Reviewer 1:

1: Line 6: “Bushland” is misspelled.

Response: Corrected.

2: Measurement of Net Radiation: The authors should add more discussion about the measurement of net radiation, which is the largest SEB term. It is not sufficient to assume that there is no error in the net radiation measurement. Characterization the true variability and/or variance in the radiometer data over the 30 minute periods, as this is directly related to the basis for estimating SEB closure. For example, the NR-Lite radiometer is particularly prone to wind induced cooling errors (Brotzge and Duchon 2000).

Some indication of the QAQC measures used with the radiation measurement, and some indication of the calibration and maintenance of this sensor would be appropriate. Brotzge and Duchon is a good reference for the NR-Lite in particular.

Lines 233-240: If nothing else, more description of the experimental (physical) set up is needed. What height was the net radiometer mounted? Since the change in height of the crop (from 0 to >1m), there was a significant change in the surface roughness, which affects turbulent flux directly. Is it possible that the height of the radiometer could have also been a source of error (or footprint) in the radiation measurement? Did a change in the surface roughness potentially contribute to a change in wind speed at the height of the NRLite, and consequently give a biased estimate of Rnet over the course of the season? These kinds of considerations should be treated at least cursorily in the methods section, if not the results.

Response: An error in instrument model was corrected. Data from the NRLite were inconsistent, therefore an adjacent Q*7.1 was used for the net radiation. It was calibrated just prior to installation and verified according to our QA/QC procedure. A description of the QA/QC procedure for the net radiation data was added with a citation for a recent publication on QA/QC for all meteorological measurements on the lysimeter.

3: Eddy covariance calculations: It would help if the authors were more explicit about the standard correction procedures that were used, as these can have a very significant impact on the magnitude of the SEB residual calculated over different averaging periods. What method of despiking was used? Which high and low pass filtering methods were used? Referencing the chapter by Moncrieff et al. from the Handbook of Micrometeorology is not specific enough - please explain which algorithm (simple
Reynold's decomposition, linear detrending, recursive filters) was used. The chapter details that the filtering method modifies the spectral distribution of the flux contributions, especially the low frequency contributions which are linked to the time scales indicated by the authors in this study. Rannik and Vesala (1999) is a good original reference for this. Rannik et al. (2016) is a more up to date and general discussion of random and systematic error in EC.

Response: More detail was added to the section regarding EC corrections.
Specifically, the despiking method following Vickers and Mahrt, 1997 was added as well as the block averaging method for high and low pass filtering. A citation for Moncreif et al., 1997 was originally included with the citation to the Handbook of Micrometeorology, which includes the calculations selected for this study.

4: Statistics used in the manuscript: I found the authors' use of statistics, specifically the coefficient of variation, somewhat confusing and needing clarification. While there is no absolute consensus on which statistics should be used to evaluate EC accuracy in regards to closure of the SEB, previous published methods for evaluating EC accuracy (such as residual energy as a fraction of total available energy and linear regression) are numerous and fairly consistent in methods. Novel ideas (such as the CV) departing from these standard approaches are legitimate but need more thorough explanation. I am more familiar with the use of CV in single variable analysis, and the use of CV to compare model residuals is novel and worthwhile here. Readers would be better served if the authors are more explicit about how the CV was calculated. When I calculate the value of mean hourly ET from RMSE and CV in the tables (i.e. \( \mu = \text{RMSE}/\text{CV} \)), values range between 0.0008 and 0.0017, presumably in \( \text{mm}/30 \text{ min} \) (see table). Even if the authors are using the practice of multiplying the CV by 100 (as a percentage), it is unclear how this can be correct, as the 1:1 plots seem to show mean values are higher, ranging on the order of 0.1-0.6 \text{mm}/30 \text{ min}.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>All Season</th>
<th>0.54 m</th>
<th>0.80 m</th>
<th>0.91 m</th>
<th>1.07 m</th>
<th>1.1 m</th>
<th>&lt;1.13 m</th>
<th>1.13 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2m RMSE</td>
<td>0.036</td>
<td>0.037</td>
<td>0.037</td>
<td>0.038</td>
<td>0.034</td>
<td>0.033</td>
<td>0.038</td>
<td>0.032</td>
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<tr>
<td>2m CV</td>
<td>27.41</td>
<td>26.94</td>
<td>23.53</td>
<td>28.06</td>
<td>25.6</td>
<td>27.02</td>
<td>27.44</td>
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<td>( \mu = \text{RMSE}/\text{CV} )</td>
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<td>0.00137</td>
<td>0.00157</td>
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<td>0.00133</td>
<td>0.00132</td>
<td>0.00138</td>
<td>0.00124</td>
</tr>
<tr>
<td>4m RMSE</td>
<td>0.036</td>
<td>0.038</td>
<td>0.039</td>
<td>0.036</td>
<td>0.035</td>
<td>0.032</td>
<td>0.039</td>
<td>0.037</td>
</tr>
<tr>
<td>4m CV</td>
<td>25.68</td>
<td>26.33</td>
<td>23.16</td>
<td>26.18</td>
<td>26.4</td>
<td>25.98</td>
<td>27.41</td>
<td>43.54</td>
</tr>
</tbody>
</table>
Response: The CV used in this manuscript is RMSE expressed as a percentage of the mean from the lysimeter data for each variable, which is briefly and parenthetically mentioned on line 291. Usage of the CV terminology was chosen as that is how the SAS output was worded. As it is not typical terminology and causes confusion, the term CV was replaced with %RMSE.

5: It is also unclear to me if the use of the absolute value of H for the calculation of CV is valid - what happens for periods when mean flux is negligible (most night periods)? Perhaps adding the mean value of ET to Table 2 would help clarify the resulting CV. Generating a similar table for H would also help, possibly more than do the 1:1 plots in Figure 4. Regardless of these criticisms, I do agree that the use of CV is potentially a valuable contribution. That the summed daily flux values show significantly reduced CV is a particularly useful statistic quantifying the robustness of the ET estimate.

Response: The use of the absolute values was to remove the effects of positive and negative numbers creating an unrealistic mean. Using the absolute values allow for calculating the RMSE as a percentage with a more reliable mean. The periods where flux values are negligible present a case for using relative differences where negligible values can still provide comparative analysis. Replacing the term CV with %RMSE should help clarify.

6: Similarly, it would be helpful for the authors to discuss why ANOVA was used, rather than a more traditional treatment using methods from turbulence analysis (such as spectral intensity or stability conditions). Even if we assume that ANOVA is a valid technique for characterizing variability between periods, it isn’t clear to me why the authors did not include turbulent flow regimes in this analysis - the surface conditions affect not only the flux magnitude but also the transport process themselves, and this will be represented in sampling and calculation of flux. Overall, it is not clear why ANOVA was used beyond generating confidence intervals, and the relationship between the p value and the CV (for which confidence intervals are not defined) needs...
to be explained. Overall, this statistical treatment requires a stretch of belief on the part of the reader, and more explicit description of the method is needed.

