APPENDIX A. CROP CONSUMPTIVE USE ESTIMATION IN THE SACRAMENTO-SAN JOAQUIN DELTA: FALLOW FIELD 2015 CAMPAIGN REPORT

RESEARCH CONDUCTED BY THE BIOMICROMETEOROLOGY RESEARCH TEAM OF THE UNIVERSITY OF CALIFORNIA, DAVIS, DEPARTMENT OF LAND, AIR AND WATER RESOURCES AND UNIVERSITY OF CALIFORNIA COOPERATIVE EXTENSION

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EXECUTIVE SUMMARY
The motivation of this 2015 field campaign was to estimate actual evapotranspiration (ETa) from fallow fields to verify whether there is any substantial water loss when a crop is not present. Evapotranspiration from weeds or evaporation from remaining soil water could increase ETa to above zero, for instance. ETa was estimated over four fallow fields during September 2015 using an energy balance residual approach with eddy covariance and surface renewal measurements. All fallowed fields were above sea level, ranging from 1.5 m above sea level to 17 m above sea level, so our ETa results should only be considered in this elevation context and in the time frame of late summer/early fall. ETa was low for all four fields with reported values of 0.05 mm/day to 0.39 mm/day for the dry period in the month of September 2015. Error estimates as well as literature sources support the accuracy of these measurements. One of the fields with the higher values of ETa was close to sea level in elevation, and elevated water table levels were a possibility; in addition weeds were observed in the other fallow field that had higher measurable ETa. Also, after rain near the end of the measurement campaign, substantial ETa was measured for all fields, and then decreased in the final days of the campaign. Our study sites were all above sea level, and we did not measure soil moisture during this relatively short campaign. Data from these sites suggest that even higher water tables and soil moisture could result in greater fallow field ETa, than reported in this preliminary study. Further investigation is warranted for other seasons and fields (especially lower lying ones) with enhanced weather stations.

OVERVIEW AND INTRODUCTION
The motivation of this 2015 field campaign at the end of the 2015 season was to investigate whether leaving a field fallow decreases ETa to near-zero values. The main effect of ETa values being near-zero is less demand of water than when a crop is growing, and thus during periods when fields are fallow, no irrigation is required. This fallow field study in 2015 serves as a baseline of the smallest amount of ETa that would be measured over land in the Sacramento-San Joaquin Delta compared to ETa that would be measured within pasture, alfalfa and maize fields in the Delta region in 2016.
We studied four fallow fields in three locations in the Delta, and this served as a standard representation of ETa conditions across a spatial distribution for a limited range of elevations above sea level (1.5 m to 17 m). The sites were chosen by arrangement of the Office of the Delta Watermaster with growers who had voluntarily fallowed fields as participants in the 2015 Diversion Reduction Program. Actual evapotranspiration was measured over four fields with five stations for 28 days in 2015, from September 7th to October 5th. Three of the four fields were completely fallow, while one field contained heterogeneities in the form of sparse, large weeds throughout the field. We used two distinct methods to estimate ETa, and both are based on an energy budget residual, where all the terms in the energy budget are measured or estimated, except for the latent energy term, which results from ETa and therefore can be used to measure ETa. Both methods are described in more detail in the next section and the Appendix Technical Supplement.

METHODOLOGY: THEORY

The surface energy budget equation was employed to obtain evapotranspiration. Basic conservation of energy dictates that all energy flows into and out of a surface, such as bare soil or a crop surface, must sum up to zero. By convention, the energy flow sign conventions are arranged such that this energy conservation equation can be expressed as the net radiation, $R_n$, being set equal to all the non-radiative processes. These non-radiative energy flows are the latent energy flux, $LE$, representing the energy used in evapotranspiration; the sensible heat flux, $H$, representing the heat energy exchange between the surface and the atmosphere (heating or cooling of the atmosphere by the surface); and the ground heat flux, $G$, representing the heat energy stored in the soil and crop surfaces (associated with the soil and crop tissue temperature changes). The energy budget residual method, $LE = R_n - H - G$, was used to obtain $LE$, and from that, ETa. This general energy budget residual method was also used by most of the remote sensing teams for their ETa estimates. In all of these methods it is also assumed that the energy budget exchange is only vertical, and that no horizontal energy exchanges (horizontal advection-divergence is one example) occur. To accomplish the energy budget LE measurements, independent measurements and estimates were used to obtain $R_n$, $G$, and $H$. While the above equation should be valid for any time frame, such as hourly or half-hourly averages, it can be simplified for daily average estimates of LE and ETa. Under such conditions, there is usually negligible ground heat flux; that is, the daily average soil and crop temperatures do not change appreciably from day to day, so $G \approx 0$ for daily estimates of ETa, and the above equation simplifies to $LE = R_n - H$. Measurements of $G$ can be used to check this assumption of a daily average of $G \approx 0$. ETa was calculated as the LE divided by the latent heat of vaporization, all in the International System of Units (SI units) and then converted to the units presented in this report.

