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Quantifying variability in field-scale evapotranspiration measurements in an irrigated agricultural region under advection

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Abstract This study compares evapotranspiration (ET) measurements from eddy covariance (EC), lysimetry (LY), and water balance using a network of neutron probe (NP) sensors and investigates the role of within-field variability in the vegetation density in explaining the differences among the various techniques. Measurements were collected over irrigated cotton fields during a period of rapid crop growth under advective conditions. Using NP-based ET estimates as reference, differences in cumulative ET measurements from the EC systems and NP ranged between 2 and 14 %, while differences between LY and NP ranged from 22 to 25 %. The discrepancy in the ET between the three methods was largely attributed to variations in vegetation cover within the source areas of the sensors, which was reliably assessed using high-resolution remote sensing imagery. This analysis indicates that the source area contributing to the measurements must be considered, even in instances where one might consider field conditions uniform. Consequently, differences in measured ET require accounting for variability of vegetation cover conditions in measurement source areas, particularly when used for model validation. This point concerning model validation is exemplified by the difference in performance of a thermal-based energy balance model in estimating ET evaluated using LY versus EC measurements.

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Introduction

In the Texas High Plains (THP), a semiarid region where there is extensive irrigated agriculture, it is projected that the depleted groundwater resources will be unable to support irrigation within the next 30 years (Scanlon et al. 2012). Since agriculture is the largest consumer of fresh water, monitoring water use, irrigation, and other agricultural practices at the field scale is prerequisite for managing water resources effectively. This is because changes in both water use and land cover occur at the field scale and therefore need to be monitored at the same resolution (Anderson et al. 2012).

Remote sensing is the only technology that can provide the spatially continuous and temporally consistent measurements of surface states and conditions (e.g., surface temperature and vegetation cover) that are used to monitor evapotranspiration (ET) at field to regional scale. A wide variety of remote sensing-based models for estimating ET thus have been developed (see review by Kalma et al. 2008). Model output of ET is typically evaluated with ground-based measurements using micrometeorological techniques, such as the Bowen ratio and eddy covariance (EC) methods, or via mass balance techniques, such as lysimetry.

The EC method is susceptible to a range of errors and uncertainties, many of which manifested in the so-called energy balance closure issue (Foken 2008), where the available energy, defined as net radiation (R_n) less soil heat flux (G), exceeds the sum of the sensible (H) and latent (λE) heat fluxes, thus invalidating the energy balance equation:

$$R_n - G = H + \lambda E \quad (1)$$

A recent overview of past studies by Leuning et al. (2012) points to a variety of factors affecting energy balance closure including instrument alignment, the reliability of the measurements of the radiation and heat storage terms, and advective flux divergence. Other recent papers have also pointed to errors in the measurement of vertical wind velocity when using nonorthogonal sonic anemometers (Kochendorfer et al. 2012; Frank et al. 2013), the development of mesoscale circulations as a result of landscape heterogeneity that are not captured by local EC observations (Stoy et al. 2013), and heat storage within the canopy, which has been shown to account for more than 5 % of the available energy for corn and soybeans under peak biomass conditions (Meyers and Hollinger 2004).

Mass balance techniques provide a measurement of ET as a residual of the water balance equation applied to a specified control volume of soil according to

$$\mathrm{ET} = I + P - F - R - \Delta S \quad (2)$$

where I and P are inputs to the control volume from irrigation and precipitation, respectively, F is the net horizontal or vertical flux from the control volume, R is runoff, and ΔS is the change in storage within the control volume. Water balance methods make use of weighing lysimeters (LY), soil coring, or neutron probe (NP) measurements to determine the change in soil water storage in order to solve for ET following Eq. (2). Errors in any of the terms on the right-hand side of Eq. (2) will propagate into the estimates of ET. The application of this relationship for LY and NP is distinct. Due to their design, lysimeters have an enclosed soil volume and typically do not allow for runoff, in which case the terms F and R can be taken to be zero. In contrast, the soil volume for NP measurements is not confined; hence, neither F nor R can be neglected, although they may be controlled using several techniques. Techniques to reduce the impact of F on the mass balance calculations when using NP measurements include collecting the data well below both the rooting depth and penetration depth of the water inputs. Similarly, furrow diking and field borders or berms are often used so that R can be neglected. Typically, NP-based water balance technique is used only to determine ET over periods of days to weeks, months, and seasonal timescales (Evett et al. 2012b).

While some regard LY as the most accurate method for determining ET (Howell et al. 1995), there are still a number of factors affecting its performance (Allen et al. 2011). Among these is the ability of the LY measurements to represent the surrounding field (Evett et al. 2012b). Difference in ET within the lysimeter and at the field scale can result from differences in the soil moisture profile or the vegetation density due to variations in planting density, irrigation, and the application of fertilizers and other agro-chemicals.

Few, if any, studies have had ET measurements from all three methods (LY, NP, and EC) collected in the same field under strongly advective conditions in concert with high-resolution remote sensing data to quantify effects of spatial variability in plant cover conditions that might affect the ET measurements. One such study (Evett et al. 2012b) was conducted as part of the Bushland Evapotranspiration and Agricultural Remote Sensing Experiment (BEAREX08; Evett et al. 2012a). Based on comparison between ET estimates from the lysimeter in the southeast (SE) field (SLY) and the nearby flux tower, they concluded that the "EC stations routinely underestimated ET in this environment with differences in ET ranging from 31 to 43 % based on standard corrections to 17 % when closure was forced." This comparison was based on data collected during essentially the same 37-day period (DOY 182-219), the period of rapid leaf area increase. They also concluded that "the lysimeter with crop growth similar to that in the surrounding field (SLY) produced ET data similar to that found using soil water balance methods in the surrounding field (SNP)." This conclusion, however, was the result of a comparison over a much longer time period of 133 days (DOY 179-311). Over this time frame, the SLY ET was shown not to be statistically different from the ET determined by SNP network. On the other hand, even over this longer time period, the lysimeters in the northeast (NE) field (NLY) ET were statistically different from that derived from the NE neutron probe (NNP) network.

The objective of this study was to analyze differences in ET measurements from EC, LY, and NP techniques in a pair of adjacent irrigated cotton fields during the rapid growth period, defined as having significant temporal changes in leaf area index, for the 2008 growing season using data from BEAREX08. In addition to the ground-based ET measurements, 1-m-resolution aircraft imagery, which was collected several times during the period of rapid cotton growth and development, provided spatially distributed information regarding plant cover and leaf area information. These high-resolution images permitted investigating the relative influence of variation in plant cover within the various ET source areas/flux footprints for the different ET measurement techniques. Lastly, a comparison is made between ET estimates using a thermal-based surface energy balance model run with local remote sensing observations and EC and LY measurements from the NE and SE fields to illustrate how different conclusions can be reached concerning model performance depending on what measurements are used as ground truth for model validation.

Materials and methods

The BEAREX08 field campaign was conducted from June through August 2008 at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, Texas (35.183 N, 102.100 W, 1170 m, a.s.l) and is described in detail in Evett et al. (2012a). A brief overview of the field measurements relevant to this study is provided here. As a part of the field campaign, the surface energy fluxes were observed over an adjacent pair of irrigated cotton fields (NE and SE) using EC towers, large monolithic weighing lysimeters, and a network of neutron probes. The lysimeters (3 × 3 m in dimension, 2.3 m deep) were located near the center of each field with a colocated EC station positioned approximately 20 m northeast of the lysimeter (EC8 and EC9 in the NE and SE fields, respectively). In each field, a second EC station was located in the northeast quadrant (EC1 and EC2 in the NE and SE fields, respectively) in order to maximize the upwind fetch for the prevailing winds from the south-southwest (see Fig. 1). There were a total of four neutron probes in each field positioned approximately 30 m on the NE–SW and NW–SE diagonals from the corners of the lysimeter. Each of the fields measured approximately 220 × 220 m and had an area of nearly 5 ha. The main difference between the two fields was the orientation of the crop rows with the rows in the NE field oriented north–south, while the rows in the SE field were oriented east–west. The fields were contiguous, with one field (NE) directly north of the other (SE). All management practices (fertilization, irrigation, etc.) were applied uniformly for both fields, including within the lysimeters. The NE and SE fields including the lysimeters were irrigated for full production using a lateral move sprinkler irrigation system (see Evett et al. 2012a, b). During the peak of the growing season, between 15 and 25 mm of irrigation water was applied approximately every 5 days.