Response: The use of the ANOVA was to test if differences between periods were statistically significant and allow for mean separation testing. Stability conditions, or other factors, could explain the differences; however, the ANOVA was selected to test the data based solely on the values. The changing surface conditions were treated as the cause of any differences, but we felt a statistical test made evaluating the periods more robust. Additional discussion was added to lines 283 – 288.

7: Line 254: The authors suggest that negative fluxes lead to "misleading calculations" in the ratio of residual to AE, but a similar problem emerges with a discontinuity in CV (when the mean value of flux is near zero). The authors should explain more clearly what is meant by the ratio method being "misleading", and why the CV method is a better calculation.

Response: I believe this is due to the confusion caused by our choice of using the CV terminology. An explanation for the misleading calculations is discussed in the response to item 5 and replacing the term CV with %RMSE should clarify the text.

8: Spatial and temporal heterogeneity: The observation that averaging of daily flux data improves the error is helpful in qualifying the assertion that EC can be a valuable tool in measuring and managing consumptive water use (and I heartily agree with this sentiment). However, the authors might discuss in more detail that flux components (Rnet, G, H, LE) are not well coupled on a 30 minute basis, as is pointed out in terms of thermodynamic of near surface soil heat storage. This is typically shown in turbulence studies via spectral intensity, but maybe there is a simpler way to explain the concept of temporal lagging in low frequency energy transport.

Response: A brief explanation was added in lines 394 – 400.

9: Line 307-308: The use of a Kljun et al.'s footprint model is probably the best and most practical estimator of contributing area. However, please provide more detail as to how the model was executed. How was the boundary layer height estimated, and was it estimated on 30 minute periods, or daily? Were the contribution distances based on the "climatology" footprint output of the model, or are these distances the average value under neutral/unstable conditions? Why not describe the contributing area output from
the model, rather than just the fetch distance? If significant error in the 8m sensor is to be attributed to inhomogeneity in the footprint, this should be characterized explicitly—that’s the point of Kljun’s model. I also suggest that you cite their most recent paper on the FFP model (Kljun et al. 2015).

**Response:** A note was added indicating the footprint was estimated using the EddyPro processing software. As the contribution area was only briefly mentioned, additional details on calculation methodology were thought to be unnecessary. Additional details were added to lines 319 – 320. The Kljun et al., 2004 citation was used as it is the publication listed as the source for the Eddy Pro calculations.

10: Line 348: I am not convinced that the regression line (or the data) show that EC underestimates the near-zero values of ET. The linear regression compares the entire set, so can’t be attributed to a particular range, even if the overall trend is to underreport smaller values and overestimate larger values.

**Response:** The statement was removed.

11: Line 353: The procedure of forcing SEB closure and distributing the residual to H and LE via the Bowen ratio is somewhat undermined by the author’s finding of significantly greater error in H than error in LE estimates. It would be worthwhile to address this inequity if the preferred method is to force closure using the ratio of Bo = H/LE.

**Response:** A statement addressing the error in H affecting the Bowen ratio was added to lines 365 – 368.

12: Line 354: Why is it important that CV decreases when using only daytime values? Is this not just an artifact of the denominator (the mean value of flux) being much greater during the day? In this way, the relative value of variability produced by CV seems to me just as “misleading” a calculation as is the ratio of the residual to the available energy.

**Response:** Replacing the term CV with %RMSE should clarify the statement. The %RMSE decreasing indicates lower relative error. During the daytime, the mean of the flux increases, but the RMSE increases as well. An explanation for the statistic was included in lines 368-370.

13: Line 400: The discussion regarding the relative contributions of error (from measurement of H and LE) compared to differences in advection and heat storage terms is not convincing. In particular, calculating H(lys.) as a residual from the LE calculated from ET requires a lot of assumptions about capturing all energy pathways, about the
time scales associated with storage terms, about thermodynamic and phase change energy, and about the integral time scales of turbulent transport being instantaneously linked to available energy. Assigning relative magnitudes of error is not the same as attributing the source of errors, particularly when only 30 minute periods were used for determining the turbulent flux. The attribution of error to canopy height (and canopy heat storage) is also problematic considering that EC error may also be due to changes in the height of the roughness sublayer that cause flow distortion and violate the assumption of constant flux (a divergence different in nature from that caused by advection).

Response: The limitations on H evaluation were noted in lines 348 - 352 and the assertion that EC contains larger errors in H was removed.

14: I strongly suggest that the authors include additional review of the literature on sources of error in EC, including (Sakai et al. 2001; Massman and Lee 2002; Lee et al. 2004; Gu et al. 2005; Mauder et al. 2013; Martínez-Cob and Suvočarev 2015; Rannik et al. 2016), and in the problem of SEB closure (Higgins 2012; Leuning et al. 2012; Irmak et al. 2014)

Response: Additional discussion on error was added based on the references provided.

15: References: Many of the citations use the abbreviation et al., instead of listing all authors. Please update your citations to include all authors.

Response: The references have been updated to the MDPI format.
Reviewer 2:

1: Overestimation of the eddy covariance H: 50% of H underestimation from EC appears too much to me, the literature range of underestimation is around 5-20%, eg. Foken 2008, Frank 2013...

If such an underestimation occurs, likely some set-up and processing issues should be considered, such as wind blowing back to the anemometer (+/- 20°C is the disturbed sector of CSAT3), advection, coordinate rotation,...

However, if the EB imbalance is around 65%, how could H alone be underestimated by 50%? The underestimation of H is evaluated by means of H from lysimeters. The authors compute H from Lysimeters by the residuals between EB and LE (converted from ET measured from Lysimeters). Which is the uncertainty related to this estimate? Which is the uncertainty related to the computation of LE from Lysimeters and the one related to the other meteorological variables, Rn and G? (see Leuning 2012 AFM)

Considering LE, is there any reasons for which the LE from lysimeters could be underestimated? From a recent paper from Perez-Priego (AFM 2017), indeed LE from EC appears to be lower (14-35%) than the one from lysimeters. If LE from lysimeters is underestimated -> H as computed from lysimeters would be over-estimated -> H from EC under-estimated and LE from EC over-estimated. Could the authors exclude this hypothesis?

Response: The limitations on H evaluation were noted in lines 348 - 352 and the assertion that EC contains larger errors in H was removed.

2: For the reasons explained at point 1, I don't think that the discussion can be so straightforward regarding the quantitative evaluation of ET from EC without a presentation of the potential uncertainty of the results, and the limitations of the work should also be highlighted.

