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Can weighing lysimeter ET represent surrounding field ET well enough to test flux station measurements of daily and sub-daily ET? ☆

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ABSTRACT

Weighing lysimeters and neutron probes (NP) are both used to determine the change in soil water storage needed to solve for evapotranspiration (ET) using the soil water balance equation. We compared irrigated cotton ET determined using two large ($3 \times 3 \times 2.4$-m deep) weighing lysimeters and eight NP soil water profiles located outside the lysimeters in cotton fields during the BEAREX08 field campaign (see [16] Evett et al., 2012). The objectives were to (i) determine if lysimeter-based ET fluxes were representative of those from the fields, designated NE and SE, in which the lysimeters were centered, and (ii) investigate different methods of computing the soil water balance using NP data. Field fluxes were determined from the soil water balance using neutron probe measurements of change in profile water content storage. Fluxes of ET from the SE lysimeter were representative of those from the field throughout the season and can be used with reasonable certainty for comparisons of ET fluxes and energy balance closure derived from Bowen ratio (BR) and eddy covariance (EC) measurements whose footprints lay in the SE field. Comparisons of ET fluxes from EC and BR systems to those from the NE lysimeter should consider that NE lysimeter fluxes were up to 18% larger than those from the NE field during the period of rapid vegetative growth. This was due to plants on the lysimeter having greater height and width than those in the field. Nevertheless, the data from this and companion studies documents substantial underestimation of crop ET by EC stations under the conditions of BEAREX08. Comparison of zero flux plane (ZFP) and simple soil water balance methods of calculating ET from NP data showed them to be equivalent in this study; and for the ZFP method, the depth of the control volume should be determined by the depth at which the hydraulic gradient reverses, not by the depth of calculated minimum flux. If supported by a sufficiently dense and widespread network of deep soil water balance based estimates of ET in the surrounding patch and by ancillary measurements of crop stand and growth within the lysimeter and in the surrounding patch, a weighing lysimeter can provide accurate ET ground truth for comparisons with ET estimated using flux stations or ET calculated using satellite imagery. It must be emphasized that the water balance measurements must include soil profile water content measurements to well below (e.g., 0.5 to 1 m below) the root zone in order to close the water balance.

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1. Introduction

Knowledge of crop water use, which we here equate to evapotranspiration (ET), is required for experiments aimed at determining how ET and water use efficiency (WUE = economic yield divided by water use) can be affected by species and variety selection, genetic modification of cultivars, irrigation application method and management, fertilizer formulation and application practices, planting density and geometry, tillage and land forming practices, drainage method and management, climatic change, and many more factors that are part of current, proposed and possible future farming methods and environments. As water availability for agriculture becomes increasingly questionable around the globe while demand for farm production for food, fiber and fuel increases with population growth, the economic yield of agricultural

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production per unit of water used becomes a key criterion of success.

In general, ET is calculated directly from mass balance using the soil water balance equation applied over a given period of time to a control volume of soil (Fig. 1) with given depth and lateral dimensions:

$$ET = I + P + F + R + \Delta S \tag{1}$$

where I and P are irrigation and precipitation, F is flux into (taken as positive) or out of the control volume, R is the sum of runon and runoff (taken as positive when runon is greater than runoff), and ΔS is the change during the time period in soil water stored in the control volume. Calculations are often normalized to a control volume of 1 m^2 surface area with units of variables in Eq. (1) taken as depths of water. Note that by equating crop water use to ET, we are disregarding water used to leach soils of salt. Additionally, we note that each term in Eq. (1) varies in space and time.

Weighing lysimeters and neutron probes are two methods used to determine the change in soil water storage that is needed to solve for ET using Eq. (1). Errors in the soil water balance due to errors in determination of precipitation and irrigation are common to both, but a weighing lysimeter encloses a soil volume and so entails zero error in horizontal or vertical soil water flux, whereas the soil volume in the neutron probe (NP) method is unconfined, allowing soil water fluxes into and out of that volume. Vertical flux control practices for the NP method include measurement to well below the rooting zone and, where possible, the depth of penetration of irrigation and precipitation. Otherwise, vertical fluxes throughout the control volume may be calculated using measured soil physical properties and soil water flux theory. Weighing lysimeters also typically have some freeboard (i.e., some height of the soil container above the soil surface) that prevents runon and runoff during at least some precipitation and irrigation events. Equivalent runoff/runon control practices for the NP method include furrow diking and the installation of plot borders or berms. While weighing lysimeters have been described as the most accurate method of ET determination (calibrated accuracies of 0.05 mm are possible [1]), several factors can render them inaccurate, including insufficient soil depth [2], different water contents or distribution of water with depth in the lysimeter compared with adjacent field soils, small size that may lead to unrepresentative measurements, and uneven management of the lysimeter compared with the field (e.g., planting density, fertilization, tillage and pest control) [3]. These sources of error motivate the standard practices of measuring soil profile water content and temperature, plant height and width, and plant density within lysimeters and in the surrounding fields. Weighing lysimeters may employ gravity drainage, which equates the bottom interface soil water matric potential to zero (atmospheric pressure), or drainage under negative pressure achieved by vacuum systems with filters at a chosen bubbling pressure or by hanging water columns of some sort (e.g., hanging wicks). In addition, lysimeters are costly to install, maintain and operate; and so they often are used singly such that adequate replication of measurements is not possible. Still, during periods between precipitation and irrigation events, the weighing lysimeter is the only direct ET measurement method since it relies on mass balance.

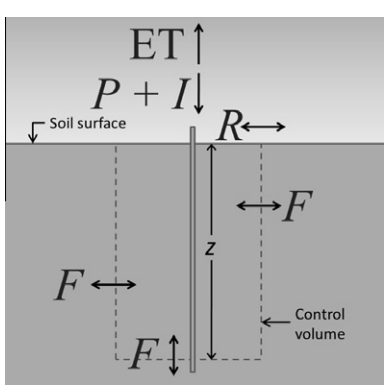

Fig. 1. Side view of a soil control volume (dashed line) of depth z for solution of the soil water balance. Lateral soil water fluxes and vertical fluxes at the bottom of the profile are considered to be Darcian fluxes (F). Fluxes at the soil surface include the sum (R) of runon and runoff, which is the infiltration flux (not shown in Eq. (1) but included implicitly within R), the evapotranspiration (ET) and the precipitation (P) and irrigation (I).

The NP has long been used for field soil water balance studies to determine ET. Field calibration accuracies of <0.01 $m^3\ m^{-3}$ are possible, which in a straightforward error analysis translates into profile water content accuracy of <10 mm per meter of control volume depth [4,5]. Considerable evidence exists, however, that profile water content errors are much smaller than 10 mm per meter of depth [5,6]. This is due to the averaging of water contents from readings at multiple depths that is entailed in computing a profile water content. Absent bias in the calibration equation, the mean value theorem dictates that the mean of water content errors should tend to zero as the number of values entailed in the mean increases. Indeed, Van Bavel and Stirk [7] found that the neutron probe was accurate to 1 mm in a 1.5-m profile, which made it a reasonable alternative to weighing lysimetry. Still, the NP is commonly used only for determining ET over periods not less than several days, extending to periods of weeks, months and cropping seasons. The depth of the control volume considered is flexible, but must extend to well below the depth of root water uptake, typically to >2 m for crops. Runon and runoff can be serious problems if not controlled (e.g., by plot borders, berms, furrow dikes, etc.). And, soil water flux into and out of the control volume, particularly across the bottom boundary, cannot be measured, only estimated using soil water dynamical theory and knowledge of the relationships between soil water content and soil water potential and hydraulic conductivity. While these relationships are often reasonably well known for the soil surface layers in many research sites, it is common that the hydraulic properties at and below 2-m depth are not well known, even at long-existing research stations. While determination of ET by soil water balance using the NP is a mass balance method, it is an indirect method to the extent that NP measurements are indirect measures of soil water content.