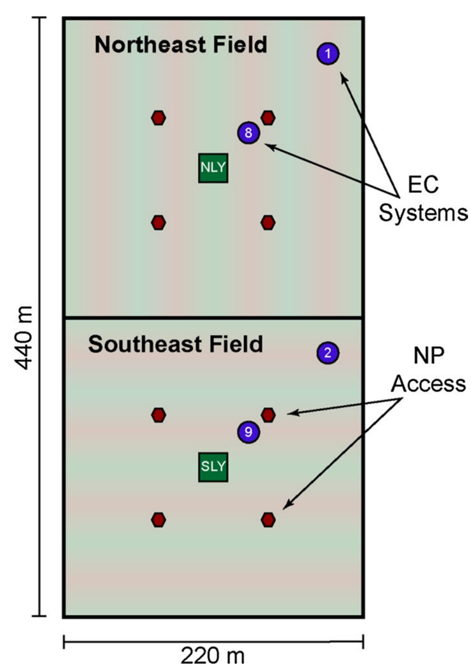


Fig. 1 Schematic showing the location of the eddy covariance systems (EC sites 1, 2, 8, and 9), stations, lysimeters (NLY and SLY), and the network of neutron probe sensors (NNP and SNP) in the northeast (NE) and southeast (SE) fields

This region has strong advective conditions during the summer growing season characterized by high winds, air temperatures, and vapor pressure deficit, resulting in high evaporative demand (Evett et al. 2012a). Figure 2 shows the daytime median, maximum, and minimum wind speed (u), air temperature (T_A), water vapor pressure (e_A), and vapor pressure deficit (D) computed from the four EC systems in the NE and SE fields, and a potential ET determined from daily ET measurements from a smaller (1.5 m × 1.5 m × 2.3-m deep) weighing lysimeter located in an irrigated grass plot adjacent to the NE and SE fields (see Fig. 1 in Evett et al. 2012a). The plots indicate frequent periods of fairly high atmospheric demand due to advection with the daytime u typically exceeding 5 m/s, T_A averaging more than 30 °C, D greater than 3 kPa, and irrigated grass ET on the order of 10 mm/day.

The EC data were post-processed using the full complement of standard corrections and adjustments, following Alfieri et al. (2011, 2012). Nonphysical values and outliers were first removed without replacement from the high-frequency (20 Hz) data using a moving window algorithm. A two-dimensional rotation was then applied to the wind velocity components so that the coordinate system was aligned with the prevailing wind direction. Next, corrections for sensor displacement and frequency response attenuation were applied. Finally, hourly mean turbulent fluxes were computed and corrected for the effects of buoyancy and water vapor density. A sensor inter-comparison study conducted by Alfieri et al. (2011) indicated that the uncertainty in H and λE was on the order of 15 and 30 W m^{-2}, respectively. A similar analysis of R_n and G found the uncertainty of these quantities to be of a similar magnitude (Alfieri et al. 2012).

A correction to R_n and G at the individual flux towers derived by Alfieri et al. (2012) was used in this analysis. The corrected R_n for each EC site was computed using site-specific upwelling shortwave and longwave measurements and the average of the four incoming solar radiation and downwelling longwave radiation measurements from EC1, EC2, EC8, and EC9, both of which were assumed to be uniform over the study site. A corrected G for each EC site was computed using the mean of the site-specific measurements along with the measurements of G from ten sensor

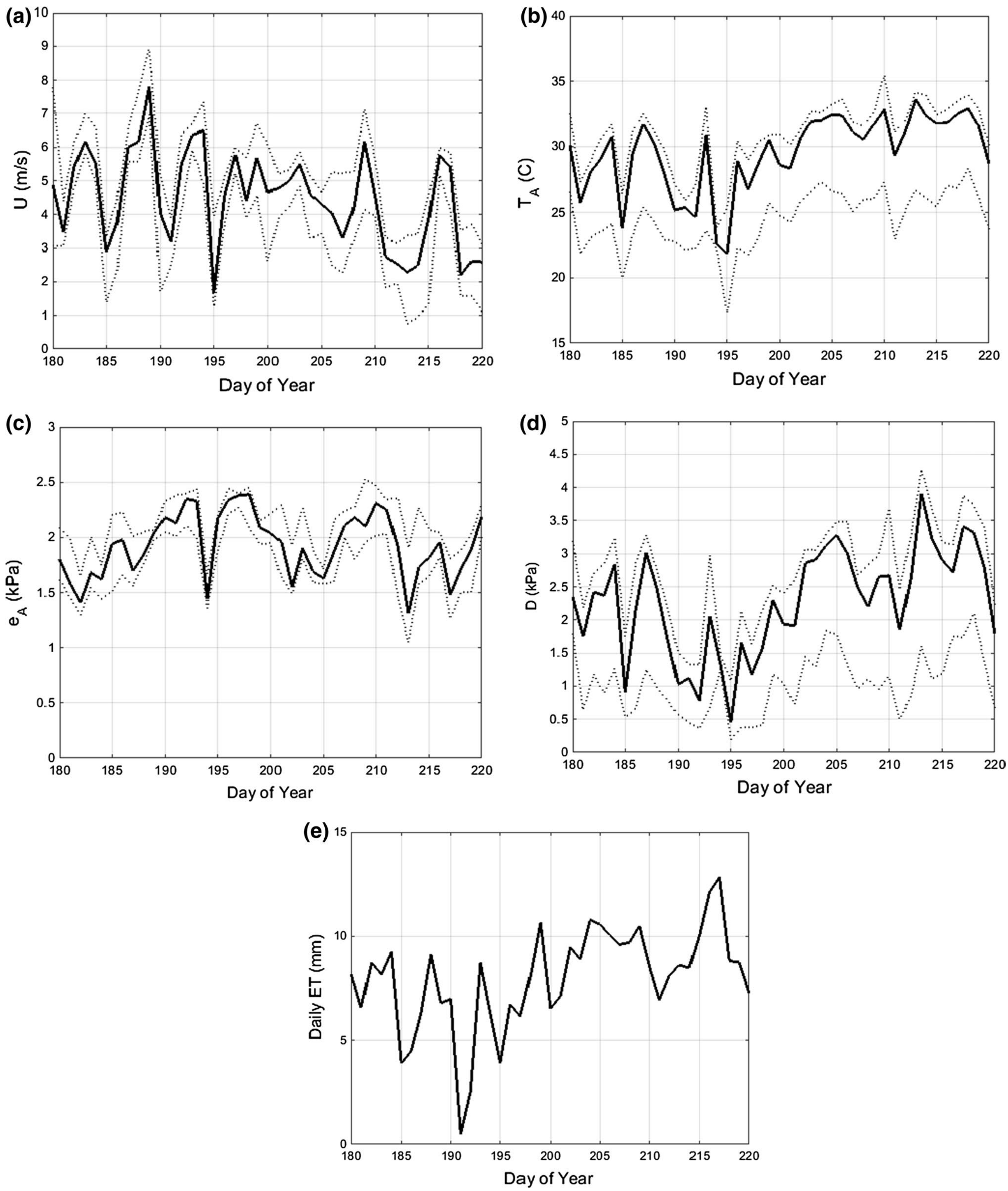


Fig. 2 Median (*solid line*) and max/min (*dotted lines*) of **a** wind speed (u), **b** air temperature (T_A), **c** vapor pressure (e_A), and **d** vapor pressure deficit (D) from the four EC systems in the NE and SE fields, and **e** potential ET determined from daily ET measurements from a weighing lysimeter located in an irrigated grass plot adjacent to the NE and SE fields (see Fig. 1 in Evett et al. 2012a)

network in each field. For details, see Alfieri et al. (2012) and Agam et al. (2012b).

The percent closure for each of the EC sites ranged from a low of 74 % at Site 2 to a maximum of 87 % at Site 8, while Site 1 and Site 9 had 84 and 85 % closure, respectively. The lack of closure was due, in part, to advective effects. While the advective contribution to the energy budget was typically near 20 W m^{-2}, Alfieri et al. (2012) showed it could contribute as much as an additional 100 W m^{-2} to the energy budget. To account for the incomplete closure of the energy balance, the correction of Twine et al. (2000), where closure is forced while maintaining a constant Bowen ratio, was applied. Due to the low values in Bowen ratio (between ~0.15 and 0.25 among the various EC systems), closure by residual instead by Bowen ratio resulted in differences in ET of less than 10 W m^{-2}, on average.