I'm not an expert in crop management but I would also add some broad considerations on the meaning of these results, such as, in what a wrong ET estimates around the percentage found (10-20%) could translate in the context of water saving or irrigation?

Response: Discussion of the impacts of error in ET estimates were added to lines 429 – 434.

3: Introduction/Discussion

I think that the introduction is unbalanced compared to the discussion. Even if well written, in the introduction is very long and too much space is dedicated to the description of other authors' work eg.from line 104 to 151.

I suggest the authors reduce this part and keep just a few short examples useful to the reader to follow the point.

The opposite is true for discussion, which appears to be actually a brief summary of the
results. I think that most of the descriptions used in the introduction could be exploited in the discussion instead. The conclusion contains some information that should be instead used in the discussion eg l.423-428

Response: The introduction was shortened and the relevant studies from the literature review were moved to the discussion to demonstrate their relevance to this study.

4: l.72 then the net exchange of these molecules between the surface and the atmosphere can be determined

Response: The sentence was corrected.

5: l.79,84 these lines could be moved in the EC paragraph in the methods section

Response: The equations were moved to the EC methods section.

6: l.165 I don't think that conversion in inches is needed. And I would express precipitation in mm

Response: The conversion to inches was removed and cm were converted to mm.

8: l.241 EC data were processed, please delete "post"

Response: The sentence was corrected.

11: l.242 Processing involved applying coordinate rotations, time lag compensation using cross-correlation maximization, Webb-Pearson-Leuning (WPL) corrections [23], and high and low-pass filtering [24, 25]

Response: The sentence was corrected.

12: l.253, this method should be referred to as energy balance ratio (EBR) (Mahrt, 1998; Gu et al., 1999) or Wilson et al 2002

Response: The sentence was corrected and the Wilson et al 2002 citation was added.
Response: Discussion and citation was added for Perez-Priego et al., 2017 as well as additional discussion and citations for Chavez et al., 2009, Alfieri et al., 2012, and Ding et al., 2010.

15: l.381-382 due to the trade-off between overestimation during daytime and underestimation during nighttime

Response: The sentence was corrected.

16: l.388 "As many EC studies either analyze several non-consecutive days or a relatively short section of the growing season" Actually this is not true, see Fluxnet, the most of EC sites are meant to be continuous, did you mean in studies which also use lysimeters or crop studies?

Response: The sentence was edited to indicate crop ET studies using EC.
Evaluation of Evapotranspiration from Eddy Covariance Using Large Weighing Lysimeters

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Received: date; Accepted: date; Published: date

Abstract: Evapotranspiration (ET) is an important component in the water budget and used extensively in water resources management such as water planning and irrigation scheduling. In semi-arid regions, irrigation is used to supplement limited and erratic growing season rainfall to meet crop water demand. Although lysimetry is considered the most accurate method for crop water use measurements, large precision weighing lysimeters are expensive to build and operate. Alternatively, other measurement systems such as eddy covariance (EC) are being used to estimate crop water use. However, due to numerous explicit and implicit assumptions in the EC method, an energy balance closure problem is widely acknowledged. In this study, three EC systems were installed in a field containing a large weighing lysimeter at heights of 2.5, 4.5, and 8.5 m. Sensible heat flux (H) and ET from each EC system were evaluated against the lysimeter. Energy balance closure ranged from 64–67% for the three sensor heights. Results showed all three EC systems underestimated H and consequently overestimated ET; however, the underestimation of H was greater in magnitude than the overestimation of ET. Analysis showed accuracy of ET was greater than energy balance closure with error rates of 20–30% for half-hourly values. Further analysis of error rates throughout the growing season showed energy balance closure and ET accuracy were greatest early in the season and larger error was found after plants reached their maximum height. Therefore, large errors associated with increased biomass may indicate unaccounted for energy stored in the plant canopy as one source of error. Summing the half-hourly data to a daily time-step drastically reduced error in ET to 10-15% indicating EC has potential for use in agricultural water management.

Keywords: water management; irrigation scheduling; energy balance;

1. Introduction

Fresh water is an essential resource that is becoming increasingly limited. In some arid and semi-arid regions, groundwater resources are being exhausted with little to no surface water available as an alternate source. Proper water resources management is essential for these areas to extend the availability of water resources. In many cases, water management strategies rely on the use of evapotranspiration (ET) to account for some of the water losses. ET is a combined term that represents water lost through evaporation from the soil or plant surface, as well as water lost through transpiration from the plant. In many regions, such as the Texas High Plains (THP), ET is the largest water loss component in the hydrologic budget [1]. This fact makes accurate ET estimates vital for...
accurately and properly managing crop water. In the THP, and the remainder of the Southern
Ogallala Aquifer region, groundwater recharge is very low at ~11 mm yr⁻¹ [2]. With such little
recharge, the Ogallala Aquifer is deemed a finite resource. To preserve this natural resource for future
generations, conserving the remaining water is paramount.

The THP lies in the Southern Great Plains near the southern end of the Ogallala Aquifer (Figure
1). Agriculture is the predominant land use and irrigated land accounts for the majority of the
agricultural production in this region. In the state of Texas, irrigation accounts for 60% of total water
use; however, in the THP, irrigation accounts for 89% of the total water use [1]. The THP is a major
corn, cotton, wheat, and sorghum producing region with much of the agricultural production under
irrigation. The vast majority of irrigation water is withdrawn from the Ogallala Aquifer. With limited
and sporadic rainfall, the Ogallala Aquifer receives little to no recharge in this region, and is
essentially being mined; therefore, conservation is an integral part of the regional water plan [3]. The
northern and southern parts of the THP are similar in size; however, 1.1 million ha are irrigated in
the northern THP while over 760,000 ha are irrigated in the southern THP [4]. In both regions average
irrigated crop yields are at least double that of dryland yields.

Figure 1. Ogallala Aquifer and Texas High Plains Regions.

Conservation strategies such as effective irrigation scheduling, in addition to water availability
modeling, rely on ET estimates with greater accuracy leading to greater efficacy. Many instruments
and methods are available for estimating ET, from simple equations using only one or two
meteorological parameters to very complex sensor systems or models. Lysimetry is considered the
standard for ET measurement [5], but lysimeters are typically labor and cost prohibitive. Eddy
covariance (EC) is a portable and manageable system for estimating ET. EC systems have predominantly been used for meteorological and research purposes, however, their popularity and availability has led to their use in agricultural and water resources research.