A common model of the soil water content (θ_v, $m^3\ m^{-3}$) as a function of soil water matric potential or hydraulic head (h, m) is van Genuchten's [8] equation:

$$\theta_v = \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} \tag{2}$$

where θ_r ($m^3\ m^{-3}$) is called the residual water content and is usually a fitted value, θ_s ($m^3\ m^{-3}$) is the water content at saturation, and α (m^{-1}) and n (nondimensional) are fitting coefficients with $m = 1 - 1/n$. It follows that the hydraulic head is represented by:

$$h = -\left[\left(\frac{\theta_s - \theta_r}{\theta_v - \theta_r}\right)^{1/m} - 1\right]^{1/n} \Big/ \alpha \tag{3}$$

A common and related model of the soil relative hydraulic conductivity (K_r, m/s) as a function of water content is Mualem's [9] equation:

$$K_r = \left\{1 - \left[1 - \left(\frac{\theta_v - \theta_r}{\theta_s - \theta_r}\right)^{1/m}\right]^m\right\}^2 \left(\frac{\theta_v - \theta_r}{\theta_s - \theta_r}\right)^{1/2} \tag{4}$$

The hydraulic conductivity is $K(\theta_v) = K_r K_s$ where K_s is the hydraulic conductivity at saturation. Finally, the soil water flux (q, m/s) is calculated using Darcy's law: the local gradient of the total hydraulic head (H) multiplied by $K(\theta_v)$.

Alternatively, if a zero flux plane exists at some depth in the soil profile, then ET can be calculated from ΔS sensed in the control volume above the zero flux plane [10]. Zero flux planes exist where a reversal of the total hydraulic head (H) gradient exists such that soil water flux is upward above the plane and downward below the plane [11,12]. Zero flux planes commonly develop in a soil profile that is relatively full of water at the beginning of a growing season during which plant roots take up water, drying the upper soil layers and creating an H gradient that moves water upward into the drier layers while water in deeper layers is still draining. Identification of a zero flux plane can obviate the requirement that soil water flux at the bottom of the control volume be calculated since the control volume depth can be chosen such that the bottom of the control volume coincides with the zero flux plane. Kirsch [13] found that using the zero flux plane method resulted in ET estimation errors that were no larger than those resulting from use of other ET determination methods (e.g., modified pan evaporation, the Blaney–Criddle method or various forms of Penman's equation). If the vertical position of the zero flux plane is not stationary in time (negligible changes aside), then the control volume based on its depth is unstable and direct ET calculation based on Eq. (1) is not feasible without additional assumptions and calculations involving interpolation between the depths of the zero flux plane during the period over which the depth changes.

Several other methods of determining ET depend on measurements of wind speed (horizontal and vertical), air humidity and temperature and solar irradiance or net global radiation. Chief among these are the eddy covariance (EC) and Bowen ratio (BR) methods [14]. Eddy covariance methods rely on rapid (e.g., 20 Hz) concurrent measurements of humidity (and/or air temperature) and vertical wind speed, which are amalgamated into longer period estimates of vertical latent heat flux (LE) on the basis of a conceptual model of vertical transport in the fully adjusted internal boundary layer without flow divergence. If net radiation (R_n), soil heat flux (G) and sensible heat flux (H) are concurrently measured or estimated, the surface energy balance closure can be computed

$$0 = R_n + G + LE + H \tag{5}$$

Closure is obtained when the sum of LE, R_n, G, and H is zero. Closure errors of 10% to 20% are typical with EC, with underestimation of LE being the largest source of error [14]. The Bowen ratio method is a flux gradient approach involving measurements of humidity and air temperature at two different heights to establish a vertical gradient, estimates of aerodynamic and/or sensible heat flux transport coefficients (usually based on wind speed and crop height), the assumption that both measurements are made in the fully adjusted boundary layer, and the critical assumption that transport coefficients for water vapor and heat are equal. Several problems exist for Bowen ratio methods, including indeterminacy of the solution when the Bowen ratio approaches unity, the difficulty of obtaining both the higher and lower measurements within the fully adjusted layer, the fact that transport coefficients for water vaport and sensible heat are often not equal, and the dependence on net radiation and soil heat flux measurements.

Both EC and BR methods have several advantages over weighing lysimeter and NP approaches, including ease of deployment, less initial expense (compared with lysimeters), automation of measurements and suitability in rough and rocky terrain. For studies of ET over large areas, neither weighing lysimeter nor NP methods are economically feasible, and in some soils and terrains they are impractical. However, EC systems commonly do not achieve energy balance closure. In the BEAREX08 campaign for example, after all typical corrections were applied, Alfieri et al. [15] found that average closure for the EC systems situated in irrigated fields adjacent to weighing lysimeters ranged from 74% to 87%. The relatively smaller initial costs of EC and BR methods, compared with weighing lysimeter costs, must be balanced against the long term costs of using relatively poor and erroneous data for management and planning decisions.

During the Bushland Evapotranspiration and Remote Sensing Experiment 2008 (BEAREX08) [16], seven EC and three BR systems were deployed on, and adjacent to, two cotton fields in which ET was determined by weighing lysimetry and NP methods. The expectation was that the weighing lysimeters, the ET values from which are based on mass balance, would provide ground truth against which EC and BR system ET estimates could be compared in both the short (e.g., hourly) and long (e.g., multi day and week) terms, and in so doing the problems with EC and BR estimates could be better understood, including the underlying reasons for closure errors. Because the surface area of even a large weighing lysimeter is much smaller than the footprint area for an EC or BR system, and because the footprint moves and changes size with the direction and speed of the wind and the atmospheric stability, the weighing lysimeter is typically not sensing the same ET flux as does the EC or BR system. Even so, the ET flux rates for lysimeter and EC or BR should be equal if (i) the lysimeter is representative of the field, (ii) the EC or BR footprint is well within the field, and (iii) the ET flux from EC or BR system is itself representative of ET from the field.

Note that the accuracy of the weighing lysimeters used in BEAREX08 is not in question as it has been previously determined to be on the order of 0.05 mm [1] with a standard deviation typically <0.1 mm [14] during operation. Importantly, the Bushland, Texas site was chosen for the BEAREX08 campaign precisely because the important interferences to successful field soil water balance measurements of ET were absent. The soil is deep, spatially uniform, includes a high clay content Bt horizon that precludes most deep percolation, was furrow diked to minimize runoff, has a deep water table (~100 m depth) that precludes upward flux contributions to ET, and has potential ET (1800 mm y^{-1}) that greatly exceeds precipitation (450 mm y^{-1}) throughout the year and summer growing season.

It was the purpose of this study to determine if ET from two large weighing lysimeters was the same as that derived from the field soil water balance determined using a network of neutron probe access tubes in the field around each lysimeter. This approach was predicated on previous positive results in using the NP to determine ET in fields and lysimeters and comparing the two [5,6,17] in which it was found that (i) using advanced methods, NP measurements within lysimeters could be used in soil water balance calculations of ET that closely matched the ET determined from the lysimeter mass balance data, (ii) soil profile water contents and changes in soil profile water storage determined in fields using the NP accurately matched those determined using volumetric/gravimetric direct soil sampling, and (iii) the numbers of NP access tubes needed to accurately determine soil water change in storage in these fields were small, typically on the order of one or two. Further motivation was derived from the need to scale up local measurements to field and regional scales in the larger BEAREX08 study. In particular, if there were agreement between ET from the surrounding NP network and ET from the weighing lysimeter then the lysimeter ET would be representative of the field and could be used with confidence as ground truth for comparison with ET derived from measurement systems with similar footprints, notably EC and BR systems placed in the field and remote sensing based ET estimates with appropriate pixel sizes representing the field.

The degree to which ET from weighing lysimeters represents that of the surrounding field area is not commonly tested due to the difficulty of obtaining adequate field soil water balance data; yet it is of primary importance if EC and BR systems are to be

tested using lysimeter data as they were in BEAREX08. Our primary objective was to determine if ET derived from lysimeter measurements of ΔS was the same as ET calculated for the surrounding field area using the NP to determine ΔS, i.e., to test the hypothesis that the lysimeters were representative of the field. We used rigorous field soil water balance methodology during BEAREX08 to demonstrate how this can be done. The primary assumption in this approach is that the mean ET value, derived from the soil water balance data from multiple NP access tubes spaced widely in the surrounding field, would be more representative of the field mean ET than would data from a single weighing lysimeter. A secondary objective was to compare calculated field ET based on (i) the simple soil water balance (SSWB) method based on a predetermined control volume depth of 2.4 m and the assumption that $F = 0$ through the bottom of the control volume, to (ii) 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 to (iii) the soil water balance based on a control volume depth of 2.4 m with F across the bottom of the control volume calculated based on soil hydraulic characteristics and Eqs. (2)–(4) (SSWB+F). An ancillary objective was to compare ET determined by soil water balance with ET determined using EC stations placed such that their measurement foot prints overlapped the patch defined by each weighing lysimeter and network of NP measurements.