The LY and NP measurements of ET are described in detail by Evett et al. (2012b). The accuracy of the LY systems has been analyzed extensively and determined to be on the order of 0.05 mm (Howell et al. 1995). This is the depth of water equivalent to the mass measurement accuracy. It is not a rate of change or flux rate accuracy, but rather is an absolute mass measurement accuracy. The same accuracy is obtained regardless of the duration of the measurement period since the temperature-compensated mass measurement system is enclosed in an underground chamber in which temperature varies little over a growing season. With measures in place to minimize or account for runoff (R) and horizontal and vertical soil water transport (F) at the experimental field sites in Bushland, combined with accurate precipitation and irrigation data (Marek et al. 2014), Evett et al. (2012b) assumed the water balance estimates of ET from the NP network provided field-scale estimates of ET. Specifically, there were three NP-based water balance estimates computed. They included (1) the simple soil water balance (SSWB) method based on a predetermined control volume depth and the assumption that $F = 0$ through the bottom of the control volume; (2) the soil water balance based on taking the depth of the zero flux plane (ZFP), if any, as the depth of the control volume; and (3) the soil water balance based on a control volume depth with F across the bottom of the control volume calculated based on soil hydraulic characteristics (SSWB + F).

The ET computed with the NP network using all three methods (SSWB, ZPF, and SSEB + F) were not substantially different, providing further evidence that F at the bottom of the control volume was a minor term. Moreover, extensive prior field studies at this site have shown that both profile water contents and changes in profile water storage determined by this NP network can accurately represent soil water balance changes within weighing lysimeters and can be used to estimate ET (Evett et al. 2003, 2009; Tolk and Evett 2009). Moreover, it was noted by Evett et al. (2012b) that from past studies, only 1–2 NP access tubes were needed to accurately determine soil water change in storage in these fields. Hence, the set of four NP access tubes are assumed to represent a ~40 × 40 m square area within the field. This area is taken to be representative of the field-scale ET and used as a reference similar to the assumption used by Evett et al. (2012b). While assuming that the water balance estimates of ET from the NP network provided field-scale estimates of ET, Evett et al. (2012b) cautioned that "Differences between lysimeter ET and field ET (based on NP data) should be considered in light of the standard deviation of field ET, which ranged from <1 to 11 mm with means of 5.2 and 6.5 mm for the NE and SE fields, respectively, for the 11 periods considered." Hence, when computing ET differences with the NP technique, one needs to keep in mind that there is a level of uncertainty in NP estimates of field-scale ET. Nonetheless, the ET from the NP technique using the SSWB adopted by Evett et al. (2012b) is presented in this study.

Airborne imagery collected using the Utah State University multispectral imaging system was used to map the spatial variation in vegetation cover at 1-m resolution (Neale et al. 2012). The Normalized Difference Vegetation Index (NDVI) calculated using the airborne multispectral measurements was related to Leaf Area Index (LAI) measurements collected via destructive sampling at six locations in the cotton fields. The 1-m-resolution LAI maps of the cotton fields were developed using the best-fit sigmoidal relationship between the in situ LAI and remotely derived NDVI from the airborne observations (Alfieri et al. 2012). Six images were collected on 26 June [day of year (DOY) 178], 12 July (DOY 194), 20 July (DOY 202), 28 July (DOY210), 5 August (DOY 218), and 13 August (DOY 226), respectively.

The analytical footprint model of Hsieh et al. (2000) was used in combination with a simple Gaussian plume dispersion model to identify the source area contributing to the flux measured by each of the EC systems. The flux footprint was calculated for each hourly period and then spatially averaged to produce a composite footprint representing the typical source area (e.g., Fig. 3) for each flux tower. The composite footprint was then used to estimate the LAI within the source area of each EC system (Alfieri et al. 2012). The LAI within the area sampled by the lysimeters and neutron probes was also determined.

The difference between the estimates of ET was analyzed in units of mm since for daily and longer time scales and for purposes of operational irrigation management, this unit of water loss is often used. The values of λE were converted from W m^{-2} to mm using latent heat of vaporization as a function of air temperature and the conversion from the density of water yielding a depth in mm. The differences in

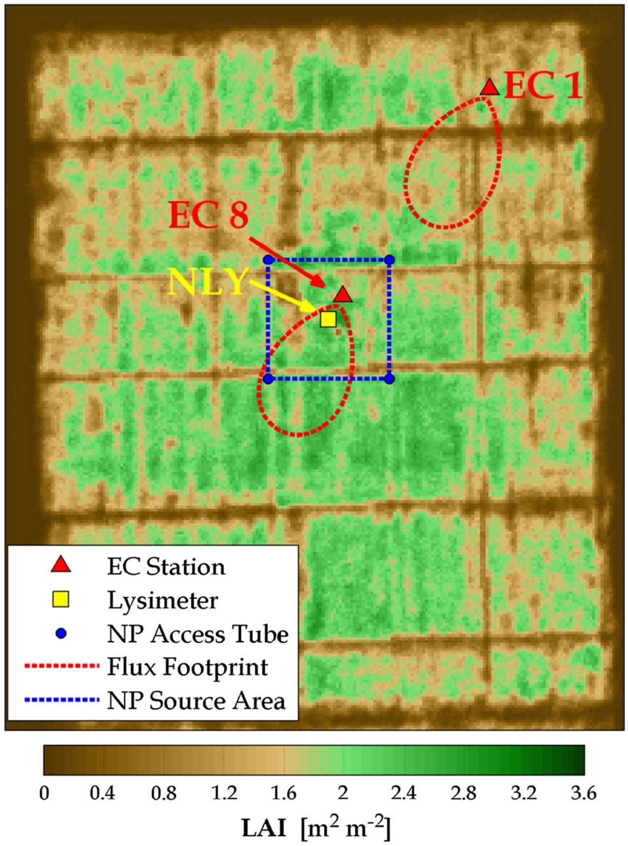


Fig. 3 The typical source area (flux foot print) for the EC towers in the NE field (EC1 and EC8) along with the source area for the NE lysimeter (NLY) and NE neutron probe network (NNP) network are shown overlaying the LAI map from DOY 202

ET measurements of the source areas from the NP and both EC and LY systems were analyzed in terms of the mean bias (MB, Eq. 3) and the mean absolute percent differences (MAPD, Eq. 4) to evaluate the effect of LAI.

$$\mathrm{MB} = \frac{1}{N}\sum X - \mathrm{NP} \tag{3}$$

$$\mathrm{MAPD} = \frac{100}{N}\sum\left|\frac{X - \mathrm{NP}}{\mathrm{NP}}\right| \tag{4}$$

where N is the number of data points, X is the ET estimate from either EC or LY, and NP is the ET estimate from NP. The use of ET from the NP technique as reference is based on the results from Evett et al. (2012b), suggesting that the NP method provided reliable field-scale ET estimates.

Results and discussion

The estimates of cumulative ET for the period DOY 183–DOY 219, which was the time frame of rapid crop growth, from each of the techniques are compared in Fig. 4 (see also Table 1). Differences in ET estimates from NP and LY are significant in both fields. Evett et al. (2012b) found ET from the NP network in the SE field in good agreement with SE lysimeter over a 133-day period. This suggests that the bias in ET between SE LY and SE NP during the period analyzed in this study (DOY 183–219) must have reversed during the later period (DOY 219–311) as evidenced in Fig. 7 from Evett et al. (2012b). In contrast, the cumulative ET from EC agreed more closely with those from NP, particularly for the NE field. In the NE field, the MB value (Fig. 5a) for LY increased continuously throughout the study period, while for the EC systems, they reached a plateau (for the EC8 case) or actually decreased somewhat (as in the case of EC1). In terms of MAPD (Fig. 5b), the difference between the ET estimates from the NE LY and NP remained at nearly 25 % after approximately 1 week. In contrast, the MAPD associated with EC1 and EC8 decreased to <10 % over the course of the study period. While the MAPD for LY in the SE field was similar (Fig. 5c), again exceeding 20 %, the differences in cumulative ET between both EC systems (EC2 and EC9) and NP in the SE field were somewhat larger in magnitude, approximately 12–22 %. The MAPD for both LY and EC increased and then decreased over time.