EC systems are based on the theory that as wind moves, it does not move unidirectionally but in three-dimensional circular patterns [6]. In addition, as the air moves, it carries molecules of water vapor and other gasses such as carbon dioxide and methane. If the speed of these eddies can be measured in all three directions, then the net exchange of these molecules between the surface and the atmosphere can be determined. In conjunction, a gas analyzer can be used to measure the amounts of water vapor (or other gases) the air contains at that moment in time. The covariance between the movement of the air mass and the composition of that same air mass can be used to determine the heat and water flux (or fluxes of carbon dioxide and methane), which can be used to calculate the sensible heat flux (H), latent heat flux (LE), and ET. This is the basis for EC systems, where a three-dimensional sonic anemometer and an infrared gas analyzer (or krypton hygrometer) are used to collect the aforementioned data at a high frequency.

\[ F = \frac{\bar{\rho} \bar{w} \bar{s}^2}{\xi} \]

\[ H = \frac{\beta C_p \bar{w} T}{\xi} \]

\[ LE = \lambda \frac{M_v}{M_a} \frac{\bar{w} \bar{s} \bar{e}}{\xi} \]

With H and LE derived from EC fluxes, the net radiation (\(R_n\)) and soil heat flux (G) can be measured to obtain the four energy balance (EB) components. Assessing the EB closure is one metric of evaluating the accuracy of the H and LE measurements from EC. A widely acknowledged issue with EC is the lack of energy balance closure. Based on the laws of thermodynamics, the \(R_n\) should be partitioned into the other three energy balance components yielding a zero sum:

\[ R_n - LE - H - G = 0 \] (4)

When using H and LE from EC measurements, these energy components do not converge, especially for heterogeneous land-surface (canopy) conditions. This type of imbalance of energy components along with main components of H and LE, is not explicitly known. Even with the widely acknowledged EB closure issue [7], EC has been used extensively for various applications all over the world. The use of EC has increased in agricultural research for crop coefficient development [8,9], remote sensing analysis [10,11], carbon sequestration [12], and perhaps the areas of any atmospheric-land surface interaction processing. Although the EB closure aspect has been investigated, the effects on accuracy of ET has not been thoroughly evaluated.

Typical EB closure errors of approximately 20 - 30% are widely reported in the literature [13]. In the past, measurement errors for \(R_n\) and G were commonly attributed as the cause for the closure problem; however modern sensors are considered much more reliable and accurate [14]. Other reasons for the errors include different scales between the energy balance components, the energy storage in the soil and canopy, and the heterogeneity of the land surface.

In addition to the physiological sources of errors, instrument limitations [15] and data processing can impact flux accuracy and EB closure. Imam et al. [16] showed residual energy from EC can be affected by the growing season and frictional wind speed, based on data collected over a maize (Zea mays L.) field in Nebraska. Higgins [17] showed variation in residual energy could be attributed to energy stored in the soil and underestimation of soil heat flux and underestimation of H and LE did not contribute to the residual based on data from salt flats in Utah. However, Rannik et al. [18] showed EC fluxes can contain 10 - 30% random error based on theoretical calculations and field measurements.

Deleted: [6].

Deleted: movement

Moved down [1]: The flux for any gas (\(F\)) can be calculated from the EC data by:

\[ F = \frac{\bar{\rho} \bar{w} \bar{s}^2}{\xi} \]

Deleted: where \( \bar{\rho} \) is the mean air density, and \( \bar{w} \) and \( \bar{s} \) are deviations from the mean for wind speed and dry mole fraction, respectively [6].

Moved down [2]: The dry mole fraction can be determined for any gas or variable of interest. From this principle, H and LE can be calculated by:

\[ R_n - LE - H - G = 0 \]

Deleted: Even with the widely acknowledged EB closure issue [7], EC has been used extensively for various applications all over the world. The use of EC has increased in agricultural research for crop coefficient development [8, 9], remote sensing analysis [10, 11], carbon sequestration [12], and perhaps the areas of any atmospheric-land surface interaction processing....

Deleted: [13].

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Deleted: The canopy storage is typically negligible, especially for shorter agricultural crops, and the EB has been closed during night time hours, indicating

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Based on the available literature, it is evident that EC systems commonly have EB closure errors, indicating errors exist in both H and LE measurements. Due to the complexity of determining H and LE values, few studies quantify the error of the fluxes against actual measurements. Lysimeters provide the most accurate ET validation data. The highly accurate ET measurements from a well-designed and operated lysimeter can also be used to derive the turbulent fluxes of H and LE, which should have a high degree of accuracy. However, few studies have evaluated EC systems compared to lysimeters for flux and ET accuracy. Therefore, the objective of this study was to evaluate EC as compared to a lysimeter for accuracy in determining H and ET values in addition to investigating the source of any potential errors.

2. Materials and Methods

2.1. Study Area

The study area was the USDA-ARS-Conservation and Production Research Laboratory (CPRL), located 17 km west of Amarillo, TX (35.188 N, 102.095 W). The region is classified as semi-arid with approximately 450 mm average annual precipitation. The study site is located inside a 19 ha square field, which is split into four, 4.7 ha quadrants (see Figure 2). Each quadrant is roughly 200 by 220 m and contains a large weighing lysimeter located in the center of the field. The east half of the field is irrigated with subsurface drip and the west half is irrigated using a lateral move sprinkler irrigation system. The northeast (NE) quadrant was used for this study as it provides the greatest fetch with respect to the predominant wind direction (SSW). The field was planted with grain sorghum at a rate of 210,000 seeds per ha (85,000 seeds per acre), which was fully irrigated using subsurface drip at a 23 cm (9 in.) depth and 150 cm (59 in.) lateral spacing.

Figure 2. Study location and layout of the lysimeters (yellow arrows) in the northeast (NE), southeast (SE), northwest (NW), and southwest (SW) quadrants with the location of the eddy covariance system in the NE quadrant.

2.2. Lysimeters

Deleted: Li et al. [14] conducted an evaluation of EC fluxes over an irrigated maize field with plastic mulch in China. They compared EC-derived ET measurements with ET determined using the field water balance method. They calculated fluxes and ET at 10-minute intervals over the 2007 cropping season. They first determined the EB closure by conducting a regression between the available energy (AE, Rn – G) to the turbulent fluxes (H + LE). Their results showed good correlation with an R² of 0.93 but a failure to close the EB with a slope of 0.93. They cited possible reasons of low frequency loss by the 10-minute averaging interval and possible source mismatch between the EC system and Rn and G measurements. Later, Li et al. [14] evaluated daily ET estimates between the EC and water balance. The regression results showed strong correlation with an R² of 0.84, but the water balance ET estimates were lower than EC-based ET by an average of 4%.