2. Methods and materials

Cotton was planted on 21 May 2008, day of year (DOY) 141, on a 10-ha irrigated field at the USDA-ARS Conservation & Production Research Laboratory, Bushland, Texas (35° 11′ N, 102° 06′ W, 1170 m elevation above MSL) on a Pullman fine, mixed, superactive, thermic Torrertic Paleustoll. The soil profile has three primary layers of importance, a 20-cm deep Ap horizon, a clayey Bt horizon extending from 30 to 130 cm depth, and a calcic B (Btk) horizon containing up to 50% $CaCO_3$ and extending from 130 to 230 cm depth. The field comprised north and south halves, each a 5-ha square in the center of which was a large weighing lysimeter (nominally $3 \times 3 \times 2.4$-m deep). Details of the lysimeters are given by Marek et al. [18]. After pre-plant irrigations, the north half was planted in the north-south direction and the south half in the east–west direction (the previously commonly used row direction), both on rows spaced 0.76-m apart. A plant density of 158,000 plants per ha (16 plants m^{-2}) was achieved after emergence. Lysimeters were hand seeded and plants thinned after emergence to match the field plant density. Each lysimeter had four rows approximately 3.0 m in length with about 36 plants per row in each lysimeter. Planting on, and adjacent to, the lysimeters was done such that the lysimeter edges parallel to the rows were midway between two rows. Thinning was done to match plant density on the lysimeters to that in the field and so that plants closest to the edge of the lysimeter would be equidistant from the edge. These measures were taken to ensure that equal amounts of leaf area were inside and outside of the lysimeter so that lysimeter-measured ET would be representative of the lysimeter surface area. Plant height and width were measured periodically on each lysimeter and at three locations in each field. Plant height was measured from the top of the bed to the terminal growing point. Plant width was measured at the widest extension of the leaves. Leaf area index (LAI, $m^2\ m^{-2}$) was measured periodically at three locations in each field by harvesting all plants from a 1 m^2 area at each location, stripping the leaves and measuring leaf area using a leaf area meter (model 3100, Li-Cor, Lincoln, NE). This destructive measurement was, of course, not performed on the lysimeters. The fields were furrow diked [19] to minimize runoff from the slightly sloping (~0.3% gradient to the SE) field.

2.1. Weighing lysimeter measurements of soil water storage changes

The lysimeter weighing system consisted of a multiple-lever balance with the force at the end of the final lever counter balanced so that it was within the range of a 22 kg load cell. The high-resolution load cell measurement system was described by Howell et al. [1]. Lysimeters were calibrated in January 2008 using test masses traceable to NIST. During calibration, masses were added in increments of ~50 kg until a mass of ~450 kg was achieved (equivalent to ~50 mm of stored water), then removed in increments of ~50 kg. Load cell readings taken at 6-s intervals were averaged to five-min means and further averaged to 15-min and half-hourly means. Conversion of mass changes to mm of water was initially done using the 9 m^2 nominal inside surface area of the lysimeters. Since plants were arranged so that canopies overlapped over the edges of the lysimeter, and since these edges had a non-negligible thickness, the lysimeter change in storage (mm) was later adjusted to represent the surface area as calculated to the midpoint of the lysimeter edge. This is necessary so that lysimeter data reflect the contributing leaf area of the plants on the lysimeter, avoiding the bias introduced by using the inside surface area of the lysimeter in these calculations. Measurements of the lysimeter widths in the north-south and east-west directions (five in each direction) indicated that the inside surface area was 8.95 m^2, the outside surface area was 9.35 m^2 and the surface area to the midpoint of the edges was 9.15 m^2. Values of lysimeter storage were thus multiplied by a correction factor of 0.9836 to calculate values representative of the plants growing on the lysimeters. The correction factor had the same value for both lysimeters.

Lysimeter calibration accuracy was represented as the RMSE of linear regression between mm equivalent mass added and load cell output, and it was 0.04 mm for the NE lysimeter and 0.01 mm for the SE lysimeter. A check was conducted by comparing the theoretical calibration slopes to those of the linear regressions. For the NE lysimeter, the load cell factory calibration was 3.148 mV/V for a full load of 22.68 kg at standard gravity. Given the lysimeter inside surface area of 9 m^2, and the 100:1 mechanical advantage of the lever-beam scale system, this is equivalent to a theoretical calibration slope for the NE lysimeter of 80.05 mm/(mV/V), which compares well with the slope of 81.01 mm/(mV/V) from the linear regression of calibration. For the SE lysimeter, similar calculations resulted in a theoretical calibration slope of 83.47 mm/(mV/V) versus a linear regression calibration slope of 84.30 mm/(mV/V). The counter weights in the lysimeter balance systems were managed such that the range of load cell output did not vary by >3 mV/V during the growing season. Thus, the maximum discrepancy between ET calculated using theoretical versus actual calibration slopes was <3 mm over the season ($(81.01 - 80.05) \times 3 = 2.88$ and $(84.3 - 83.47) \times 3 = 2.49$).

To calculate lysimeter change in storage, ΔS, we used 15-min mean data representing lysimeter mass converted to storage of water in mm referenced to an arbitrary zero. To find a mean storage value centered at midnight, we took the average of the 15-min mean value for the quarter hour just before midnight and the 15-min mean value for the quarter hour just after midnight. The difference between successive midnight-centered mean storage values was the daily change in soil water storage, which represented ET if no precipitation, irrigation or scale system counterweight adjustment occurred during that 24-h period. If irrigation and precipitation occurred, those amounts, as indicated by lysimeter mass change, were included in the soil water balance calculation of ET. Drainage was stored in two tanks that were suspended from the lysimeter soil container by load cells and connected to a regulated vacuum system (10 kPa suction). Because drainage did not change the mass of the lysimeter system, the flux

term, F, in Eq. (1) was set to zero for lysimeter-derived ET. Precipitation and irrigation events were not large enough to cause runon to or runoff from the lysimeters. On days when neutron probe readings were taken, the midpoint of the period (usually one hour) during which readings were taken was considered to be the time at which one period for evaluating ET ended and another began. Therefore, lysimeter storage at that time was used to compute ΔS values from the previous midnight to that time and from that time to the next midnight. Values of total lysimeter ET were thus computed for each period from the midpoint of one NP reading to the midpoint of the next, which occurred a week or more later.

2.2. Neutron probe measurements of soil storage changes

Three-meter long NP access tubes were installed and 30-s neutron counts were taken periodically using methods described by Evett [4], including use of a depth control stand [20] to ensure accuracy of the shallowest reading, which was centered at 10-cm depth. Readings below 10-cm depth were taken in 20-cm increments to the deepest reading at 230-cm depth. Standard counts were taken on each day that readings were taken. Four access tubes were installed in the north field at distances of ~30 m in the NE, SE, NW and SW directions from the lysimeter (designated NE Lys) there. Four access tubes were similarly installed around the lysimeter (designated SE Lys) in the south field. We note that two NP access tubes are permanently installed in each lysimeter. Measurements were taken in these at the same times as in the field and at the same depths except that the deepest reading was at 190-cm depth to avoid interefrence with the drainage system at the bottom of the lysimeter. Lysimeter NP data are not reported here because they were representative of the lysimeter [6], not necessarily the field.

The NP (model 503DR1.5,[1] Campbell Pacific Nuclear, Concord, Calif.) was field calibrated for θ_v using methods described by Evett [4] to an accuracy of better than (i.e., less than) 0.01 $m^3\ m^{-3}$ for each of the three calibrations, one for the 10-cm depth, one for the 30–110-cm depths, and one for the 130–230-cm depths, required due to varying soil properties and the shallow depth of the 10-cm reading. Water content values were integrated from the bottom of the control volume to the soil surface to calculate a water storage value in mm for each reading time and access tube; and differences between water stored at each access tube at the beginning and end of each time period were considered equal to ΔS for that access tube and time period. Change in storage data for the four access tubes around each lysimeter were averaged and combined with irrigation and precipitation data to compute field soil water balance ET for the area around each lysimeter and each time period. The depth of the control volume was 2.4 m for the SSWB method. For the SSWB+F method, the effective control volume depth was 2.2 m since the vertical soil water flux was calculated between the bottom two depths of NP measurement, which were centered at the 2.1 and 2.3 m depths. The depth of the control volume for the zero flux plane (ZFP) soil water balance method was set to the depth of the zero flux plane.