Although every effort was taken to ensure uniformity, as reported by Evett et al. (2012a, b), there was significant spatial and temporal variability in the vegetation density in both the NE and SE fields due to delayed crop emergence (more than 2 weeks from first to 90 % emergence), caused by unusually hot, dry conditions and persistently strong winds after planting. The LAI estimates from the high-resolution aircraft imagery indicated that variations in LAI existed through much of the growing season when canopy was only partially closed (Fig. 6) with the greatest variability occurring during the period from 12 July (DOY 194) to 5 August (DOY 218).

The mean LAI within the source area of each EC system, as well the source areas of the other sensor systems and the field as a whole, was computed from the images collected during each overflight (Fig. 7). For the NE field, the differences in LAI, particularly between the LY and EC sites, were quite pronounced during much of the study period. It is not until the canopy neared full coverage, i.e., the LAI exceeded 3 $m^2\ m^{-2}$, that the LAI values within the various source areas converged. The SE field was somewhat more homogeneous, and as a result, the differences in the LAI within the various source areas were smaller. Similar trends were observed with NDVI (Fig. 7). Due to the strongly nonlinear nature of the sigmoidal relationship between NDVI and LAI, relatively small variations in NDVI can lead to large differences in LAI. Hence, the generally larger variation in source area LAI illustrated in

Fig. 4 The cumulative ET based on the EC, LY, and NP approaches is shown for the NE and SE fields

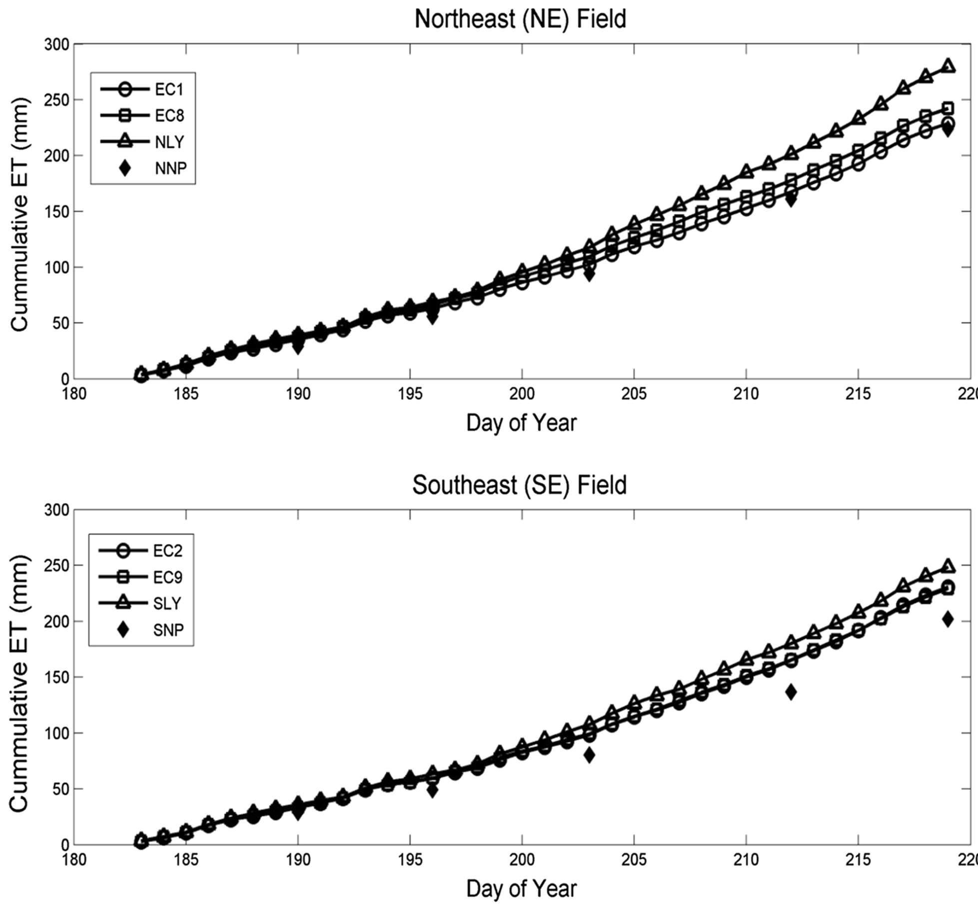


Table 1 The cumulative ET over the whole of the study period (DOY 183-220) is shown for each measurement technique for both the NE and SE fields

	EC1	EC8	LY	NP
Northeast (NE) field				
Cumulative ET (mm)	229	242	279	224
Difference with NP (mm)	5	18	55	
Percent difference with NP (%)	2.2	8.0	24.6	
	EC2	EC9	LY	NP
Southeast (SE) field				
Cumulative ET (mm)	230	229	248	202
Difference with NP (mm)	28	27	46	
Percent difference with NP (%)	13.9	13.7	22.8	

The differences between the ET estimate from NP versus EC and LY techniques are also shown

Fig. 6 compared with NDVI is expected. Again using NP as the reference, the mean biases of the LAI within the source area of both EC and LY are shown in Fig. 8. The figure clearly shows the greater bias within the source areas of LY compared with the source area of the EC systems. In all cases, the MB values were approximately zero by 7 August (DOY 220).

Typically in field experiments, there is only one type of measurement system devoted for determining field-scale ET. This study provided a unique opportunity to evaluate differences in field-scale ET determined using three techniques for two adjacent irrigated cotton fields with different row orientation. The mean and percent differences were computed for each paired set of measurement

