taylor parameterization, otherwise utilized for sparse canopies. Although this single-source approach then became susceptible to errors caused by non-equivalence between aerodynamic and radiometric temperatures, it did not require adjustment to the $PT \alpha$ parameter for water stressed or strongly advective conditions in arid environments.

Using the camelina results as a preliminary guide to irrigation requirements for the crop in the central Arizona environment suggests that seasonal water consumption of camelina ranged between 333 and 423 mm. This range was based on the range of cumulative ET between 23 January and 18 March, 233 and 323 mm, plus early-season applications ~ 100 mm (Table 5). By comparison, seasonal water consumption at optimal yield for another oil seed crop grown in Arizona, *Lesquerella fendleri*, was 668 mm (Hunsaker et al., 1998). As seen in Fig. 7, dry seed yield was apparently independent of water schedules provided by the main treatment types [T1 (40%), T2 (55%), T3 (65%) and T4 (75%)]. There was significant drop in yield only where the crop experienced severe water deficits in treatment T5 (85% depletion). In that case, 168–229 mm, about 75% of mean applications for non-stressed plots, was applied. Note that the progression of mean values for the treatments (indicated by solid boxes in Fig. 7) mostly agrees with expectations where a regular progression of mean ET values follows designed water depletions. The main exception occurs between T3 (65%) and T4 (75%) treatments where there was little differentiation between applied irrigations, a consequence of experimental logistics and the necessity for scheduling irrigations during regular work days. The resulting mean yield difference, 187 kg ha^{-1} , may be representative of experimental variability for a fixed irrigation amount of

251 mm. Because of this large yield variability, results from this experiment are unfortunately insufficient for defining yield response. Why significant variability within plots occurred is unknown but could be related to large variability in near-surface soil water, uneven availability of nitrogen and possibly large variations in planting densities otherwise unrecognized by field photography. Experience at Maricopa, as well as elsewhere (Angelini et al., 1997), shows that sufficient and timely deliver of water are critical for yields on the order of 1000 kg ha^{-1} . Conceptually, the relationship observed in 2007 was a bilinear response function (Fig. 7), whereby a minimum seasonal water requirement for the Robinson camelina variety was 250 mm. Irrigation amounts greater than this amount provided no yield benefit, while lesser amounts (demonstrated for T5 (85%) treatment plots) reduced camelina seed yield by as much as 76%.

6. Conclusions

An experiment testing the ability to monitor water consumption and irrigation requirements for an oil seed plant, camelina, was conducted in central Arizona from December 2006 to April 2007. Results from modeling the surface energy balance using observations of canopy radiometric surface temperatures, readily available meteorological data, and nadir-view photography, showed agreement within 1.1 mm d^{-1} of independently obtained ET observations based on soil water depletions. This shows that energy balance modeling is a feasible and potentially valuable method for scheduling irrigations in arid environments. The experiment also showed that seed and oil yield were weakly correlated with ET for seasonal water supplied between 250 and 290 mm for camelina planted at 8.2 kg ha^{-1} . Future work will investigate correlation between yields and water management for different camelina varieties and considering multiple levels of fertilization.

Acknowledgments

The camelina experiment would not have been possible without the dedicated support provided by Suzette Maneely, Don Powers, Bill Luckett, and Diaa Elshikha. This work also would not have been possible without the support of the Maricopa Agricultural Center, University of Arizona. In particular we thank Bob Roth, Greg Main, and Clinton Jones for their assistance.

REFERENCES

- 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, Food and Agriculture Organization of the United Nations.
- Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., Snyder, R.L. (Eds.), 2005. The ASCE Standardized Reference Evapotranspiration Equation. American Society of Civil Engineers, prepared by Task Committee on Standardization of Reference Evapotranspiration of the Environmental and Water Resources Institute of the American Society of Civil Engineers.