Extensive prior field work at the experimental location has shown that profile water contents and changes in profile water storage determined using the NP do accurately represent changes in the soil water balance and can be used to accurately determine ET [5,6,17].

[1] The use of trade, firm, or corporation names in this article is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the United States Department of Agriculture or the Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

2.3. Determination of other water balance components: precipitation, irrigation and soil water flux

Irrigation and precipitation amounts at each lysimeter were computed from lysimeter storage data by subtracting the smallest storage value just before the event from the largest storage value at the end of the event. We have found that values so obtained commonly do not agree with tipping bucket rain gage data, with the latter often under representing the amount of irrigation or precipitation [14]. The 9 m^2 lysimeter surface area and scale accuracy of 0.05 mm make the weighing lysimeter a much better gage for rain and irrigation events so long as those events are not large enough to cause runon and runoff. The I and P values so obtained were not corrected for ET that occurred during the events because of the short duration of irrigations (~0.5 h on the lysimeters) and most precipitation events. These I and P data were used for the field soil water balance calculations as well. The I data were compared to flow meter data to verify concordance.

Soil matric potential for each depth of NP measurement in the three primary horizons was calculated from Eq. (3). Parameters for the van Genuchten equation for the Ap horizon were from Evett et al. [21]; for the Bt horizon from Schwartz et al. [22] and [23]; and parameters for the Btk horizon were from Baumhardt and Lascano [24] with modifications for the Pullman soil from R.C. Schwartz (personal communication).

The sum of horizontal soil water fluxes into and out of the control volume around each access tube in the field was assumed to be practically zero in light of the facts that the field soil is quite uniform [5], the irrigation applications were uniform (coefficient of variation = 0.005), the plant stand was uniform and the furrow dikes prevented overland flow. Vertical soil water flux between adjacent depths of NP measurement was computed based on the θ_v values and on the soil characteristics of unsaturated hydraulic conductivity (K, m s^{-1}) versus water content (θ_v, $m^3\ m^{-3}$), or $K(\theta_v)$, and soil water matric potential head (h, m) versus θ_v, or $h(\theta_v)$, and Darcy's law:

$$q = -K_m(\theta_v)\Delta H/\Delta z \tag{6}$$

where q is soil water flux rate (m s^{-1}), H is total soil water potential head (m) (the sum of h and the gravitational potential difference, 0.2 m, between the two depths), ΔH is the total potential head difference between the two depths, and Δz is the difference in elevation (0.2 m) between adjacent depths at which θ_v, h, H, and K were evaluated. The mean value of K, K_m, for the soil layer between adjacent measurement depths was calculated from the $K(\theta_v)$ values at the two depths; and this was assumed to be the effective hydraulic conductivity for the layer.

Values of H were plotted versus depth for each NP access tube and each date of measurement; and the depth of the zero flux plane, if any, at each tube was identified visually. Values of θ_v were also plotted versus depth for each access tube, with all dates of measurement shown on one graph; and the maximum depth of crop water uptake at each tube was identified visually from the soil water extraction patterns. Linear regression of ET from the NP methods against ET from the lysimeters was performed; and the slopes were tested for equality to unity. If slopes were significantly different from unity, then the lysimeter ET was considered not representative of the field ET.

3. Results

Unusually hot, dry and persistent winds dried the soil after planting, which inhibited seed germination and required more irrigations. The winds also damaged some seedlings that did emerge. Cotton emergence, which typically takes place over a period of a

few days, was stretched over a period of more than two weeks, which delayed the field plant density counts needed to determine the degree of thinning on the lysimeters. Thinning occurred on 15 June 2012. Hand planting on the SE lysimeter and surrounding area resulted in a plant stand not too much greater than that in the field, which stand was thinned back to match field plant density. The same procedure was used on the NE lysimeter, but the hand planted stand was initially greater and plants competed with each other for light, causing taller initial growth on the NE lysimeter. Overall, the problems with germination and emergence caused more uneven plant stand and leaf area index across the field than is normal, a fact investigated further in [15].

Neutron probe measurements were taken on twelve days during the cropping season, usually once per week, but with some weeks missed due to weather conditions. Due to user error, data were missing for four access tubes on day of year (DOY) 227 and one access tube on DOY 304 (Table 1). It was possible to calculate 44 values of ET using NP data near the NE lysimeter (four access tubes times 11 periods) and near the SE lysimeter for 39 periods ($4 \times 11 - 5$ missing values). The ZFP was never more shallow than the depth of soil water extraction by the crop (Table 1); therefore the ZFP method was usable for all ET calculation periods. Examples of the determination of the ZFP and depth of extraction are shown in Fig. 2.

In the unusually hot, dry spring, precipitation totaled only 48 mm from 1 January 2008 until planting. Pre-plant irrigation totaling 65 mm was applied. Irrigation after planting totaled 301 mm on the NE lysimeter and 282 mm on the SE lysimeter; the 20-mm discrepancy indicated decreased discharge at the distal end of the linear-move sprinkler, which was likely due to nozzle plugging and by uneven pressure in the lateral not being completely compensated by the pressure regulators that were in line above each spray nozzle. All of the irrigation during the growing season occurred early in the season between DOY 180 and 225 (12 August 2008, Fig. 3). Precipitation totaled 435 mm on the NE lysimeter and 425 mm on the SE lysimeter, the 10-mm discrepancy being attributed to the variability of rainfall across the 225-m separation distance between the two lysimeters. This kind of variability is not uncommon given the regional predominance of summer time precipitation from convective thunderstorms with their sharp-edged rain shafts and is well documented [14]. That the difference in precipitation was not due to lysimeter calibration bias was evidenced by the fact that precipitation caught by the NE lysimeter was sometimes smaller than that caught by the SE lysimeter and the fact that precipitation amounts <10 mm agreed closely.

Early in the season, ET from the two lysimeters was nearly equal; but by the DOY 203-212 period, the ET from the NE lysimeter became greater than that from the SE lysimeter (Fig. 4A). This was in line with reduced irrigation amounts at the SE lysimeter.

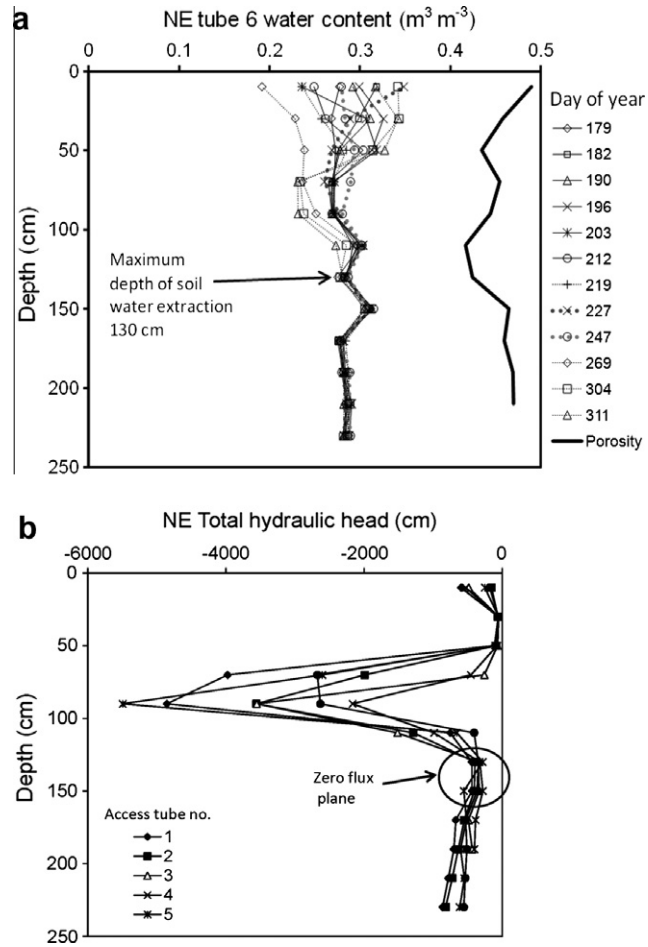

Fig. 2. Examples of the determination of (a) the depth of soil water extraction by the crop as 1.30 m for access tube number 6, and (b) of the depth of the zero flux plane (ZFP) zone at six access tubes in and around the NE lysimeter on day of year 311. Access tubes numbered 3 and 4 were in the lysimeter. The zero flux plane was at 1.30-m depth for most tubes and at 1.50-m depth for the rest.