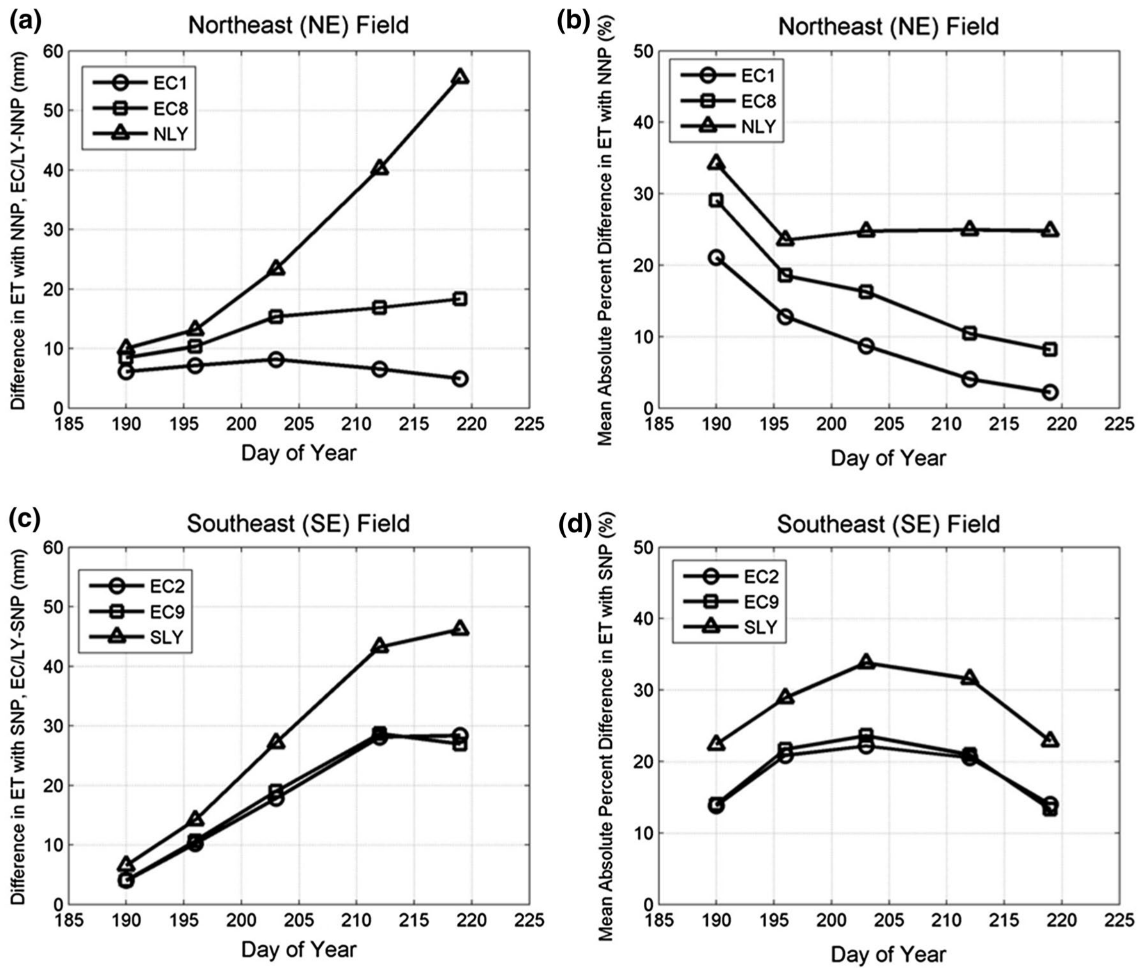
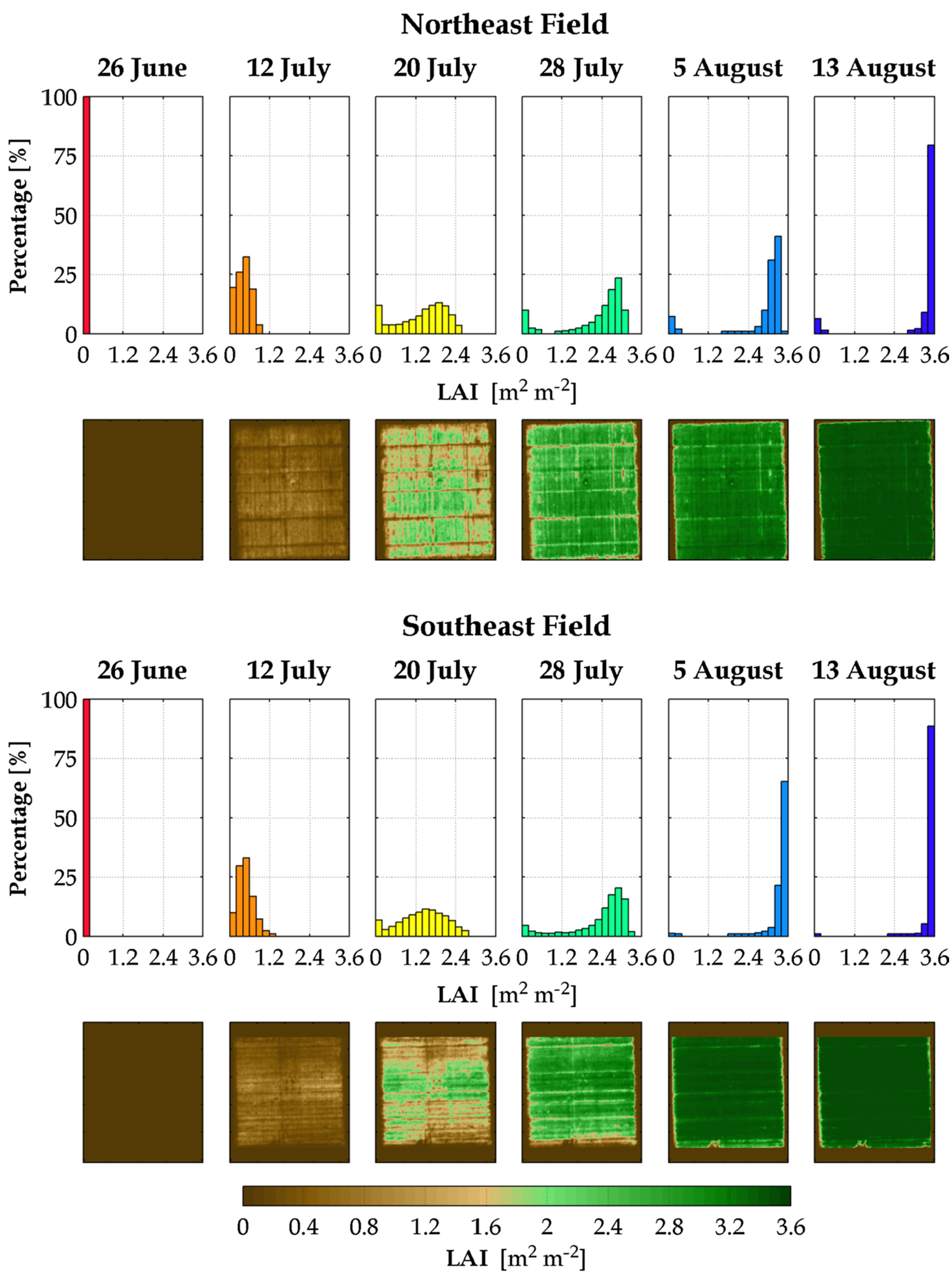


Fig. 5 Differences between the weekly NP estimates of ET and those from LY and EC technique in terms of both mean bias (MB) and mean absolute percent difference (MAPD)

systems in the northeast and southeast field (Table 2). For the EC systems, two differences were calculated: The first was between the systems in the corner of the fields (EC1 and EC2), and the second was between the systems colocated with the lysimeters (EC8 and EC9). The difference between the cumulative ET estimates from the EC systems ranged from <1 % to approximately 6 %. Both water balance-based approaches (NP and LY) indicated nearly 10 % greater ET in the NE compared with the SE. With the exception of the estimates from EC1 to EC2, which were in close agreement, all of these difference values suggest that there was greater ET in the NE field.

A comparison of the LAI within the respective source areas (Fig. 9) shows that, in the case of the comparison between NLY and SLY source areas, LAI is noticeably different throughout the study period except at the end (~DOY 220). Although the difference in the LAI between the two lysimeters was strongly correlated with the greater ET in the NE field, there were clearly other factors—for example, variations in soil water content, amount of irrigated water applied, errors in the LAI estimation procedure, the source area of the EC and other measurement systems, or the row orientation (Agam et al. 2012a, b)—that contributed to the difference in the ET estimates from the two fields or complicated the relationship between ET and LAI. A comparison of the field-scale LAI between the NE and SE fields was very similar to the LAI comparison between NNP and SNP in Fig. 9, which indicated little overall LAI difference between the two fields. Irrigation for this period was ~4 % greater in the NE field (11 mm), which would have combined to result in larger ET in that field. Moreover, as shown by Agam et al. (2012a, b), row orientation may have affected ET rates, with the N–S row orientation of the NE field potentially enhancing soil evaporation for the predominant wind directions from the south. The combined effects of greater irrigation and the N–S row orientation in the NE field could cause a larger ET rate from the NE field.

Fig. 6 Leaf Area Index (LAI) histogram and maps generated from the 1-m multispectral imagery collected over the NE and SE fields. The six images were collected on 26 June (DOY 178), 12 July (DOY 194), 20 July (DOY 202), 28 July (DOY210), 5 August (DOY 218), and 13 August (DOY 226)



Nonetheless, this inter-comparison suggests that the same measurement approach can yield cumulative ET estimates that differ from nearly zero to slightly more than 10 % under very similar weather and crop cover conditions for a pair of relatively small irrigated cotton fields located adjacent to one another. Considering the greater irrigation amount and the N–S row orientation potentially enhancing soil evaporation for the NE field, the 5–10 % higher ET estimated from the comparison between EC8 and EC9, and NNP and SNP may be plausible since the differences in LAI for these source areas were negligible. More perplexing, however, is the difference of 20 % or more seen among the various measurement techniques in the same field. Since employing three different measurement techniques in a single field is very rare, even for research purposes, this inter-comparison highlights the ambiguity that may exist in any routine measurement of short-term water use in irrigated agricultural fields when variability in vegetation cover/LAI exists.