- Anderson, M., Norman, J., Diak, G., Kustas, W., Mecikalski, J., 1997. A two-source time-integrated model for estimating surface fluxes from thermal infrared satellite observations. *Remote Sens. Environ.* 60, 195–216.
- Angelini, L.G., Moscheni, E., Colonna, G., Belloni, P., Bonari, E., 1997. Variation in agronomic characteristics and seed oil composition of new oilseed crops in central Italy. *Ind. Crops Prod.* 6, 313–323.
- Bartholic, J., Namken, L., Wiegand, C., 1970. Combination Equations Used to Calculate Evaporation and Potential Evaporation. *Tech. Re 41-170, USDA-ARS-Bull.*, 14 pp.
- Bastiaanssen, W., Menenti, M., Feddes, R., Holtslag, A., 1998. A remote sensing surface energy balance algorithm for land (SEBAL) 1. Formulation. *J. Hydrol.* 212/213, 198–212.
- Bonjean, A., Goffic, F.L., 1999. La cameline- *Camelina sativa* (L.) Crantz: une opportunité pour l'agriculture et l'industrie européennes. *Oleagineux Corps gras Lipides* 6 (1), 28–34.
- Brown, K., Rosenberg, N., 1973. A resistance model to predict evapotranspiration and its application to a sugar beet field. *Agron. J.* 65, 341–347.
- Brutsaert, W., 1982. Evaporation into the atmosphere: theory, history and applications. D. Reidel Pub. Co., Dordrecht, Holland.
- Budin, J.T., Breene, W.M., Putnam, D.H., 1995. Some compositional properties of camelina (*Camelina sativa* L. Crantz seeds and oils. *J. Am. Oil Chem. Soc.* 72 (3), 309–315.
- Campbell, G.S., Norman, J.M., 1998. An introduction to environmental biophysics, 2nd ed. Springer-Verlag.
- Colaizzi, P., Evett, S., Howell, T., 2006. Comparison of five models to scale daily evapotranspiration from on-time-of-day measurements. *Trans. ASABE* 49 (5), 1409–1417.
- Doorenbos, J., Pruitt, W., 1984. Guidelines for predicting crop water requirements. 24. Food and Agriculture Organization of the United Nations, Rome.
- Evett, S., Steiner, J., 1995. Precision of neutron scattering and capacitance type soil water content gauges from field calibration. *Soil Sci. Soc. Am. J.* 59 (4), 961–968.
- Evett, S., Tolk, J., Howell, T., 2003. A depth control stand for improved accuracy with the neutron probe. *Vadose Zone J.* 2, 642–649.
- Evett, S., Howell, T., Steiner, J., Cresap, J., 1993. Evapotranspiration by soil water balance using tdr and neutron scattering. In: *Proceedings of the Management of Irrigation and Drainage Systems*. ASCE Irrigation and Drainage Division, Reston, VA, pp. 914–921.
- French, A.N., Schmugge, T.J., Kustas, W.P., Brubaker, K.L., Prueger, J., 2003. Surface energy fluxes over El Reno, Oklahoma, using high-resolution remotely sensed data. *Water Resour. Res.* 39 (6), 1164.
- French, A., Hunsaker, D., Clarke, T., Fitzgerald, G., Luckett, W., Pinter Jr., P.J., 2007. Energy balance estimation of evapotranspiration for wheat grown under variable management practices in Central Arizona. *Trans. ASABE* 50 (6), 2059–2071.
- Fröhlich, A., Rice, B., 2005. Evaluation of *Camelina sativa* as a feedstock for biodiesel production. *Ind. Crops Prod.* 21, 25–31.
- Fuchs, M., Kanemasu, E., Kerr, J., Tanner, C., 1967. Effect of viewing angle on canopy temperature measurements with infrared thermometers. *Agron. J.* 59, 494–496.
- Gugel, R., Falk, K., 2006. Agronomic and seed quality evaluation of *Camelina sativa* in western Canada. *Can. J. Plant Sci.* 86 (4), 1047–1058.
- Hatfield, J., Reginato, R., Idso, S., 1984. Evaluation of canopy temperature-evapotranspiration models over various crops. *Agric. For. Meteorol.* 32, 41–53.
- Henriksen, P.S., Robinson, D., 1996. Early iron age agriculture: archaeobotanical evidence from an underground granary at Overbygaard in northern Jutland, Denmark. *Veget. Hist. Archaeobot.* 5, 1–11.
- Hunsaker, D., Nakayama, F., Dierig, D., Alexander, W., 1998. Lesquerella seed production: water requirement and management. *Ind. Crops Prod.* 8, 167–182.
- Hunsaker, D.J., Barnes, E.M., Clarke, T.R., Fitzgerald, G.J., Pinter Jr., P.J., 2005. Cotton irrigation scheduling using remotely-sensed and FAO-56 basal crop coefficients. *Trans. ASAE* 22 (4), 1395–1407.
- Hunsaker, D.J., Fitzgerald, G.J., French, A.N., Clarke, T.R., Pinter Jr., P.J., 2007. Wheat irrigation management utilizing multispectral crop coefficients. I. Crop evapotranspiration prediction. *Trans. ASABE* 50 (6).
- Jackson, R., 1981. Canopy temperature and crop water stress. In: Hillel, D. (Ed.), *Advances in Irrigation*, vol. 1. Academic Press, New York, USA, pp. 43–85.
- Jackson, R., Reginato, R., Idso, S., 1977. Wheat canopy temperature: a practical tool for evaluating water requirements. *Water Resour. Res.* 13, 651–656.
- Jensen, M., 1968. Water consumption by agricultural plants. In: Kozlowski, T. (Ed.), *Water Deficits and Plant Growth*, vol. II, Chapter 1. Academic Press, NY, pp. 1–22.
- Kustas, W., Norman, J., Schmugge, T., Anderson, M., 2002. Mapping surface energy fluxes with radiometric temperature. In: Quattrochi, D., Luvall, J. (Eds.), *Thermal Remote Sensing in Land Surface Processes*, Chapter 7. CRC Press, Boca Raton, Florida, USA, pp. 205–253.
- Lenschow, D., 1986. Probing the Atmospheric Boundary Layer. American Meteorological Society, Boston, MA.
- Mecikalski, J., Diak, G., Anderson, M., Norman, J., September 1999. Estimating fluxes on continental scales using remotely sensed data in an atmospheric-land exchange model. *J. Appl. Met.* 38 (9), 1352–1369.
- Norman, J., Kustas, W., Humes, K., 1995. A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. *Agric. For. Meteorol.* 77, 263–293.
- Paulsen, H.M., 2007. Mischfruchtanbausteme mit Ölpflanzen im ökologischen Landbau 1. Ertragsstruktur des Mischfruchtanbaus von Leguminosen oder Sommerweizen mit Leindotter (*Camelina sativa* L. Crantz) [Organic mixed cropping systems with oilseeds 1. yields of mixed cropping systems of legumes or spring wheat with false flax (*Camelina sativa* L. Crantz)]. *Landbauforschung Völkenrode* 57 (1), 107–117.
- Post, D., Mack, C., Camp, P., Sulliman, A., 1988. Mapping and characterization of the soils of the University of Arizona, Maricopa Agricultural Center. In: *Proceedings of the Hydrology and Water Resources in Arizona and the Southwest*, Tucson, Arizona. The University of Arizona, pp. 49–60.
- Priestley, C., Taylor, R., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weath. Rev.* 100, 81–92.
- Putnam, D., Budin, J., Field, L., Breene, W., 1993. Camelina: a promising low-input oilseed. In: Janick, J., Simon, J. (Eds.), *New Crops, Exploration, Research and Commercialization*, Proceedings of the Second National Symposium. Indianapolis, October 6–9, 1991. John Wiley & Sons, Inc., New York, pp. 314–322.
- Reginato, R., Jackson, R., Pinter Jr., P.J., 1985. Evapotranspiration calculated from remote multispectral and ground station meteorological data. *Remote Sens. Environ.* 18, 75–89.
- Saucke, H., Ackermann, K., 2006. Weed suppression in mixed cropped grain peas and false flax (*Camelina sativa*). *Weed Res.* 46, 453–461.
- Schultze-Motel, J., 1979. Die Anbaugeschichte des leindotters, *Camelina sativa* (L.) Crantz. *Archaeo-Physika* 8, 267–281.