The sensible heat flux, $H$, was measured in two ways, by eddy covariance in the “full” station, and by surface renewal in the “lite” stations, with the supporting theory detailed below and in the Appendix Technical Supplement. $R_n$ was measured with net radiometers, described below. $G$ was measured with ground heat flux plates and soil temperature probes at station D5 and at the
other stations $G$ was assumed to be either zero or a specified function of $R_n$. These approaches for estimating $G$ from $R_n$ for are described in the Appendix Technical Supplement.

**METHODOLOGY: STUDY SITES AND EQUIPMENT**

Four “lite” surface renewal stations and one “full” eddy covariance station were installed in fallow fields in the Sacramento-San Joaquin (SSJ) Delta region (Figure A-1). Lite stations included measurement of net radiation with a net radiometer and measurement of sensible heat flux with fine-wire thermocouples, using surface renewal analysis. The full station added a sonic anemometer for measurement of wind components and air temperature, yielding the measurement of sensible heat flux using the eddy covariance technique in addition to the surface renewal technique from the fine wire thermocouples, so the full station was also equipped to serve as an additional lite station. Ground heat flux plates and soil temperature thermocouples were deployed at the full station near the end of the measurement period. All stations were installed from September 7th to September 9th, 2015 and were removed on October 5th, 2015. Earlier installation of the equipment was not possible because of administrative delays related to the project agreement, funding, and other logistics.

*Figure A-1. Google Earth image of all research stations and CIMIS station locations.*
Lite stations D1 and D2 were installed in a single field off of Byron Highway near Brentwood, CA. This field, unlike the other fields where measurements were taken, had sparse weeds growing in it (Figures A-SIV-1, A-SV-1, and A-SV-2). Lite stations D3 and D4 (Figure A-SIV-4, A-SV-3, and A-SV-4) were deployed in two adjacent fallow fields off of S Kasson Road near Tracy, CA. Full and lite station D5 (Figures A-SIV-2 and A-SV-5) was deployed in a field off of Crocker Road near Manteca, CA. The results from D4 were removed from this report after an audit indicated that its net radiometer calibration was of uncertain accuracy.

In addition to the measurements we recorded over fallow fields, we used measurements from California Irrigation Management Information System (CIMIS) stations that provide meteorological measurements used to calculate reference evapotranspiration (ETo), the ET expected from a well-watered grass surface under given meteorological conditions. We used daily ETo data from three nearby CIMIS stations for comparison against the actual evapotranspiration (ETa) estimated over fallow fields (Figure A-1). Hourly wind speed data was also used for the wind correction to the net radiometer data (Appendix Technical Supplements II.3 and III.).