There were also, however, differences in plant growth that influenced ET differences. Plant height in the NE field was significantly less than that in the NE lysimeter for DOY 182, 200, 210 and 220 (Fig. 5A). Except for DOY 220, plant height in the SE field matched that on the SE lysimeter (Fig. 5B). Plant heights in the NE and SE fields were similar. Also, plant width in the NE field was significantly less than that on the NE lysimeter on DOY 220, 238, 263 and 283, while on DOY 220, 238 and 263 plant width on the NE lysimeter was notably greater than in either the NE or SE fields

Table 1
For the NE and SE fields, depths (m) of zero flux plane by day of year (DOY) and access tube number, and depths (m) of crop water extraction over the season as determined from graphs of total hydraulic head and water content versus depth of measurement. Water content at each access tube was determined by neutron probe; and total hydraulic head was estimated from the water content using Eq. (3) and the gravitational potential head due to the measurement depth, which was referenced to the soil surface. Access tubes in the lysimeters were numbered 3, 4, 9 and 10, and are not shown here.

Field-access tube no.	Zero flux plane depths (m) by days of year, 2008												Depths of extraction
	179	182	190	196	203	212	219	227	247	269	304	311	
NE-1	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.10
NE-2	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.10
NE-5	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
NE-6	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.30
SE-7	1.70	1.70	1.70	1.70	1.70	1.70	1.70	No data	1.70	1.70	1.70	1.70	1.50
SE-8	1.50	1.70	1.70	1.70	1.70	1.70	1.70	No data	1.50	1.50	1.70	1.70	1.30
SE-11	1.10	1.10	1.10	1.50	1.70	1.50	1.50	No data	1.10	1.10	No data	1.50	1.10
SE-12	1.50	1.50	1.50	1.50	1.50	1.90	1.50	No data	1.50	1.50	1.50	1.50	1.10

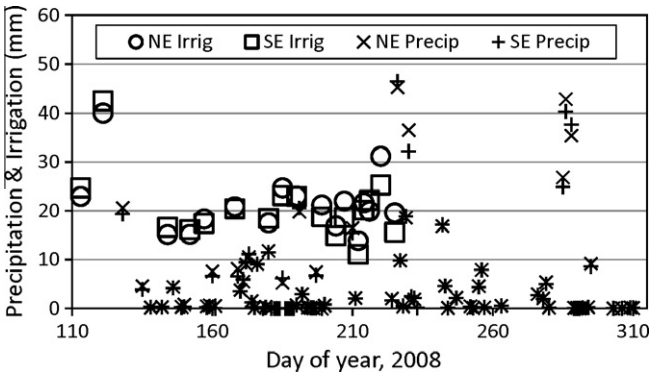

Fig. 3. Magnitudes (mm) of precipitation and irrigation events on the NE and SE irrigated cotton lysimeters from the beginning of pre-plant irrigations through the 2008 cotton growing season. Two pre-plant irrigations totaling, on average, 65 mm were applied. Planting was on day of year 141.

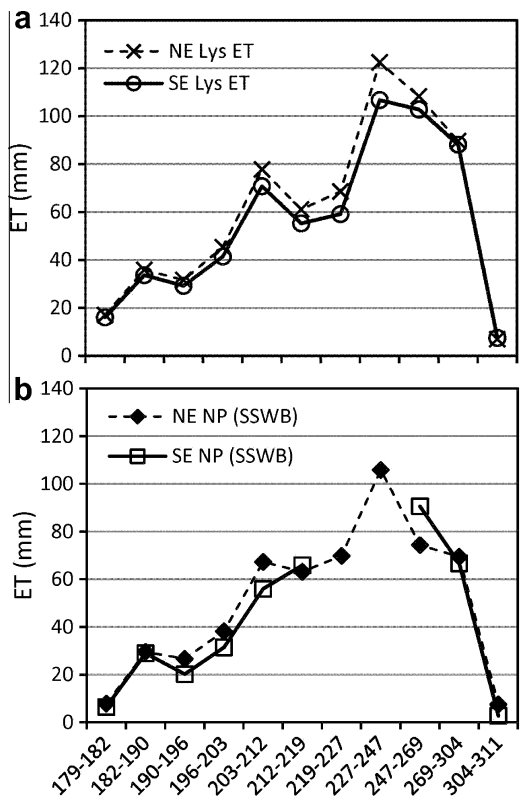

Fig. 4. Evapotranspiration (ET) for the eleven measurement periods as measured by the NE and SE weighing lysimeters (a), and by the simple soil water balance (SSWB) methods using the neutron probe (b). Some SSWB data are missing due to user errors in neutron probe readings.

(Fig. 5C,D). Although LAI was similar in the NE and SE fields for the first part of the season (through DOY 210) and near its end (DOY 304), there were large differences in mid season, with the LAI in the NE field significantly smaller than that in the SE field on DOY 220 and 263 (Fig. 6). Reasons for the relatively smaller LAI in the NE field were not obvious, although row orientation may have played a role. However, Lunagaria and Shekh [25] found that north-south row orientation increased LAI of narrow-row winter wheat, rather than decreasing it. Whatever the reasons for the greater plant width and height on the NE lysimeter relative to the NE field, the differences were likely related to presumed greater LAI on the NE lysimeter than in the field, which would explain the greater ET from the lysimeter water balance. Also, greater plant height on the lysimeter could have reduced the aerodynamic resistance to ET flux on the lysimeter. The effect was not constant. During the period of rapid LAI increase from DOY 182 to 220, the NE lysimeter ET was from 16% to 21% greater than the NE field ET, but by the time that full LAI was achieved (~DOY 220) lysimeter and field ET matched closely before lysimeter ET again exceeded field ET during a period of heavy rainfall late in the season. These results should be considered in light of the coefficient of variation of field ET, which ranged from 0.03 to 0.23 during the DOY 182-220 period.

Using the SSWB approach on a control volume of 2.4-m depth, the SE field ET matched the SE lysimeter ET well ($r^2 = 0.96$, RMSE = 9.5 mm, slope = 0.94, intercept = 10.3 mm; slope not significantly different from unity, and intercept not significantly different from zero) (Fig. 7B). The NE field ET was less than the NE lysimeter ET ($r^2 = 0.93$, RMSE = 10.1 mm, slope of 1.15 and intercept of 1.7 mm; slope not significantly different from unity; intercept not significantly different from zero) (Fig. 7A). Nearly identical linear regression results were obtained when the ZFP water balance was used to calculate ET from the fields (Table 2), lending confidence in these results. Since intercept terms were not significant at the $P = 0.05$ level, regressions were run again with no intercept term (i.e., intercept = 0); and for both SSWB and ZFP methods of field ET calculation, slopes were significantly <>1 only for the NE lysimeter ET regressed against the NE field ET. Differences between lysimeter ET and field ET 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. In separate field experiments on the Pullman soil, Evett et al. [5,26] found that a single neutron probe access tube was sufficient to represent soil profile water content to within 10 mm over a 1-m depth. For a 2.4-m profile, a single tube should provide data to within 24 mm (95% confidence interval); but change in storage data could, at worst, have 48 mm variation for the SSWB method applied to a 2.4-m deep control volume using a single access tube. According to the central limit theorem, absent bias in the NP calibration, use of multiple access tubes (four in the present case) should reduce the variation of the mean change in storage. It may be that the documented variation in plant height, width and LAI in the field induced variation in field ET that in turn would have required more than four access tubes per field in order to obtain a mean field ET value representative of the overall field ET to within <10 mm. We note that the variation in plant characteristics in this field during the BEAREX08 campaign was much greater than has typically been found in prior studies.