Ding et al. [15] evaluated ET from an EC system with ET measured from a lysimeter growing maize in China. They used 10 Hz data from a 3-D sonic anemometer and a krypton hygrometer to determine 30-minute fluxes and ET. They found mean bias errors ranging from -3.5% to 10.7% in their ET comparison after forcing EB closure. Their results were consistent for each growth stage. In addition, the EC-based ET was evaluated against ET determined by the water balance for the same field. Good agreement was found with an R² of 0.83. Upon investigating EB closure, Ding et al. [15] found that the AE was greater than the turbulent fluxes and closure error was 22% for 30-minute fluxes and 16% for daytime fluxes. They determined the cause of the error was likely due to footprint mismatch between the EC system and the net radiometer and soil heat flux plates.

Chávez et al. [16] conducted a study employing two EC systems (denoted EC1 and EC2) over an irrigated cotton crop grown on the large weighing lysimeters at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX. In this study, they also investigated if more stable nighttime conditions affected the flux calculations. They calculated the total daily H and LE and the H and LE only during daytime using a 15 min averaging period. They found EB closure errors of 46% and 27% for EC1 and EC2, respectively for the 24-hour period and 22% and 27% closure error, respectively, during daytime. They suggested common potential causes for the errors, such as the flux averaging interval and corrections for the...
labeled 2m, 4m, 8m for simplicity) to SWC readings, plant mapping and stand counts were periodically provided by [22]. The lysimeter measures the difference in mass due to captured precipitation or irrigation, as well as ET, extending beyond the lysimeter container resulting in an effective area larger than the physical area of the lysimeter. Evett et al. [5] reported the outside lysimeter surface area was 9.35 m². In this case, a correction factor of 1.05 (9.35 m²/8.95 m²) was applied to ET measurements from the lysimeter.

Evett et al. [5] reported the outside lysimeter surface area was 9.35 m². A correction factor of 1.05 (9.35 m²/8.95 m²) was applied to ET measurements from the lysimeter.

Calculated ET in units of equivalent depth of water requires that the change in lysimeter mass be divided by the effective evaporating and transpiring area of the lysimeter [23]. Evett et al. [5] reported that the Bushland lysimeter inside surface area was 8.95 m². However, the area of

The lysimeter was designed to be representative of the surrounding field so that measured lysimeter ET closely mimics field ET. Experienced support scientists and technicians are responsible for maintaining lysimeter representativeness as compared to surrounding fields. Careful attention is given to agronomic operations including planting, harvesting, tillage, fertilization, irrigation, and pesticide application such that there should be no distinguishable differences, particularly in height, between the crop grown on the lysimeter and that grown in the surrounding field. To confirm this, multiple neutron probe access sites were located throughout the field and in the lysimeter to monitor the soil profile water content. Weekly soil water content (SWC) readings from the neutron probes throughout the field are compared to SWC readings from the lysimeter to determine representativeness. In addition to SWC readings, plant mapping and stand counts were periodically taken to ensure the crop growth on the lysimeter approximates the surrounding field. The lysimeter box contains a ~50 mm freeboard lip that extends above the soil surface to limit runoff or runon to the lysimeter. Similarly, furrow dikes are used to limit runoff and runon for the surrounding field.

In some instances, field operations prohibited measurements with the lysimeter. For example, maintenance on the lysimeter, or instruments mounted near the lysimeter, would require personnel to step onto the lysimeter box, temporarily increasing the mass. Other operations include draining the percolation storage tanks, which causes an overall decrease in the mass, irrigation applications, and taking neutron probe soil moisture readings. The amount of water drained is measured, but data recorded during the process of draining the tanks are not usable. For sub-daily data, periods of precipitation will reduce data availability since the precipitation cannot be accounted for in the ET for short periods, such as hourly or 30-minute intervals. In the instance where operations prohibited data collection, the data from those time intervals were omitted. In the instances where lysimeter data were omitted, the corresponding EC data were also excluded.

2.3. Eddy Covariance System

In this study, three EC systems were installed within an experimental field containing a large weighing lysimeter, planted with grain sorghum, located at the CPRL. The EC systems were installed at 2.5, 4.5, and 8.5 m heights (labeled 2m, 4m, 8m for simplicity) approximately 40 m to the north of the lysimeter and facing due south. The distance between the EC systems and the lysimeter should...
provide an arrangement where the lysimeter is in the area where the EC systems obtain the greatest contribution to the flux measurements. The NE lysimeter field quadrant (Figure 2) was chosen to provide the maximum amount of fetch so that the EC footprint would contain a highly homogenous surface.

The EC systems consisted of a three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, Utah) and an open path infrared gas analyzer (LI-7500A, LI-COR Biosciences, Lincoln, Nebraska). Additional instruments installed near the lysimeter included an air temperature and relative humidity sensor (HMP155, Vaisala, Helsinki, Finland), six soil heat flux plates (HTF-3, Radiation Energy Balance Systems, Bellevue, Washington), four soil moisture sensors (Acclima 315, Acclima Inc., Meridian, Idaho), an infrared thermometer (IRT), and a net radiometer (Q77, Radiation Energy Balance Systems, Bellevue, Washington). The instruments were connected to a datalogger (CR6, Campbell Scientific, Logan, Utah) with measurements taken at 6 second intervals, which were then summed or averaged to 30-minute data. The additional sensors installed near the lysimeter underwent QA/QC analysis according to [24], performed on each 30-minute period. OA/QC for the R, involved comparing measured R, with the sum of measured downwelling and upwelling short- and longwave radiation. In addition, the solar irradiance component was compared with the calculated theoretical maximum clear sky solar irradiance. Following QA/QC analysis, the sensor calibration was trusted, and the R, measurements were believed to be accurate.

The 20 Hz EC data were processed using standard corrections and adjustments prior to the flux calculations. Processing involved applying coordinate rotations, despiking [25] time lag compensation using cross-correlation maximization, Webb-Pearman-Leuning (WPL) corrections [26], and high and low-pass filtering [27] using block averaging. The EC system determines ET from the LE values determined by the water flux. The EC data analysis software EddyPro (LI-COR Inc., Lincoln, Nebraska) was used to calculate H and LE at 30-minute intervals from the 20 Hz measurements. After all standard corrections half-hour H and LE were calculated. The flux for any gas i can be calculated from the EC data by:

\[ F_i = \bar{w}_i \bar{e}_i \]  (1)

where \( \bar{\rho} \) is the mean air density, and \( \bar{w}_i \) and \( \bar{e}_i \) are deviations from the mean for wind speed and dry mole fraction, respectively [6]. The dry mole fraction can be determined for any gas or variable of interest. From this principle, H and LE can be calculated by:

\[ H = \bar{\rho} \bar{w}_H \bar{T} \]  (2)

and

\[ LE = \lambda \frac{M_u}{\bar{w}_e} \bar{w}_e \]  (3)