- Seguin, B., Itier, B., 1983. Using midday surface temperature to estimate daily evaporation from satellite thermal IR data. *Int. J. Remote Sens.* 4, 371–383.
- Shukla, V., Dutta, P., Artz, W., 2002. Camelina oil and its unusual cholesterol content. *J. Am. Oil Chem. Soc.* 79 (10), 965–969.
- Soer, G., 1980. Estimation of regional evapotranspiration and soil moisture conditions using remotely sensed crop surface temperatures. *Remote Sens. Environ.* 9, 27–45.
- Su, Z., 2002. The surface energy balance system (SEBS) for estimation of the turbulent heat fluxes. *Hydrol. Earth Sci.* 6 (1), 85–99.
- Sun, J., Mahrt, L., 1995. Determination of surface fluxes from the surface radiative temperature. *J. Atmos. Sci.* 52, 1096–1106.
- Vollmann, J., Moritz, T., Kargl, C., Baumgartner, S., Wagentristsl, H., 2007. Agronomic evaluation of camelina genotypes selected for seed quality characteristics. *Ind. Crops Prod.* 26, 270–277.
- Wright, J., 1982. New evapotranspiration crop coefficients. *J. Irrig. Drain. Div. ASCE* 108 (IR1), 57–74.
- Zubr, J., 1997. Oil-seed crop: *Camelina sativa*. *Ind. Crops Prod.* 6, 113–119.
- Zubr, J., 2003. Qualitative variation of *Camelina sativa* seed from different locations. *Ind. Crops Prod.* 17, 161–169.