Calculations of soil hydraulic conductivity [$K(\theta_v)$, m/s] averaged over each of the eleven periods between NP readings and over the layer between each pair of adjacent neutron probe measurement depths showed that hydraulic conductivity was minimized and approached zero at 100- and 120-cm depths (example in Fig. 8A). Calculations of total hydraulic head gradient ($\Delta H/\Delta z$, dimensionless) similarly averaged showed that $\Delta H/\Delta z$ approached zero in the layer between 30- and 50-cm measurement depths and in the layer between 130- and 150-cm measurements depths, and that it was small below 150-cm depth (example in Fig. 8B). Subsequent calculations of the period-averaged soil water flux (mm) showed that flux was near zero in the layer between 110- and 130-cm depths (Table 3), with total flux between DOY 179 and 311 of <1 mm in the NE field and <3 mm in the SE field. A total downward flux over the season was calculated for the NE and SE fields between 130- and 150-cm depths of 23 and 17 mm, respectively. Overall, these results are coherent with the depths of soil water extraction listed in Table 1. However, they do not agree with the depths of the zero flux plane listed in Table 1. That is because the Table 1 depths were determined by observing the depths at

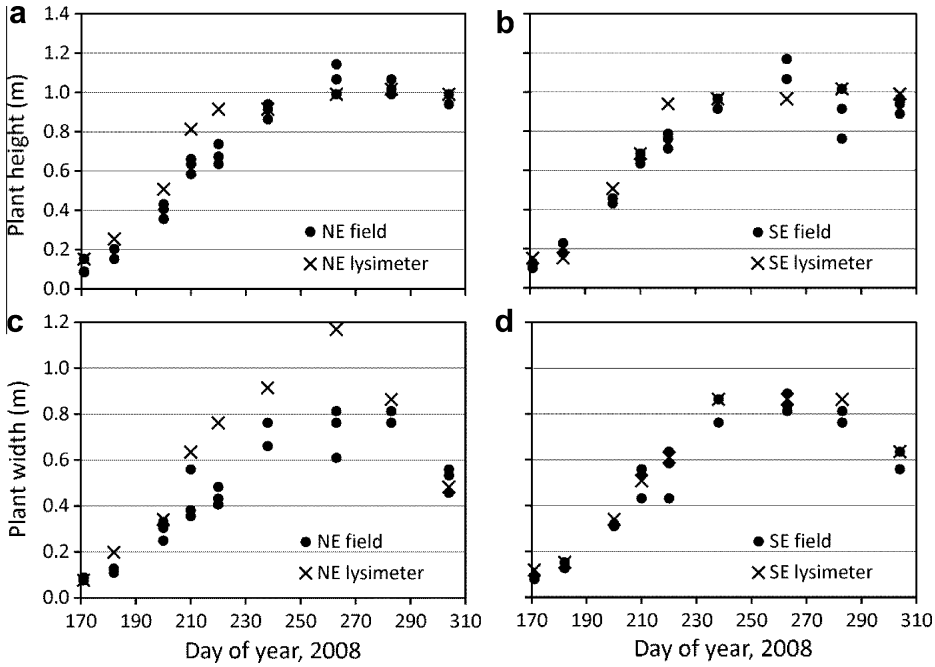

Fig. 5. Plant height (m) in the NE field and lysimeter (a) and the SE field and lysimeter (b); and plant width (m) in the NE field and lysimeter (c) and the SE field and lysimeter (d).

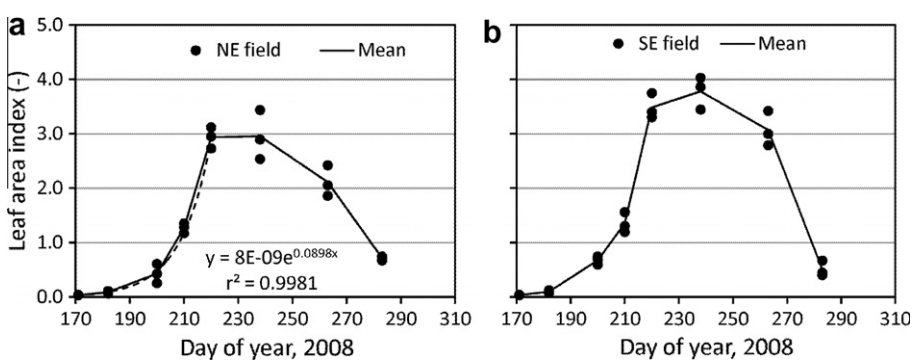

Fig. 6. Leaf area index (dimensionless) in the NE field (a) and the SE field (b) for the 2008 cotton season. The NE field LAI was significantly less than that in the SE field for DOY220 and 263.

which $\Delta H/\Delta z$ sign reversal appeared to have occurred. This apparent dichotomy can be explained thusly. First, the apparent depth of $\Delta H/\Delta z$ sign reversal may differ from the actual depth by up to 20 cm in our case since measurements were discretized depthwise by 20 cm. Second, soil water flux is a function of both $\Delta H/\Delta z$ and $K(\theta_v)$, and calculations showed that the latter was minimized due to soil dryness at a depth slightly above that at which hydraulic gradient sign reversal occurred, so the apparent minimum of flux occurred at depths somewhat more shallow than indicated by observations of $\Delta H/\Delta z$ alone. However, fixing the ZFP at 130 cm did not improve estimates of field ET.

Soil water flux values were negligible at the ZFP depth (Table 3). Adjusting the ET computed using the SSWB+F method applied to a 2.2-m deep control volume and using fluxes calculated for the soil layer centered at 2.2-m depth would result in decreasing the ET estimate by 13 mm in the NE field and 16 mm in the SE field for the period from DOY 179 to 311, or ~0.1 mm/d. In comparison, drainage under vacuum measured from the NE and SE lysimeters during this period was 9.2 and 0.1 mm, respectively. The fact that ET computed using all three methods (SSWB, ZFP and SSWB+F) did not differ substantially is further evidence that vertical flux at the bottom of the control volume was minor at all times except late in the season after substantial rains. This late season flux was after the dates of data used for any comparisons of ET from EC systems with ET from lysimeter and field soil water balance measures in this or other papers in the BEAREX08 special issue. The mean daily ET between crop emergence and senescence was 6.2 mm d^{-1}, while the mean daily ET during the period of rapid crop growth was 7.6 mm d^{-1}. Estimated vertical soil water flux at the bottom of the profile ranged from 2.2% to 6.0% of period total ET over the time from crop establishment to senescence, with most flux occurring later in the season during and after the period of heavy rainfall.

4. Relative accuracy of ET from water balance and flux station methods

Comparison of weighing lysimeter to field soil water balance data indicated that ET measured using the NE lysimeter averaged 0.6 mm d^{-1} greater than that measured in the field during the period of rapid leaf area expansion when crop growth on the NE lysimeter did not match that in the surrounding field. ET differences in the NE field (ET_lys/ET_SSWB) ranged from −5% to 18% during this period, with minimum error of the NE lysimeter (ET_lys – ET_SSWB) of

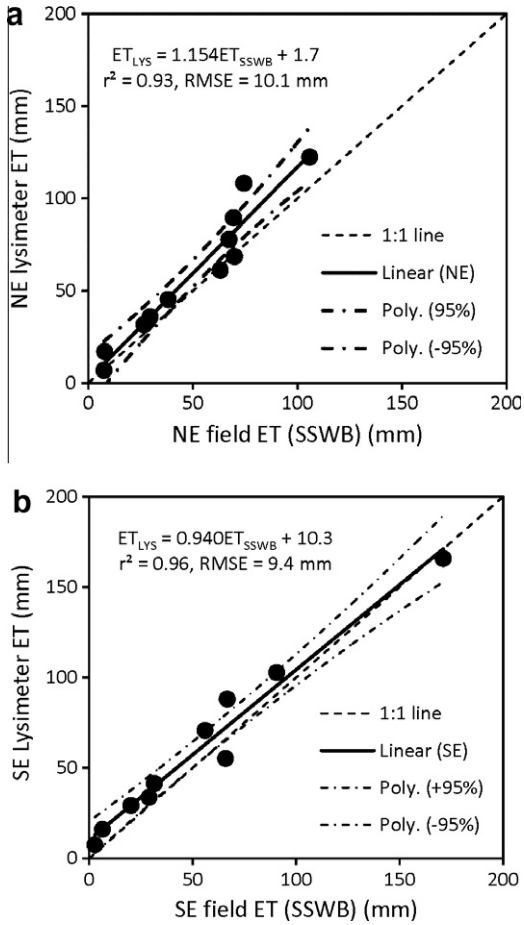

Fig. 7. (a) Comparison of the ET calculated from neutron probe data for the NE field using the simple soil water balance on a control volume of 2.4-m depth with zero deep flux assumed (SSWB) to the NE lysimeter ET. (b) Comparison of the SE field ET determined using neutron probe data by SSWB to the SE lysimeter ET. The solid line (Linear) is the regression line. The curved lines (Poly) are polynomial curves fitted to the +/−95% confidence interval data.