Soil water and temperature data were used to calculate G at the soil surface by the calorimetric method, and surface G was used in all EB calculations. The calorimetric method used in this study was described by Colaizzi et al. [28]; briefly, it used the soil water and temperature measurements to calculate the change in soil heat storage between the surface and the depth of the soil heat flux plates in 30-min time steps. The H, LE, and G were subtracted from the R to determine the EB residual. EB closure was evaluated using the slope of the regression equation, as well as the RMSE expressed as a percentage (%RMSE) of the available energy (AE = R - G). Using the regression slope has been a common method for evaluating EB closure for EC; however, there are studies in the literature that use other methods, such as the energy balance ratio (AE/ET) [29]. As the ratio method can cause misleading calculations when negative values are used, the %RMSE was used for this study to provide a comparison with the regression slope. After determining the magnitude of the residual energy, the residual was distributed between H and LE to force the EB close to balance and preserve the Bowen ratio at each 30-minute interval. The corrected H and LE were used for evaluation and to determine ET for the EC system at the 30-minute time-step.

2.4. Accuracy Analysis
In addition to evaluating ET, H from EC was compared to H from the lysimeter. H was back calculated from the lysimeter by converting the ET to LE and accounting the residual of the EB to H. Latent heat flux can be calculated from ET by:

\[ LE = \frac{ET (mm) \lambda}{time (sec)} \]

where \( \lambda \) is the latent heat of vaporization. The latent heat of vaporization can be calculated from the surface temperature, \( T \) (°C) by:

\[ \lambda = (2.501 - 0.0236T) \times 10^6 \]

Surface temperature was obtained from the IRT installed on the lysimeter and used to determine the latent heat of vaporization for each 30-minute period. Using the lysimeter ET data, the LE was calculated by multiplying the ET by the latent heat of vaporization and dividing by 1800 seconds to convert to the 30-minute period.

During nighttime hours, LE, and subsequently ET, becomes very small. The much smaller values can exhibit much more variation. Even though the magnitude of the differences may be small, relative percentage differences can be large. To determine the effects of including nighttime ET, evaluations were included using only daytime ET data. This analysis should provide an indication as to how much of the overall variation is influenced by the much smaller nighttime values. In addition, since most water management practices and decisions are performed at a daily time-step, the half hourly lysimeter and EC data were summed to evaluate the effects of daily data from EC.

As the crop height increases, the surface roughness and dynamics change, which affects flux calculations. To investigate the effects of the changing surface, analyses were separated into periods corresponding to crop height. Analysis of variance (ANOVA) tests were used to evaluate differences between various periods. Although the ANOVA results do not provide any explanation of differences, it was selected for this study to evaluate the significance of any differences in values for the different periods and comparisons.

For the accuracy analysis, the H and ET from the EC were compared against the lysimeter. Statistics were calculated using SAS version 9.4 (SAS Institute Inc., Car, NC) where RMSE and the %RMSE were used to evaluate accuracy, in addition to regression analyses to test the EC-lysimeter relationship for linearity and for how well the data fit the 1:1 line. The RMSE provided the magnitude of errors for each analysis and the %RMSE provided relative error. In many cases with ET data using short time intervals, the values can be quite small, making differences appear insignificant. Using relative statistics changes the perspective allowing differences to be more easily detected.

### 3. Results

The period of data for this study was from July 28, 2015 through October 29, 2015. As the sorghum was planted on June 23, 2015, the crop height at the beginning of this study was 0.54 m and reached a maximum height of 1.13 m on August 24, 2015. The crop height throughout the year is presented in Table 1. Installation of the instruments was delayed allowing field operations that would not be possible after the instrument towers were in place. Instrument removal took place October 30, 2015 to allow for harvest, which took place November 13, 2015.

The maximum height measurement on August 24, 2015 coincided with the majority of the field reaching the flowering stage and having the maximum leaf area index (LAI) of 4.20 m^2. After reaching maximum height, the crop reached the soft dough stage on September 14, 2015 (LAI = 3.72), hard dough on September 28, 2015 (LAI = 3.6), and finally reaching black layer on October 20, 2015 (LAI = 3.19).

### Table 1. Crop height measurements for the 2015 summer growing season.

<table>
<thead>
<tr>
<th>Date Range</th>
<th>Crop Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>7/25 – 8/4</td>
<td>0.54 m</td>
</tr>
<tr>
<td>8/5 – 8/10</td>
<td>0.80 m</td>
</tr>
<tr>
<td>8/11-8/16</td>
<td>0.91 m</td>
</tr>
</tbody>
</table>
3.1. Energy Balance Closure

EB closure was 67, 65, and 64% for the 2m, 4m, and 8m EC systems (see Figure 3), respectively, based on the slope of the regression lines. Using the ARMAISE as a measure of EB closure resulted in 57, 50, and 51% closure for the 2m, 4m, and 8m systems, respectively. The values from the regression slopes are comparable to those typically found in the literature. Similar closure was found for each of the three sensor heights. ANOVA results showed statistical differences (p<0.001) between the AE and fluxes for all sensor heights. Closure may have been related to sensor height as the lowest sensor produced the greatest EB closure. It is well known that EC source area increases with sensor height.

Flux footprint was determined using the Kljun et al. footprint model [30] as calculated by the EddyPro software for each half-hourly interval. The average contribution distance which accounted for 70% of flux contribution was 65.6 m, 189.2 m, and 530.9 m downwind for the 2m, 4m, and 8m sensors, respectively. The fetch from the tower to the end of the lysimeter field was around 400 m, meaning the 8m sensor footprint extended beyond the lysimeter field, which included non-irrigated area.

<table>
<thead>
<tr>
<th>Date</th>
<th>EB Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/17-8/20</td>
<td>1.07 m</td>
</tr>
<tr>
<td>8/21-8/23</td>
<td>1.10 m</td>
</tr>
<tr>
<td>8/24-10/29</td>
<td>1.13 m</td>
</tr>
</tbody>
</table>
The EB closure was further analyzed by period corresponding to crop height using the Students T method which showed the early period with a crop height of 0.54 m, the vegetative period with crop heights of 0.80 – 1.10 m, and the period with maximum crop height were significantly different with regard to EB closure based on the regression slopes. Therefore, these results show EB closure is greatest early in the season when plants are smaller and decreases as the plants grow and biomass accumulates. This could be an indication of canopy heat storage contributing to EB closure error since the error is smaller when less biomass is present.