RESULTS

For the duration of the field campaign, no precipitation fell between 9/9/15 and 9/30/15; this is considered the dry period. The last rain event before our experiment was recorded on August 7, 2015, at two nearby CIMIS stations; Manteca reported 0.25 mm of rain and Modesto, 0.51 mm of rain. Near the end of the field campaign, it rained on 10/1/15, and thus that date and the remaining days of our field measurements through 10/5/15 are referred to as the wet period, during which enhanced evaporation occurred due to the additional moisture present in the fallow ground. The measurements of ETa using an estimated ground heat flux, G, during the dry period were found to be low (Figure A-2.1, Table 1). The ETa values ranged from 0.05 mm/day to 0.39 mm/day, with 95% confidence intervals that ranged from +/- 0.10 mm/day to +/- 0.30 mm/day. These confidence intervals are similar in magnitude to estimates of the nominal sensor errors used in the energy budget residual method, of approximately 0.55 mm/day (corresponding to an error of 15 W m\(^{-2}\)). ETa values were slightly greater than when using the assumption of zero ground heat flux averaged over a day (Figure A-2.2).
Figure A-2.1. Box (+ & - one quartile) and whisker (maximum and minimum data point values) plots of daily ET\textsubscript{a} from each station and daily ETo from nearby CIMIS stations. This ET\textsubscript{a} was during the experiment period without rainfall (9/9 to 9/30) and was estimated using surface renewal (and eddy covariance at station D5), with the G having been estimated from G/R\textsubscript{n} or measured for some days at D5. Dots represent outliers that are greater than 1.5 times the quartiles, so for those box and whisker symbols with associated dots, the whisker represents the maximum or minimum value except for the outlier point(s); this is a standard depiction in box and whisker plots.
Figure A-2.2. Box (+ & - one quartile) and whisker (maximum and minimum data point values) plots of daily ETa from each station with comparison of assuming the ground heat flux is zero when averaged over a day (“G zero”) to using estimated ground heat flux based on the ratio G/Rn and G measurements during the dry period of the last week of the field campaign (“G estimated”). ETa estimated using both surface renewal and eddy covariance is shown for station D5. Dots represent outliers that are greater than 1.5 times the quartiles, so for those box and whisker symbols with associated dots, the whisker represents the maximum or minimum value except for the outlier point(s); this is a standard depiction in box and whisker plots.
Table A-1. Daily average ETa for Five Stations, Student's t value, and 95% confidence interval. D5 (SR) is the surface renewal part of the full station at D5, which also included eddy covariance D5 (EC). Ground heat flux for D1-D5 was calculated based on the ratio of G/Rn measured at D5, and directly measured ground heat flux on some days for D5 (EC) when those measurements were available.

<table>
<thead>
<tr>
<th>Site</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D5 (SR)</th>
<th>D5 (EC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ETa (mm/day)</td>
<td>0.17</td>
<td>0.35</td>
<td>0.051</td>
<td>0.39</td>
<td>0.14</td>
</tr>
<tr>
<td>t</td>
<td>1.5643</td>
<td>2.6396</td>
<td>0.35052</td>
<td>2.8094</td>
<td>2.8234</td>
</tr>
<tr>
<td>95% Confidence Interval (+/-)</td>
<td>0.23</td>
<td>0.28</td>
<td>0.30</td>
<td>0.29</td>
<td>0.10</td>
</tr>
<tr>
<td>Number observations</td>
<td>20</td>
<td>20</td>
<td>21</td>
<td>17</td>
<td>22</td>
</tr>
</tbody>
</table>

These results of higher ETa values (D2 & D5 SR; still under 0.5 mm/day) are compatible with the presence of weeds in the D2 fallow field, and the location of the D5 stations on a fallow field with an elevation of 1.5 m above sea level. Due to tidal cycles, the water level surrounding the island with the D5 field had the potential to affect the local water table height in the soils, presenting the possibility for the near-surface soil moisture to be enhanced at times.

Understanding the results from these stations would be enhanced if field soil moisture and water table data were available, but unfortunately these measurements were beyond the scope of the preliminary 2015 study. Nevertheless, our low ETa results are consistent with literature values for bare soil, which report comparable low ETa values based on both theoretical and experimental studies (Allen et al., 2005; Deverel et al., 2005; Jalili et al., 2011; Shah et al., 2007; Wythers et al., 1999), under dry conditions when significant rain and irrigation has not taken place for one month or longer, and with water tables below 1 m or deeper.

All ETa measurements were substantially less than the reference ETo from the CIMIS stations (Figure A-3) when averaged over the dry period of measurements. When the daily ETa values were examined day by day, all stations showed the rain signal on 10/1/15 at the end of the measurement period (Figure A-3).
Figure A-3. Daily ETa from each station (SR and EC), along with daily ETo from the nearby CIMIS stations. Lines represent mean values across the stations and darker gray shading represents one standard deviation from the mean.

On 9/19/15 and 9/20/15, the average ETa of all five stations (D1, D2, D3, D5 (EC), and D5 (SR)) was between ~0.5 mm and 2 mm, and on some other days, the averages were low and below ~0.5 mm. Days 9/19/15 and 9/20/15 corresponded to high nighttime relative humidities of around 100%, suggesting the possibility of dew formation leading to available soil surface moisture (see Figure A-SIII-4). Earlier in the growing season (before our measurements), lower nighttime relative humidities are expected, so there would less possible dew formation and condensation sources of water to the soil surface. However, this is not enough to explain the anomalously high ETa that all the stations displayed on those two days. Some other reasons for the anomaly were discounted, such as differences in net radiation $R_n$, or marked differences in wind speed, or daytime humidity (because the ETo doesn't show an increase during this time).