In the earlier inter-comparison of EC, LY, and NP techniques conducted by Evett et al. (2012b), they recognized a significant bias in NE lysimeter ET during the rapid growth period due to greater vegetation cover/biomass in the NE lysimeter. Evett et al. (2012b) also computed

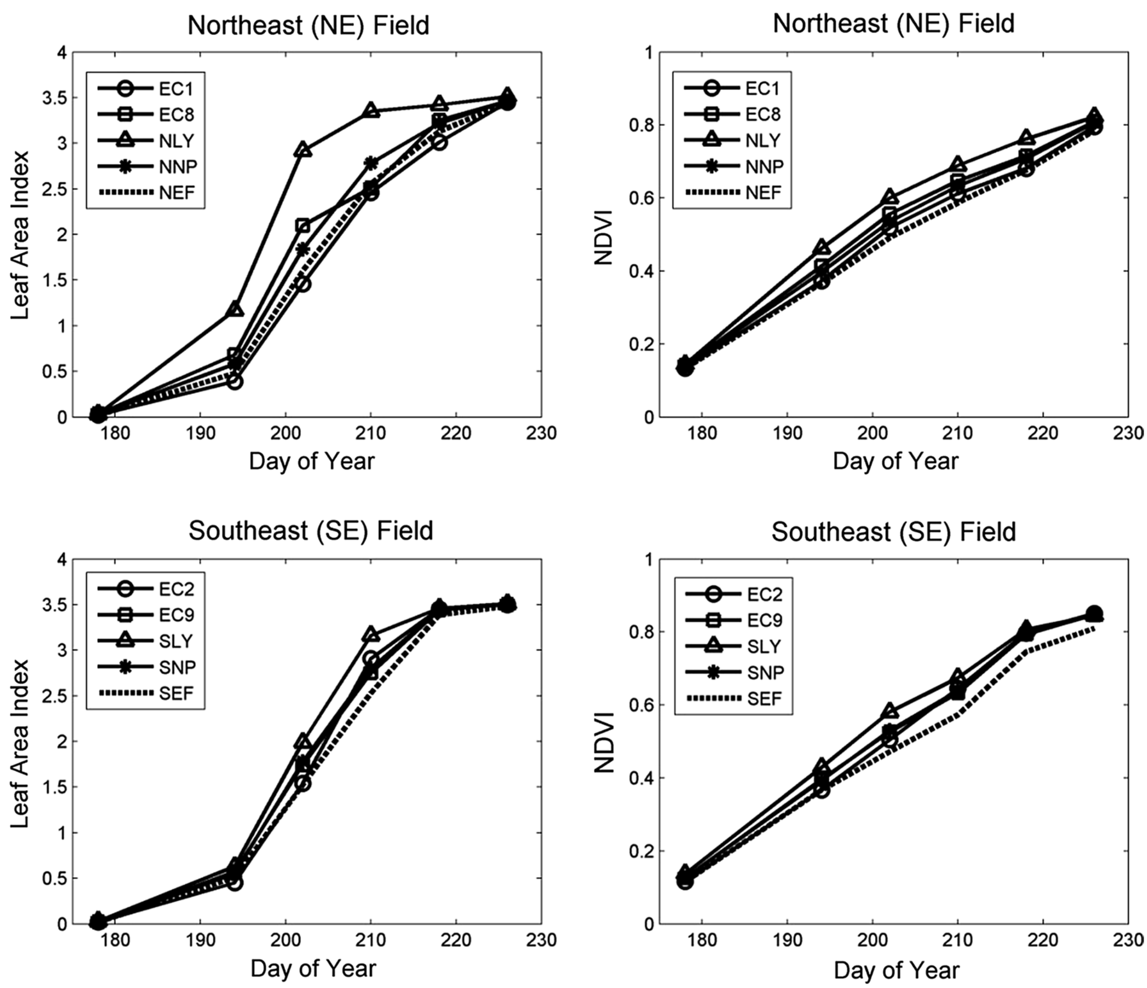


Fig. 7 Leaf Area Index (LAI) and Normalized Difference Vegetation Index (NDVI) values for source areas contributing to ET estimates from EC, LY, NP methods, and for the field as a whole, is shown for the NE (NEF) and SE (SEF) fields

cumulative ET for the NE and SE fields with the LY and NP techniques spanning from crop emergence to harvest, a significantly longer time frame from DOY 179 to DOY 311 and found generally good agreement between the SE LY and NP cumulative ET. Hence, the discrepancies between LY and NP estimates of cumulative ET for the SE field over this time frame were modulated since differences in cotton cover/LAI for the LY and NP source areas were insignificant by DOY 225. The greater differences between the NLY and NNP ET during the period of rapid growth would not actually allow a similar recovery as the NE field even with the longer time period for computing cumulative ET. It was estimated that approximately 40 % of the growing season ET occurred during the period analyzed in this paper. Hence, 60 % of the crop ET occurred after canopy closure, and unfortunately, the EC systems were not maintained after the BEAREX08 experiment until the end of the growing season. Clearly, it remains important to understand and quantify the full season crop ET in order to understand how the estimated ET varies using the different measurement techniques employed for estimating field-scale ET.

Kustas et al. (2012) evaluated the thermal-based two-source energy balance (TSEB) model (Norman et al. 1995) and the dual-temperature-difference technique (DTD; time differencing of surface and air temperatures applied to TSEB formulation; Norman et al. 2000) using local thermal observations collected at the EC towers (EC1 and EC2). A comparison of the DTD output in ET over the daytime period with both EC and lysimeter estimates (NP technique could not provide daily estimates) for the NE and SE field is illustrated in Fig. 10. The comparison for the NE field between NLY and DTD model would suggest a noticeable bias (underestimate) in ET by the model, while the comparison with both EC1 and EC8 systems does not indicate such a trend. Similar to the NE field, the DTD

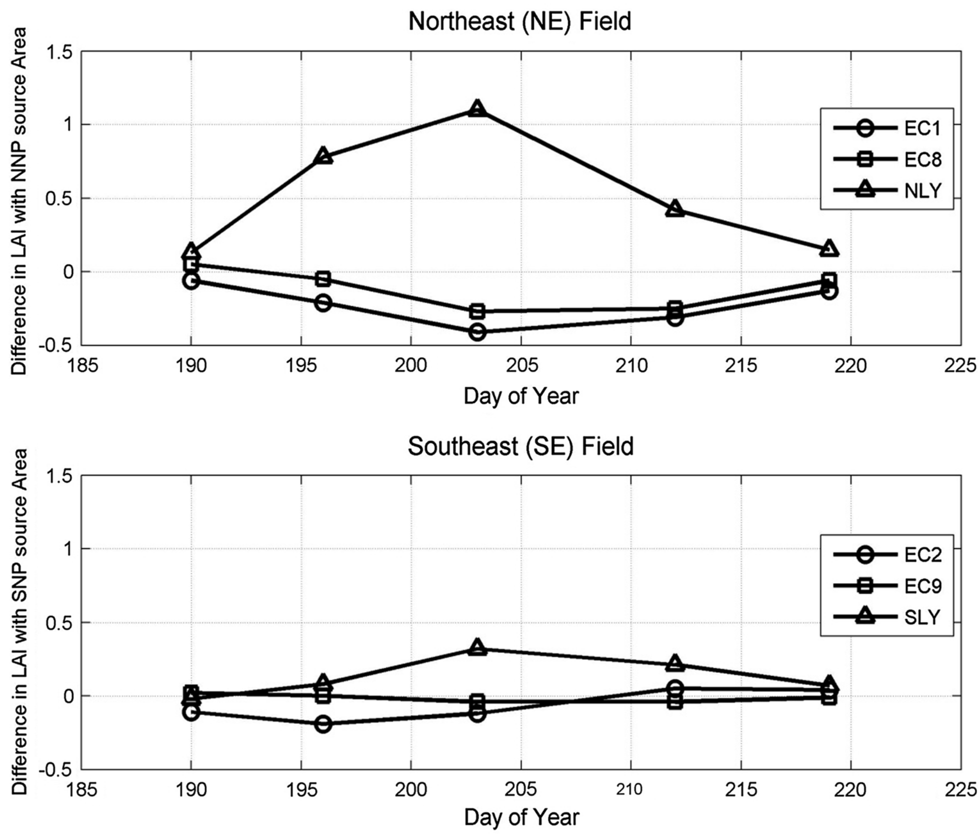


Fig. 8 The mean bias (MB) values of LAI estimated within the source area of the EC and LY techniques versus NP method for the NE and SE field

Table 2 Difference and mean absolute percent differences (MAPD) between the cumulative ET estimates from the NE and SE fields for EC, LY, and NP measurement pairs

Measurement system	EC1 EC2	EC8 EC9	NLY SLY	NNP SNP
Difference (mm)	−2	13	31	22
MAPD (%)	0.1	5.4	11.1	9.8

underestimated ET compared with SLY measurements. The DTD model agreement with EC2 and EC9 measurements is slightly weaker in comparison with EC1 results. In Table 3, the difference statistics reveal how the DTD model performance would be considered good using the EC measurements with approximately 5–10 % "error" and <0.5 mm bias, while the comparison with lysimetric data would indicate errors of about 15 % with a bias of nearly 1 mm. The comparison with the lysimetric data also implies that adjustments to model parameters may be necessary under these environmental conditions. This suggests that the model inputs and ET measurements more closely reflect similar source areas coming from the EC systems and highlights the need to consider the footprint of the method against which models are tested even under field conditions considered to be uniform, as one might expect in irrigated agricultural fields.