Table 2
Linear regressions of lysimeter ET against field ET for the simple soil water balance (SSWB) method and the zero flux plane (ZFP) soil water balance method. Data are presented for the NE field and lysimeter and for the SE field and lysimeter. Where indicated by NA in the column for the intercept term, the intercept was not fitted, resulting in the regression line being forced through zero.

Location\method	Intercept (mm)	Slope	r^2	RMSE (mm)
NE\SWB	1.7^{NS}	1.15^{*}	0.93	10.1
NE\SSWB	NA	$1.18^{*\dagger}$	0.88	9.6
NE\ZFP	3.2^{NS}	1.13^{*}	0.91	11.0
NE\ZFP	NA	$1.18^{*\dagger}$	0.88	10.6
SE\SSWB	10.3^{NS}	0.94^{*}	0.96	9.4
SE\SSWB	NA	1.05^{*}	0.87	11.4
SE\ZFP	9.2^{NS}	0.96^{*}	0.96	9.7
SE\ZFP	NA	1.05^{*}	0.87	11.1

^{NS}Not significant at $P = 0.05$.
* Significant at the $P = 0.05$ level.
† Significantly different from unity.

−0.4 mm d^{-1} and maximum error of 1.3 mm d^{-1}. The ET values from the SE lysimeter, which exhibited crop growth similar to that in the surrounding field, were found to have much smaller (negligible) errors when compared with ET from the soil water balance method applied in the surrounding field. Even when weighing lysimeters did not represent the field well (the NE lysimeter), the error rate (mm d^{-1}) was substantially smaller than that observed using flux stations unless closure was forced using an abundance of net radiation and soil heat flux data not normally collected at EC stations [15].

For the four EC systems used on the NE and SE weighing lysimeter fields during the BEAREX08 campaign, Alfieri et al. [15] showed that the EC system errors relative to the mass balance meaures of ET depended on the degree of data correction and adjustment applied (Table 4). Due to the problems with overestimation of ET by the NE lysimeter, most discussion in the following will involve comparisons between the two EC stations and the weighing lysimeter in the SE field. With stringent quality control and routine error correction and data transformations normally applied to EC station data, mean EC system ET errors amounted to between 1.9 and 2.7 mm d^{-1}, while mean EC method sensible heat flux errors ranged between 1.4 and 1.9 mm d^{-1}; both being under estimated by EC systems. These ET errors were 32% and 44% of the mean SE lysimeter ET of 6.2 mm d^{-1} during the period of comparison (DOY 182-219). Surface renewal (SR) and flux variance (FV) estimates of sensible heat flux were comparable to those from EC systems at this level of correction [27], indicating that error rates for ET estimation by SR and FV methods would also be comparable to those from the EC stations.

The second step of adjustment to EC data was to force energy balance closure for the EC systems. The available energy at each station was computed from the net radiation data from six net radiometers in the field and the soil heat flux data from 20 soil heat flux plates in intensive heat flux measurements in each field [15]. Note that when EC stations are deployed singly, as is common when EC stations are used to estimate field crop ET, forcing closure depends on net radiation and soil heat flux data only from the one net radiometer and three or four soil heat flux plates normally deployed at an EC station. After energy balance closure was forced using the mean available energy (6 R_n and 20 G measurements), ET estimated by EC in the SE field was closer to that measured using the SE lysimeter, but mean errors were still 17–19% of lysimeter ET. Note that in this and subsequent steps of adjustment, the ET estimate available is only for the daylight hours since the Bowen ratio used for closure was not reliable at night. Thus, long term ET estimation is compromised in this advective environment where nighttime ET routinely is important and may be as large as 12% of total 24-h ET for full cover cotton and alfalfa [28] and as large as 50% of 24-h ET for bare soil conditions and for LAI <0.1 [29]. Note that other methods of EC data closure are available that do not use the Bowen ratio, but were not tested.

The third step in adjustment of EC station data was a correction for leaf area index, which was larger on the NE lysimeter than in the footprints of the EC stations in the NE field. This adjustment applied only to the NE field; and it reduced the NE field EC station ET errors to ~14%, still underestimating ET. The final step in EC station data adjustment involved estimating the effect of advection of energy across the field to the EC stations [15]. This adjustment involved application of theory to micrometeorological data collected at several upwind sites. It reduced the EC station ET error to the 6–7% range. Both the leaf area index and advection adjustments went well beyond what can be considered normal for EC station corrections, or even routinely feasible.

5. Conclusions

In the BEAREX08 experiment, the standard practice of measuring plant height and width in the lysimeters and the surrounding fields worked to alert us that the NE lysimeter would not be representative of the field; this fact was confirmed by results of the standard practice of measuring soil profile water content in a network of neutron probe access tubes in the field surrounding each lysimeter and computing the field soil water balance based ET for

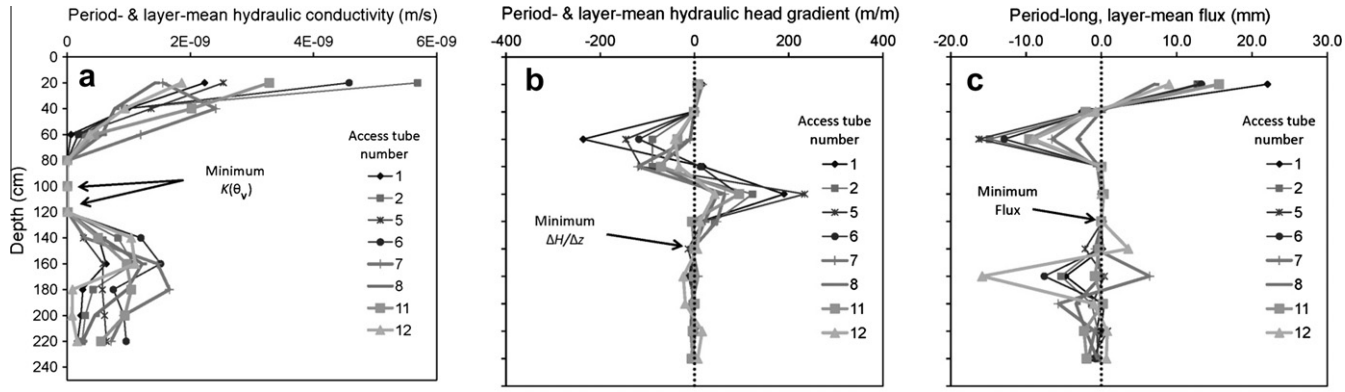

Fig. 8. Depth-wise examples of hydraulic conductivity, hydraulic head gradient and total flux for the period from day of year 304 to 311: (a) hydraulic conductivity [$K(\theta_v)$, m/s] averaged over the period and over the layer between each pair of adjacent neutron probe measurement depths; (b) total hydraulic head gradient ($\Delta H/\Delta z$, dimensionless) averaged over the period and over the layer between each pair of adjacent neutron probe measurement depths; (c) total flux (mm) for the period calculated from period- and layer-mean hydraulic conductivities and total hydraulic head gradients for each depth.

Table 3
Period-averaged, layer-centered soil water flux (mm, positive means upward, negative means downward) for each period in days of year. Note that for the SE field, data for the period day of year (DOY) 219–227 are missing due to a lack of neutron probe readings on DOY 227. Soil water flux values were calculated for the SE field for the period DOY 219–247.