One possibility is that some form of regional advective energy might have violated the energy budget residual method's assumption of only vertical transport of energy budget processes. This potential regional advection would also diminish the accuracy of other remotely-sensed ET methods dependent on an energy budget and any other conventional, one-dimensional, vertically based micrometeorological methods, such as eddy covariance. Another possibility is that the local water tables for all sites became sufficiently shallow during 9/19/15 and 9/20/15 to allow increases in vapor phase evaporation from these shallow water levels in the soil. Further investigations that are longer term and involve other independent measures of ETa, such as direct eddy covariance of water vapor exchange, and measurements of soil moisture and water table depth, would strengthen our understanding of these results and potentially reduce uncertainties.
Not surprisingly, the daily crop coefficients, $K_a$ (Figure A-4) reflect the same resulting trend as $\text{ET}_a$, that some of the days show a crop coefficient near zero and others with values between 0.10 and 0.13, with a high value of approximately 0.25 during the dry period, and surpassing 0.5 after rainfall.

![Figure A-4](image)

**Figure A-4.** Daily actual crop coefficient ($K_a = \text{ET}_a / \text{ET}_o$) over the measurement period for each station (D1, D2, D3, D5 (EC), and D5 (SR)). Lines represent mean values across the stations and darker gray shading represents one standard deviation from the mean.

**2015 SUMMARY**

Micrometeorological measurements of $\text{ET}_a$ were made over four fallow fields with five stations in the Sacramento-San Joaquin Delta region, representing a range of Delta microclimates. As expected during the dry period in September, a month or longer from the last measureable rainfall or irrigation, $\text{ET}_a$ was low for all of the fields, and ranged from 0.05 mm/day to 0.39 mm/day. The higher $\text{ET}_a$ values were for a site with potentially shallow water table levels, and another site that had some weed growth. Additionally, after a period of rain near the end of the measurement campaign, substantial $\text{ET}_a$ was measured by all stations. In general, the crop coefficient and $\text{ET}_a$ were low, except following rainfall.
PLANS FOR 2016 AND BEYOND

While the 2015 portion of this project investigated and displayed low values of ET₀ over fallow fields at the end of the 2015 growing season, the 2016 campaign focuses on the measurement of ET₀ and K₀ in three crop types in the Delta region during the 2016 growing season. Through surface renewal and eddy covariance measurements, ET₀ will be measured using three full stations, two direct eddy covariance stations, and 11 lite surface renewal stations in maize, irrigated pasture, and alfalfa fields.

Our 2015 experimental set-up and preliminary results raise questions that could be answered with further studies to decrease measurement uncertainty, to expand measurements to fallow fields in different seasons and locations that could exhibit shallower water tables closer to the surface; to add additional measurements of soil water content and water table level; and to implement independent eddy covariance measures of water exchange from surfaces.

ACKNOWLEDGEMENTS

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REFERENCES


APPENDIX A TECHNICAL SUPPLEMENT I: THEORY

Eddy Covariance

Eddy covariance of sensible heat flux involves the high frequency measurement (10 to 20 times a second) of temperature and the vertical wind velocity. It is a careful thermodynamic analysis using the turbulence analytical technique of Reynolds decomposition, where the turbulent fluctuations of the vertical velocity $w'$ are multiplied by the turbulent fluctuations of temperature $T'$ and are then averaged over the measurement period (generally a half hour). The general assumptions made to use eddy covariance in the vertical, for scalars that include temperature, are outlined in Paw U et al. (2000), with some of the first work on this concept in Swinbank (1951). Paw U et al. (2000) proposed that the ‘sonic’ temperature perturbations reported by sonic anemometers should be used for sensible heat $H$ instead of the ‘dry’ temperature perturbations. Some key assumptions are that there is no horizontal divergence of turbulent or mean fluxes of sensible heat, and there are zero vertical mean fluxes of sensible heat (Paw U et al., 2000).

Eddy covariance can be used to directly measure evapotranspiration when high frequency water vapor concentrations are measured. Besides the corrections and assumptions discussed in Paw U et al. (2000), other limitations exist related to the technology of measuring water vapor concentrations at high frequencies. These include the inability for the sensors to measure the concentrations at sufficiently high enough frequencies; non-zero averaging volumes; differential and changing time lags in the reported concentrations and the vertical velocities; errors in the vertical velocity measurements; corrections necessary for volumetric changes of the air parcels being measured when pressure variations may also be occurring; and other issues. When the energy budget discussed in this report is checked for ‘closure,’ then the following should be true: $R_n - G = H + LE$.