Conclusions

A comparison was performed between the cumulative ET estimates for two adjacent 5-ha fields using three common observation techniques, EC, LY, and NP, over a 36-day period that encompassed the period of rapid crop growth and development. Following Evett et al. (2012b) in using the NP technique as a reference for field-scale ET, the cumulative ET estimates from the LY systems were between 20 and 25 % larger than the NP approach. The LY estimates of cumulative ET were also consistently larger than the estimates from all four EC towers. In the NE field, EC-based cumulative ET estimates were greater than, but within 10 % of, the estimates derived from the NP method. For the SE field, this difference was on the order of 15 %.

Based on the LAI derived from high-resolution imagery, the vegetation density was consistently greater within the source area of the NE LY compared with either the field as a whole or the source areas of the EC systems and NP network. This fact was also reported by Evett et al. (2012b) based on field observations of plant height and width. There was a slight difference between the LAI in the SE LY and that for the SE NP network (Fig. 8). When comparing differences in the cumulative ET estimates between NE and SE fields, the largest difference, approximately 11 %, was between the ET estimates from the two LY systems

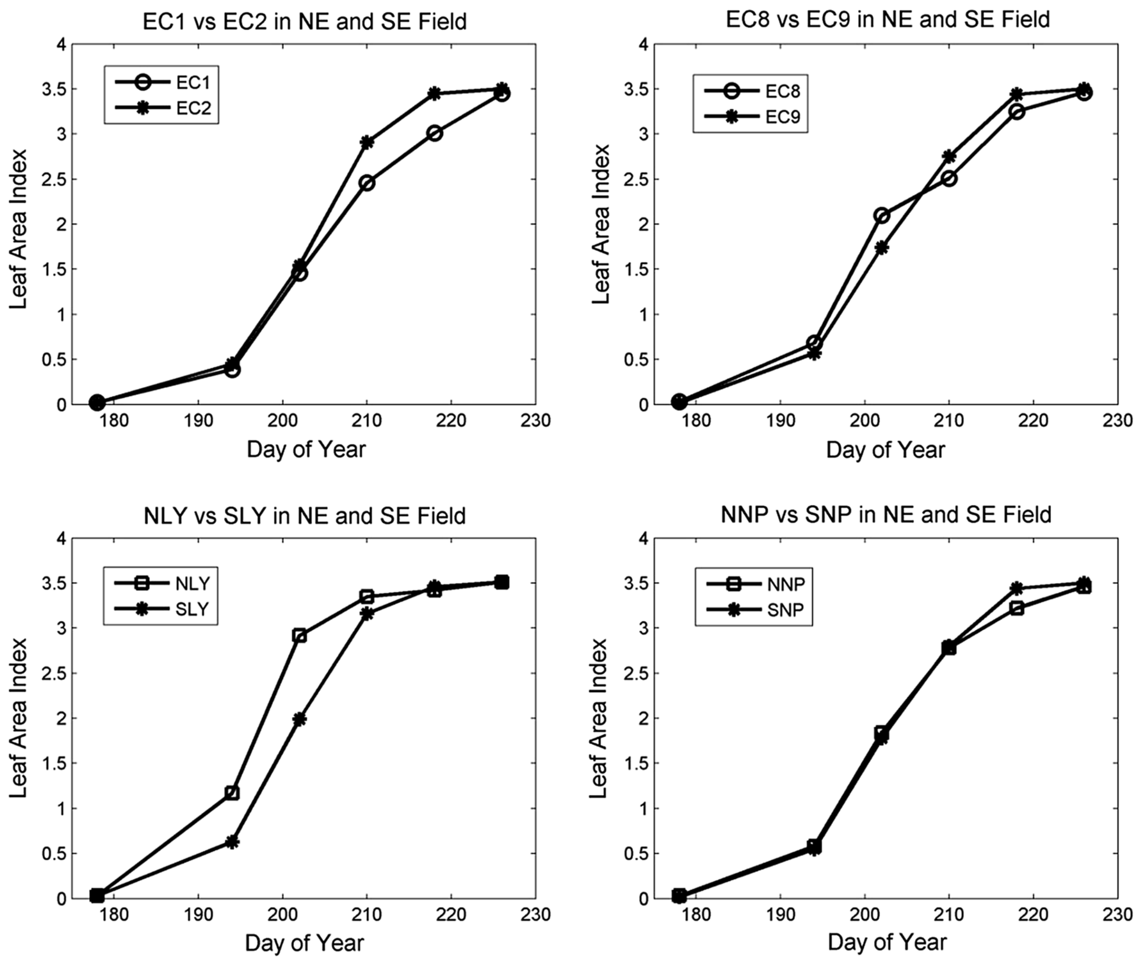


Fig. 9 Comparison of the LAI within the source areas for EC1 versus EC2, EC8 versus EC9, LY in the northeast (NLY) and southeast (SLY) fields, and NP in the northeast (NNP) and southeast (SNP) fields

followed by the 10 % difference between the cumulative ET determined using the NP. Much of the difference in cumulative ET between NE LY and SE LY is related to LAI differences within the lysimeter source area (3 × 3 m) illustrated in Fig. 9. However, differences in source area LAI between NE and SE NP networks were minor, which is similar to field average LAI for the NE and SE fields (Fig. 9). Similarly, there was little difference in the source area LAI for EC8 and EC9. Both indicate that the NE field had 5–10 % higher ET than the SE field.

Given the greater amount of irrigated water (~4 %) applied to the NE field over this study period, and the possibility of enhanced soil evaporation for N–S row orientation suggested by Agam et al. (2012a, b), the observed greater ET for the NE field may be credible. The small difference between the EC1 and EC2 cumulative ET is due, at least in part, to the higher LAI estimated for the source area of EC2 in the SE field at the later half of the study period (Fig. 9), which may have compensated for the additional irrigated water and enhancement of soil evaporation due to row orientation, yielding higher ET for the NE field. This again suggests that variations in the ET estimates may be linked to differences in the vegetation cover within the source areas of the various measurement systems.

Overall, the differences in the cumulative ET estimates from the various techniques, both within the same field and between two adjacent fields differing in row orientation but otherwise may have appeared fairly uniform “by eye,” can exceed 20 % when canopy cover is variable and there are differences in amount of irrigated water applied. Indeed, Evett et al. (2012b) reported a 21 % difference between NE LY and NE NP results during this period.

In terms of using ET measurements for validation of ET models, the comparisons between model and measured output using EC and LY observations indicate that depending on the measurements used to compare with model output, one could reach different conclusions about the utility of the model in computing reliable ET for these irrigated