3.2. Sensible Heat Flux
H from EC underestimated H from the lysimeter by approximately 50% (see Figure 4). The RMSE was 55.5, 63.8, and 70.4 W m\(^{-2}\) for the 2m, 4m, and 8m sensors, respectively. Calculating the \%RMSE was more difficult with H since values can be positive or negative; therefore, the absolute values for H were also used to calculate RMSE and \%RMSE. The 2m, 4m, and 8m sensors had a \%RMSE of 44.3, 54.0, and 54.4, respectively. The regression graphs show EC has a more limited range of values for H compared to the lysimeter, possibly indicating the lysimeter having a greater capacity to capture H dynamics.

Separating the data for H by crop height gave better results when the crop was taller. After the grain sorghum reached maximum height the \%RMSE for H was 35.4, 45.6, and 47.1 for the 2m, 4m, and 8m, respectively, producing a reduction in \%RMSE of 20.1, 15.6, and 13.4%, respectively.

Although the lysimeter is considered very accurate for ET, it does not directly measure H. As H was calculated as the residual of the energy balance in this study, any error from the energy balance on the lysimeter would be included in the determination of H. Therefore, while the evaluation of H is included in this study, the accuracy of lysimeter H cannot easily be verified and the evaluation is presented for illustrative purposes.
3.3. Evapotranspiration

Average 30-minute ET for the lysimeter and each EC system is presented in Figure 5. Each EC system followed a similar daily pattern as the lysimeter; however, each EC system over-estimated ET. The three EC systems were similar for each half-hourly period throughout the day. Peak ET occurred around 13:00 for each system. Although the EC overestimated ET as compared to the lysimeter for the daytime hours, ET from EC was essentially zero for nighttime hours while the lysimeter recorded small values for ET. The nighttime lysimeter measurements are in agreement with Tolk et al. [31] who showed small amounts of ET do occur at night.

Figure 4. Sensible heat flux (H) from the three EC systems regressed against H calculated from the lysimeter.
Figure 5. ET averaged for each 30-minute interval across the entire growing season for the lysimeter and the three EC systems.

Results from the regression analyses are presented in Figure 6 and Table 2. The slopes of the regression lines support the conclusion that EC overestimates ET as compared to the lysimeter with values above one. The slopes, intercepts, $R^2$, and RMSE values were similar between the three sensor heights (see Table 2). Error rates for ET (approximately 27%) are less than the closure error (approximately 35%) by regression slope indicating that although EC may have EB closure errors, EC may yield better results for ET after corrections and distributing residual energy by preserving the Bowen ratio. The large errors found in H based on comparison with the lysimeter indicate there are likely errors in the Bowen ratio; however, the magnitude of H is much lower than the magnitude of LE. The resulting error in the Bowen ratio should be lower and may still provide an acceptable ratio for distributing the residual energy.

Evaluating only the daytime ET showed improvement in $\Delta \text{RMSE}$ for all three sensor heights with $\Delta \text{RMSE}$ values of 21.9, 30.0, and 30.7 for the 2m, 4m, and 8m sensors, respectively. Using the larger daytime values, the magnitude of the RMSE increased for all sensors (i.e. 0.036 to 0.044 for the 2m), however, the $\Delta \text{RMSE}$ decreased in each case, further illustrating the benefit of using relative differences in addition to error magnitudes. Removing the nighttime data still contained aggregated data points around the origin with overestimation of ET at higher values and a slight underestimation at values near zero.

Deleted: Comparing the regression line to the 1:1 line shows small, near-zero values are slightly underestimated by EC. ...
Figure 6. Regression graphs for ET from the lysimeter and EC.

Table 2. Statistics from three EC systems evaluated against the lysimeter.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>RMSE</th>
<th>%RMSE</th>
<th>R²</th>
<th>Slope</th>
<th>Intercept</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2m</td>
<td>0.036</td>
<td>27.41</td>
<td>0.93</td>
<td>1.15</td>
<td>-0.02</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>4m</td>
<td>0.036</td>
<td>26.68</td>
<td>0.91</td>
<td>1.17</td>
<td>-0.01</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>8m</td>
<td>0.037</td>
<td>26.72</td>
<td>0.90</td>
<td>1.14</td>
<td>-0.02</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

RMSE and %RMSE values for ET from the three EC sensor heights separated by crop height are presented in Table 3. Mean separation testing using the Students T method showed no significant differences between sensor heights for RMSE or %RMSE; however, a significant difference was found between %RMSE for the period after maximum plant height of 1.13 m was achieved and all periods.
prior. The 2m sensor is an exception where the period after maximum plant height has a lower
RMSE; however, this sensor suffered a malfunction on September 13, 2015 yielding only 19 days of
data for this period. The results from the 4m and 8m sensors show the RMSE for ET from EC is less
early in the growing season when sorghum plants are still actively growing. Further, separating the
period after maximum plant height was reached by seven-day intervals (9 total weekly periods)
showed the last four weeks (September 28 – October 29) of the 2015 growing season had much higher
RMSE values, ranging from 78 – 90. ANOVA results showed each weekly period was significantly
different with all p-values < 0.0001. These data show ET error is greatest at the end of the growing
season during grain fill.

Table 3. RMSE and %RMSE for ET separated by period of crop height.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>All Season</th>
<th>0.54 m</th>
<th>0.80 m</th>
<th>0.91 m</th>
<th>1.07 m</th>
<th>1.1 m</th>
<th>&lt;1.13 m</th>
<th>1.13 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>2m RMSE</td>
<td>0.036</td>
<td>0.037</td>
<td>0.037</td>
<td>0.038</td>
<td>0.034</td>
<td>0.033</td>
<td>0.038</td>
<td>0.032</td>
</tr>
<tr>
<td>4m RMSE</td>
<td>0.036</td>
<td>0.038</td>
<td>0.039</td>
<td>0.036</td>
<td>0.035</td>
<td>0.032</td>
<td>0.039</td>
<td>0.037</td>
</tr>
<tr>
<td>8m RMSE</td>
<td>0.037</td>
<td>0.038</td>
<td>0.038</td>
<td>0.038</td>
<td>0.034</td>
<td>0.032</td>
<td>0.039</td>
<td>0.039</td>
</tr>
<tr>
<td>2m %RMSE</td>
<td>27.41</td>
<td>26.94</td>
<td>23.53</td>
<td>28.06</td>
<td>25.60</td>
<td>27.02</td>
<td>27.44</td>
<td>25.81</td>
</tr>
<tr>
<td>4m %RMSE</td>
<td>26.68</td>
<td>26.33</td>
<td>23.16</td>
<td>26.18</td>
<td>26.40</td>
<td>25.98</td>
<td>27.41</td>
<td>43.54</td>
</tr>
<tr>
<td>8m %RMSE</td>
<td>26.72</td>
<td>25.72</td>
<td>23.99</td>
<td>27.12</td>
<td>24.71</td>
<td>25.61</td>
<td>27.54</td>
<td>44.89</td>
</tr>
</tbody>
</table>

Finally, aggregating the half-hourly data to daily values improved results for ET and reduced
RMSE values to 16.04, 10.59, and 13.72 for the 2m, 4m, and 8m sensors, respectively. The summed
daily data drastically reduced the error rates, by as much as 50% in the case of the 4m sensor. The
decrease in error when summing the data is likely due to various cases of overestimation and
underestimation evening out when the data are summed due to the trade-off between overestimation
during daytime and underestimation during nighttime. Periods of overestimation and
underestimation could be the result of a time lag between the measurements from EC and physical
processes required to create a change in mass on the lysimeter. Although the 30-minute averaging
interval is considered the most representative time period for EC flux calculation, heat and energy
transport often experience a time lag at rapid time scales as energy moves along the gradient. This
time lag may contribute to greater error at half-hourly intervals but may be better accounted for in
the daily sums.