However, for almost all eddy covariance sites, $H$ and $LE$ measured by eddy covariance are less than $(R_n - G)$ when all four energy budget components are measured; so direct measure of $LE$ by eddy covariance itself may substantially underestimate $LE$ by 20% to 30% (see Wilson et al., 2002). Even when various corrections are attempted, the $H$ and $LE$ measured by eddy covariance still incurs substantial underestimation of fluxes (Foken et al., 2010). It is likely that this, in large part, is related to the complexity of the eddy covariance system, with two sophisticated sensors requiring frequent maintenance to produce accurate measurements, and that this is also related to the conditions where horizontal advection may carry a substantial amount of the exchange (Kochendorfer and Paw U, 2011).
Surface Renewal

Based on the concept of turbulent coherent structures dominating surface exchange of heat and other scalars, surface renewal theory has been developed to use fast-response measurements of scalars to estimate fluxes (Paw U et al., 1995). The general concept is that an air parcel in the coherent turbulent structure drops into the surface region, is heated or cooled by the surface, resulting in a slow increase (or decrease) in its temperature. Then when a new parcel suddenly gusts into the surface area, there will be a sudden decrease (or increase) in temperature. By measuring the temperature trace and estimating the duration between these temperature drops (or rises) and the value of the drops (or rises), one can estimate the sensible heat. Nonetheless, some calibration is initially recommended against an independent measure such as eddy covariance (Paw U et al., 1995; Snyder et al., 1996; Paw U, 2001; Paw U et al., 2005), the adjustment parameter is called alpha (α). Once calibrated, the advantage of surface renewal is that sensible heat, H, can be measured with low-cost thermocouples and a basic datalogger, without the need for a sonic anemometer. Although the random errors from using calibrated surface renewal are only slightly greater than that of eddy covariance (Snyder et al., 1996, Paw U et al., 2005), the method is simpler, easier to maintain, and less expensive. In addition, as noted in the eddy covariance section, there could be substantial underestimation of fluxes with eddy covariance. Therefore, when attempting to measure numerous locations, using surface renewal is an efficient method to estimate sensible heat, H, and energy budget residual, LE and ET.
APPENDIX A TECHNICAL SUPPLEMENT II: STATION EQUIPMENT AND CALIBRATIONS

Sensor and Station Description

The sensors used at each site station consisted of one net radiometer and two fine-wire thermocouples. Equipment at the full station included an additional sonic anemometer, soil heat flux plates, and soil thermocouples. Both types of stations were powered with photovoltaic solar cell panels through a regulator unit and storage batteries, obtained from Campbell Scientific, Inc (CSI). The net radiometers were the Kipp & Zonen NRLITE models, measuring incoming and outgoing solar and thermal radiation in watts per meters squared (W/m²). All of the net radiometers were cross-compared and calibrated to a field standard at the UC Davis Campbell Tract Field Research Facility before deployment to the study sites (see Appendix A Technical Supplement II.2). The fine-wire thermocouples were the Campbell Scientific FW3 model, measuring temperature in degrees Celsius (°C). The sonic anemometer was the R.M. Young 8100RE model, which measured horizontal and vertical wind velocities in meters per second (m/s). These velocities allowed the calculation of the wind direction in degrees (°) both in the horizontal and vertical. The soil heat flux plates were the Radiation and Energy Balance Systems HFT3 model, measuring ground heat flux in watts per meter squared (W/m²). The soil thermocouple probes were the Campbell Scientific TCAV-L30 model, which recorded an average soil temperature in degrees Celsius (°C) based on the measurements of all four thermocouple probes. A Campbell Scientific CR1000 datalogger was used to record all measurements.

All stations, D1 through D5, had two fine-wire thermocouples installed at 1.5 meters above ground level and 1.0 meter above ground level. The temperature recorded at the 1.5 meters height above ground level was used in the surface renewal calculations to derive evapotranspiration. Stations D2, D3, D4, and D5 each had the net radiometer installed at 1.5 meters above ground level. Station D1 had the net radiometer installed at 1.82 meters above ground level; it was installed at a higher height than that of the other stations due to the presence of sparse, tall weeds in this field. The R.M. Young sonic anemometer at station D5 was sampling wind at the height of 2.15 meters above ground level.
Table A-SII-1. Station Locations (Above Sea Level Elevation; data from Google Earth)