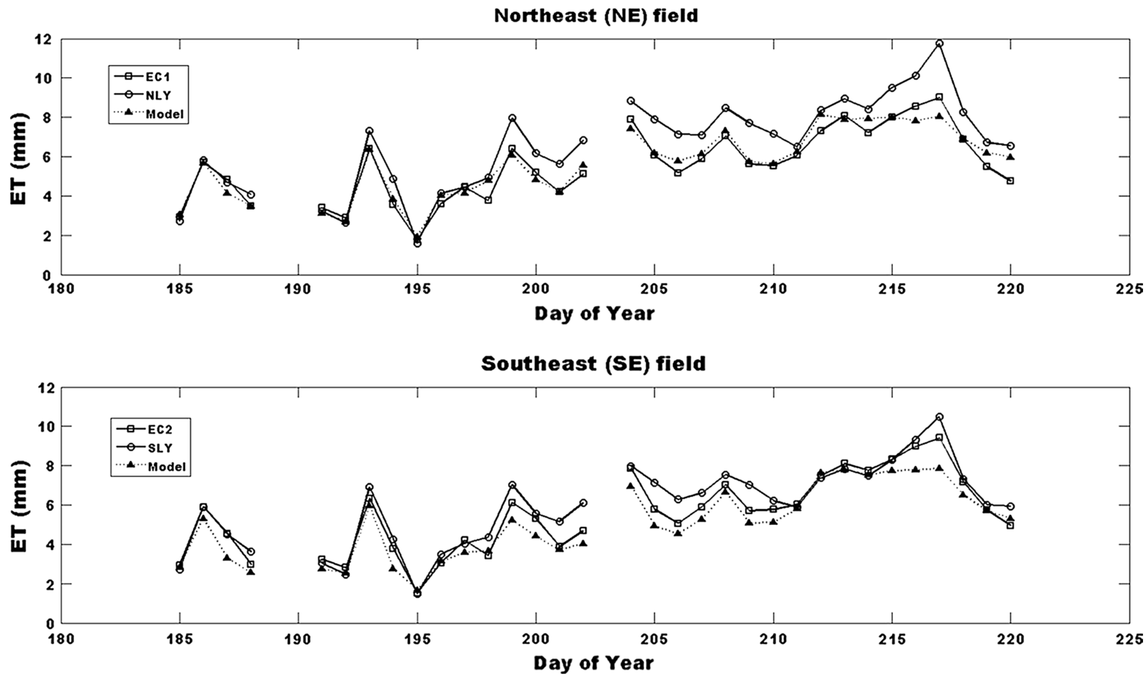


Fig. 10 ET over daytime period in mm computed by DTD model (*triangle*) and measured by EC1 and EC2 (*squares*) and NLY and SLY (*circles*) for the NE and SE fields, respectively

Table 3 Mean bias (MB = model-measured) and mean absolute percent differences [MAPD = |model-measured|/(average measured)] between the daytime ET estimates from the DTD model versus measured from EC1 and NLY for NE field and EC2 SLY for SE field

Measured DTD model	EC1 DTD	NLY DTD	EC2 DTD	SLY DTD
Difference (mm)	−0.10	0.94	0.49	0.90
MAPD (%)	6.8	15.0	10.0	15.9

fields. This underscores the importance of having detailed information concerning variability in field conditions, particularly in vegetation cover.

The results of this study indicate that ET measurements in adjacent fields having the same crop and irrigation schedule will be influenced by the spatial and temporal variations in vegetation cover and irrigation amounts, as well as row orientation, and must be carefully considered as a part of any subsequent analysis regardless of the measurement technique used to collect these data. This also means in terms of model validation and calibration that discrepancies between model and observed ET need to consider differences in vegetation conditions within the source area affecting model inputs and the measurements.

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References

Agam N, Evett SR, Tolk JA, Kustas WP, Colaizzi PD, Alfieri JG, McKee LG, Copeland KS, Howell TA, Chávez JL (2012a) Evaporative loss from irrigated interrows in a highly advective semiarid agricultural area. Adv Water Resour 50:20–30

Agam N, Kustas WP, Evett SR, Colaizzi PD, Cosh M, McKee LG (2012b) Soil heat flux variability influenced by row direction in irrigated cotton. Adv Water Resour 50:31–40

Alfieri JG, Kustas WP, Prueger JH, Hipps LE, Chavez JL, French AN et al (2011) Intercomparison of nine micrometeorological stations during the BEAREX08 field campaign. J Atmos Ocean Technol 28:1390–1406

Alfieri JG, Kustas WP, Prueger JH, Hipps LE, Evett SR, Basara JB, Howell TA, French AN, Chávez JL (2012) On the discrepancy between eddy covariance and lysimetry-based turbulent flux measurements under strongly advective conditions. Adv Water Resour 50:62–78

Allen RG, Pereirs LS, Howell TA, Jenson ME (2011) Evapotranspiration information reporting: I. Factors governing measurement accuracy. Agric Water Manag 98:899–920

Anderson MC, Allen RG, Morse A, Kustas WP (2012) Use of landsat thermal imagery in monitoring evapotranspiration and managing water resources. Remote Sens Environ 122:50–65

Evett SR, Tolk JA, Howell TA (2003) A depth control stand for improved accuracy with the neutron probe. Vadose Zone J 2:642–649

Evett SR, Schwartz RC, Tolk JA, Howell TA (2009) Soil profile water content determination: spatiotemporal variability of electromagnetic and neutron probe sensors in access tubes. Vadose Zone J 8(4):926–941

Evett SR, Kustas WP, Gowda PH, Anderson MC, Prueger JH, Howell TA (2012a) Overview of the bushland evapotranspiration and agricultural remote sensing experiment 2008 (BEAREX08): a field experiment evaluating methods for quantifying ET at multiple scales. Adv Water Resour 50:4–19

Evett SR, Schwartz RC, Howell TA, Baumhardt RL, Copeland KS (2012b) Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET? Adv Water Resour 50:79–90

Foken T (2008) The energy balance closure problem: an overview. Ecol Appl 18:1351–1367

Frank JM, Massman WJ, Brent EE (2013) Underestimates of sensible heat flux due to vertical velocity measurement errors in non-orthogonal sonic anemometers Agric. Forest Meteorol 171–172:72–81

Howell TA, Schneider AD, Dusek DA, Marek TH, Steiner JL (1995) Calibration and scale performance of Bushland weighing lysimeters. Trans Am Soc Agric Eng 38(4):1019–1024

Hsieh C-I, Katul G, Chi T-W (2000) An approximate analytical model for footprint estimation of scalar fluxes in thermally stratified atmospheric flows. Adv Water Resour 23:765–772

Kalma JD, McVicar TR, McCabe MF (2008) Estimating land surface evaporation: A review of methods using remotely sensed surface temperature data. Surv Geophys. doi:10.1007/s10712-008-9037-z

Kochendorfer JP, Meyers TP, Frank JM, Massman WJ, Heuer MW (2012) How well can we measure the vertical wind speed? Implications for fluxes of energy and mass. Bound Layer Meteorol 145(2):383–398

Kustas WP, Alfieri JG, Anderson MC, Colaizzi PD, Prueger JH, Evett SR, Neale CMU, French AN, Hipps LE, Chávez JL, Copeland KS, Howell TA (2012) Application of a time differencing technique using local thermal observations in a strongly advective irrigated agricultural area. Adv Water Resour 50:120–133

Leuning R, van Gorsela E, Massman WJ, Isaac PR (2012) Reflections on the surface energy imbalance problem. Agric Forest Meteorol 156:65–74

Marek GW, Evett SR, Gowda PH, Howell TA, Copeland KS, Baumhardt RL (2014) Post-processing techniques for reducing errors in weighing lysimeter evapotranspiration (ET) datasets. Trans ASABE 17(2):499–515

Meyers TP, Hollinger SE (2004) An assessment of storage terms in the surface energy balance of maize and soybean. Agric Forest Meteorol 125(1–2):105–115

Neale CMU, Geli H, Kustas WP, Gowda PH, Cosh MH, Evett SR, O'Shaughnessy SA, Crow WT, Prueger JH, Alfieri JG, Hipps LE, Chávez JL, French AN (2012) Soil water content estimation using a remote sensing based hybrid evapotranspiration modeling approach. Adv Water Resour 50:152–161

Norman JM, Kustas WP, Humes KS (1995) A two-source approach for estimating soil and vegetation energy fluxes from observations of directional radiometric surface temperature. Agric Forest Meteorol 77:263–293

Norman JM, Kustas WP, Prueger JH, Diak GR (2000) Surface flux estimation using radiometric temperature: a dual temperature difference method to minimize measurement error. Water Resour Res 36:2263–2274

Scanlon BR, Faunt CC, Longuevergne L, Reedy RC, Alley WM, McGuire VL, McMahon PB (2012) Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proc Natl Acad Sci 109(24):9320–9325

Stoy PC, Matthias M, Foken T et al (2013) A data-driven analysis of energy balance closure across FLUXNET research sites: the role of landscape scale heterogeneity. Agric Forest Meteorol 171–172:137–152

Tolk JA, Evett SR (2009) Lysimetry versus neutron moisture meter for evapotranspiration determination in four soils. Soil Sci Soc Am J 73(5):1693–1698

Twine TE, Kustas WP, Norman JM, Cook DR, House PR, Meyers TP, Prueger JH, Starks PJ, Wesely ML (2000) Correcting eddy-covariance flux underestimates over a grassland. Agric Forest Meteorol 103:279–300