4. Discussion

Results from this study over grain sorghum agree with a previous EC study at the CPRL over
cotton (Gossypium hirsutum) by Chavez et al. [32]. They found EB closure errors of 46% and 27%
for two EC systems installed on the lysimeter fields (denoted EC1 and EC2) for a 24-hour time-step
and 22% and 27% closure error, respectively, during daytime. This study showed similar EB closure
error at 35% using the 24-hour time interval. Evaluating the H, they found underestimations of 28%
and 45% for the 24-hour period and 35% and 37% for the daytime, similar to the 50% in this study.
They also compared ET calculated from EC to lysimeter measured ET and found under predictions
of 30% and 38% in ET from EC1 and EC2, respectively, but results improved to 24 and 27% after
forcing EB closure. This study showed an overestimation of 27% sorghum ET.

In a study by Alfieri et al. [33], two EC systems were installed in each of two lysimeter fields at
the CPRL to determine the effects from advection. When considering the full 24-hour period,
differences in LE from EC systems and lysimeters ranged from 49 to 76 W m⁻², which is similar to the
-50 W m⁻² for grain sorghum in this study. The EB closure percentage for the four EC systems ranged
from 74% to 87%, which is slightly higher than the 65% in this study. Investigating the closure error
cases, they found that the effect of advection on flux measurements was typically less than 20 W m⁻²,
although there were two days where the advection effect was larger than 100 W m⁻².

Pérez-Priego et al. [34] showed EC to underestimate LE as compared to a lysimeter for an oak
tree-grass savannah in a Mediterranean climate. Their analysis showed the selection of correction
methods can greatly impact EC results. One example given showed applying the angle-of-attack correction changed the EB closure slope from 0.92 to 1.07.

As many agricultural EC studies either analyze several non-consecutive days or a relatively short section of the growing season, this study provided the opportunity for additional analysis with complete data from early in the growing season to harvest. The ability to analyze sections of the growing season to investigate in-season dynamics of H and LE showed errors in EC are not consistent throughout the growing season.

The inconsistency throughout the growing season in this study differs from the results presented by Ding et al. [35] who showed errors of ±15% for each maize crop growth stage. They separated results into seeding, shooting, heading, filling, and maturity stages with each stage encompassing 17–45 days. The main difference in the methodology between Ding et al. [35] and this study is that they used plastic film to suppress evaporation and flood irrigation. With the potential for evaporation reduced, the microclimate of the crop canopy would likely have been different than this study, potentially reducing the energy available for storage in the plant canopy. From the analysis of the data by crop height, the results showed EB closure was better when the crop was smaller and poorer when more biomass was present on the surface. This indicates canopy heat storage may be one of the sources of error in EC-derived energy fluxes.

In terms of water for irrigation, using the overestimated ET in irrigation scheduling would lead to overapplication of water. Using the northern THP as an example, a 10% overestimation, resulting in a 10% overapplication for all irrigated acres, the annual water used for irrigation would increase by 254,000 ac-ft based on the TAMA water demand model [1]. A 20% overapplication would increase water use by 519,000 ac-ft. The water use applied to the scale of irrigated acres highlights the necessity of highly accurate ET data.

5. Conclusions

This study involved EC systems installed over irrigation grain sorghum at heights of 2.5, 4.5, and 8.5 m for the 2015 summer growing season. Results showed EC underestimated H and overestimated LE (as indicated by ET). However, the underestimation of H was not equal to the overestimation of LE. EB closure was approximately 65%, due in part to the 50% error in H. Separating EB closure analysis by crop height showed closure was greater earlier in the season and lower after the crop reached maximum height. The closure discrepancy could be caused by unaccounted energy stored in the plant canopy.

These results showing less error in LE also indicate that ET from EC may have better accuracy than would be indicated by EB closure. Half-hourly ET error rates of 20–30% may be greater than desired for many water management applications; however, the results of this study show certain periods, namely the later vegetative and early reproductive stages, have less error than the total growing season. For irrigation management, the late vegetative and early reproductive stages correspond to the greatest water use in many crops, including grain sorghum. Therefore, EC could provide the best accuracy during the periods of peak water demand.

Moreover, since error rates are drastically reduced when summed to daily values, EC may provide more potential for use in agricultural water management as most management practices, including irrigation scheduling, are performed at daily or longer time-steps. For most water availability and modeling applications, data could potentially be aggregated to weekly or monthly time steps that could further reduce error. With error in daily ET of 10-15%, EC shows potential for many uses in agricultural water management.

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Author Contributions: conceptualization, J.E. Moorhead, P.H. Gowda, X. Lin, P.D. Colaizzi, and S.R. Evett; methodology, J.E. Moorhead, P.H. Gowda, and X. Lin; validation, P.H. Gowda, X. Lin, and S.R. Evett; formal analysis, J.E. Moorhead; investigation, J.E. Moorhead, G.W. Marek, and S. Kutikoff; resources, P.H. Gowda and
X. Lin; data curation, J.E. Moorhead and S. Kutikoff; writing—original draft preparation, J.E. Moorhead; writing—review and editing, G.W. Marek, P.H. Gowda, X. Lin, P.D. Colaizzi, S.R. Evett, and S. Kutikoff; visualization, J.E. Moorhead; supervision, J.E. Moorhead, P.H. Gowda, and X. Lin; project administration, J.E. Moorhead and G.W. Marek; funding acquisition, P.H. Gowda and X. Lin.

**Funding:** This research was funded by the USDA-ARS Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

**Conflicts of Interest:** The authors declare no conflict of interest.

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2. Scanlon, B.; Reedy, R.; Gates, J.; Gowda, P. Impact of agroecosystems on groundwater resources in the central high plains, USA, Agriculture, Ecosystems & Environment 2010, 139, 700-713.

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