Period	Depth of layer center (cm)									
	220	200	180	160	140	120	100	80	60	40
NE field										
179–182	−0.1	0.0	0.0	−0.6	−0.1	0.0	0.0	0.0	0.0	−0.2
182–190	−0.9	−0.2	−0.6	−6.4	−1.2	0.0	0.1	0.0	−1.1	−1.7
190–196	−0.5	−0.1	−0.6	−4.8	−1.1	0.0	0.1	−0.2	−2.7	−0.7
196–203	−0.8	−0.1	−0.7	−6.0	−1.3	0.0	0.1	−0.7	−2.0	−0.4
203–212	−1.1	−0.3	−1.0	−7.5	−1.6	0.0	0.1	−0.7	−1.5	0.9
212–219	−0.7	−0.4	−0.7	−5.3	−1.2	0.0	0.1	−0.2	−0.4	0.3
219–227	−0.8	−0.4	−0.7	−6.0	−1.6	−0.1	0.1	−0.1	−0.3	0.1
227–247	−2.2	−0.7	−1.3	−15.1	−4.4	−0.2	0.3	−0.1	−0.5	−1.1
247–269	−2.1	−1.1	−0.8	−17.1	−4.6	−0.1	1.0	0.2	−0.5	0.4
269–304	−3.3	−0.7	−1.8	−25.4	−5.1	0.2	1.3	0.0	−17.4	26.0
304–311	−0.7	−0.1	−0.5	−4.3	−0.7	0.1	0.1	0.0	−13.2	−1.7
SE field										
179–182	−0.1	−0.1	−0.2	−0.5	−0.1	0.0	0.0	0.0	−0.3	−0.2
182–190	−1.2	−1.3	−2.8	−4.1	−0.8	0.0	0.1	−0.6	−4.9	−1.9
190–196	−0.7	−1.1	−2.7	−2.2	−0.9	0.0	0.0	−1.3	−3.1	−0.8
196–203	−0.7	−1.2	−3.5	−3.3	−1.1	−0.1	−0.3	−1.1	−1.7	−0.8
203–212	−0.9	−1.8	−4.1	−4.5	−1.5	−0.2	−0.2	−1.0	−1.6	0.7
212–219	−1.0	−1.1	−4.0	−3.2	−1.2	−0.2	−0.1	−0.6	−0.8	0.8
219–247	−3.4	−4.8	−14.5	−20.3	−6.4	−1.6	−0.2	−0.9	−1.6	1.0
247–269	−2.2	−4.8	−9.2	−17.8	−4.5	−0.8	3.4	1.8	−1.6	4.6
269–304	−4.8	−5.3	−15.1	−16.3	0.2	0.0	1.2	−0.3	−47.3	179.4
304–311	−0.9	−1.1	−2.5	−2.6	0.4	0.0	0.1	−0.2	−7.1	−1.1

comparison with lysimeter ET, a practice that has been followed at the study site for >20 years.

Evapotranspiration fluxes from the SE lysimeter were representative of those from the field throughout the season and could be used with reasonable certainty for comparisons of ET fluxes and energy balance closure derived from Bowen ratio and eddy covariance measurements at sub-daily. daily and longer time intervals. Fluxes of ET from the NE lysimeter were larger than those from the field through the period of rapid vegetative growth to when peak plant height was achieved, that is from DOY 182-220. This was due to plants on the lysimeter having greater height and width than those in the field. Comparisons of ET fluxes from eddy covariance and Bowen ratio systems to fluxes from the NE lysimeter should take into account the fact that NE lysimeter ET fluxes were up to 18% greater than ET fluxes from the NE field during this period. Even so, the error rate for the NE lysimeter was substantially less than that from the EC systems unless closure was forced. With correction for the known deviance from field ET based on field soil water balance, the ET data from the NE weighing lysimeter also could be used for sub-daily, daily and longer time period comparisons with ET from EC and Bowen ratio systems; but such correction is inhibited by the relative infrequency of neutron probe readings. In making both conclusions we are assuming that the mean ET derived using data from four NP access tubes, widely spaced in the field, is substantially representative of the mean field ET. As discussed previously, we have extensively studied the question of whether properly acquired NP data are representative of field soil water balance and ET, with positive results.

The major conclusion of this study is that weighing lysimeters, supported by a network of soil water balance based measures of ET in the surrounding field and ancillary measurements of crop stand and growth both within and outside the lysimeters, are an important and viable source of ground truth ET data for comparison with not only eddy covariance and other flux station estimates but with ET estimates derived from remote sensing. In this regard we emphasize that these mass balance methods (lysimetry and soil

Table 4
Differences between EC stations (sites 1 and 8 in the NE field and sites 2 and 9 in the SE field) and weighing lysimeters (NEL = NE lysimeter, SEL = SE lysimeter) at each stage of adjustment. Differences are given as mean 24-h or daytime LE in W m^{-2}, as daily ET in mm (calculated based on 14-h of daylight), and as percentages of weighing lysimeter measured ET (taken as a mean of 6.2 mm d^{-1} during the study period). Corrections were successive with each additional correction making further adjustment to the results from those applied before. All mean EC station estimates of ET were less than lysimeter estimates of ET. Based on data presented here and in [15].

	W m^{-2}	mm	% Difference		W m^{-2}	mm	% Difference
After routine corrections typically used with EC stations (24-h values)							
NEL-Site 1	69	2.43	39.6%	SEL-Site 2	76	2.68	43.6%
NEL-Site 8	49	1.73	28.1%	SEL-Site 9	55	1.94	31.5%
After closure was forced using data from the 6 net radiometers and 20 soil heat flux plates (daytime only)							
NEL-Site 1	102	2.10	34.1%	SEL-Site 2	56	1.15	18.7%
NEL-Site 8	76	1.56	25.4%	SEL-Site 9	52	1.07	17.4%
After closure was forced using the additional data assigning the full residual to LE under advective conditions (daytime only)							
NEL-Site 1	91	1.87	30.4%	SEL-Site 2	52	1.07	17.4%
NEL-Site 8	71	1.46	23.8%	SEL-Site 9	51	1.05	17.1%
After adjustment for LAI differences (only for the NEF) (daytime only)							
NEL-Site 1	41	0.84	13.7%				
NEL-Site 8	43	0.88	14.4%				
After adjustment for advection using data from four upwind mini weather stations (daytime only)							
NEL-Site 1	6	0.12	2.0%	SEL-Site 2	20	0.41	6.7%
NEL-Site 8	16	0.33	5.4%	SEL-Site 9	19	0.39	6.4%

water balance) are the standards of objective truth about ET fluxes. A secondary conclusion, based on the data presented in [15], is 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 using more than the amount of net radiation and soil heat flux data typically available to EC station operators.

Fluxes of ET calculated using the zero flux plane method based on neutron probe measurements to the depth of the zero flux plane agreed well with ET fluxes calculated using a simple soil water balance based on neutron probe measurements over a 2.4-m deep control volume and no flux calculation at the 2.4-m lower boundary. Based on flux calculations, the zero flux plane appeared to be located somewhat above the depth indicated by examining only the depth at which soil hydraulic head gradient apparently reversed in sign. This was due to the fact that soil water flux is calculated using both hydraulic head gradient and hydraulic conductivity; and in this case the latter reached near zero values at a depth above that at which the hydraulic head gradient reversed in sign. Still, ET estimates were not improved by fixing the zero flux plane at the depth indicated by flux calculations. In accordance with suggestions of Arya et al. [10] and others, the depth of the zero flux plane should be determined primarily by the depth of apparent hydraulic head gradient sign reversal, but due attention should also be given to the depth at which flux calculations indicate a minimum near zero.

At least in the soil and climate at Bushland, soil water balance estimates of crop ET can be made with small error using the neutron probe. The relatively larger variation in soil water balance estimates, compared with prior studies, indicated that when plant cover is quite uneven, as it was during BEAREX08, the number of neutron probe access tubes could usefully be increased. Questions about the soil water status during periods between the infrequent measurements possible with the neutron probe would be usefully answered by an accurate, automatic deep profiling soil water sensor, the existence of which would substantially improve mass balance estimates of ET at shorter time scales and over larger field areas than is currently possible. Development of such an automatic and accurate deep profiling soil water sensing system should be a high priority for agronomic, hydrologic and climatological research and management.

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