<table>
<thead>
<tr>
<th>Station</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>37°57'30.7&quot; N</td>
<td>121°38'07.7&quot; W</td>
<td>3.0 m</td>
</tr>
<tr>
<td>D2</td>
<td>37°57'30.6&quot; N</td>
<td>121°38'06.1&quot; W</td>
<td>3.0 m</td>
</tr>
<tr>
<td>D3</td>
<td>37°39'25.0&quot; N</td>
<td>121°15'52.8&quot; W</td>
<td>16.8 m</td>
</tr>
<tr>
<td>D4</td>
<td>37°39'37.2&quot; N</td>
<td>121°15'51.2&quot; W</td>
<td>14.9 m</td>
</tr>
<tr>
<td>D5</td>
<td>37°52'23.3&quot; N</td>
<td>121°22'11.02&quot; W</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>

Cross-comparison and bias correction of net radiometers

Past inter-comparisons of radiometers (e.g. Brotzge and Duchon 2000) have demonstrated possible substantial mean biases between different types of radiometers and different individual radiometers of the same type and model (including the NRLITE net radiometers used in these Sacramento-San Joaquin (SSJ) Delta measurements). We therefore performed our own inter-comparison of the net radiometers used for this study so we could correct for possible biases. The comparison was carried out for a period of fifteen days in August 2015 before measurements in the Delta stations D1-D5 were carried out. Six radiometers were mounted at 1.5 m above ground level in a fallow field at the UC Davis Campbell Tract Field Research Facility. Half-hourly net radiation from each radiometer was plotted against the radiation measured by a field reference radiometer standard (a brand new NRLITE2). Slopes and offsets needed to standardize each radiometer to the reference are given in Figure A-SII-1. The radiometer for Station D4 showed signs of tilting during the calibration period which lead to high calibration coefficients and higher net radiation. We therefore do not include data from station D4 in our measurements of ET from fallow fields.
Figure A-SII-1. Scatterplots and regression equations used to standardize the radiometer for each station (D1, D2, D3) to the reference radiometer (D5).

Before standardization with the coefficients in Figure A-SII-1, root-mean-square differences between the other radiometers (D1, D2, D3) and the reference (D5) ranged from 19 to 28 W m\(^{-2}\) (mean absolute differences from 13 to 20 W m\(^{-2}\)). Once standardized, RMSE ranged from 3 to 11 W m\(^{-2}\) (mean absolute differences from 2 to 4 W m\(^{-2}\)). Examination of remaining differences revealed signs of slight differences in tilt that would be expected if the radiometers were not exactly level in the east-west direction. As it is difficult to initially level the radiometers perfectly and keep them perfectly level in field conditions, these differences are considered part of the uncertainty of the method.

**Wind speed sensitivity correction to measured net radiation**

Net radiation measured by all thermal radiometers is sensitive to wind speed. This is especially true of domeless radiometers such as the NRLITE model used in the present work. At higher wind speeds, the NRLITE has been observed to underestimate net radiation (Brotzge and Duchon 2000). The manufacturer (Kipp and Zonen) and a distributor (Campbell Scientific Inc.) provide differing possible corrections for this bias. The former is theoretically-based while the latter is based on a study by Brotzge and Duchon (2000) that performed a careful inter-comparison between seven NRLITE radiometers and several other radiometers of different types. Their correction, which only applies when the wind speed is above 5 m/s, is adopted here.

At the station (D5), wind speed was measured, and this measurement was used to perform the correction to the net radiation. At the remaining surface renewal station locations (D1, D2, and D3), where wind speed was not measured, wind speed measurements from the Brentwood and Modesto CIMIS stations were used and were respectively assigned depending on the closest CIMIS station. CIMIS hourly-averaged wind speeds were interpolated to half-hourly averages to match the averaging period of our measurements.
At any given station, 3-6% of the half-hour measurements over the course of this study had any wind correction to the net radiation. Maximum radiation correction in any of those half-hours was 7%.

**Corrections to eddy covariance sensible heat fluxes**

Recent work has demonstrated that sonic anemometers with non-orthogonal transducer orientations (such as the model we used in this study) underestimate vertical wind velocity (and therefore sensible heat flux) due to the effect of turbulent wakes created by the transducers themselves (Kochendorfer et al. 2012). We adopt the suggested correction by increasing our half-hourly sensible heat flux measurements in this analysis by 12%. We also adopt a spectral correction of 1.5% to the sensible heat flux based on typical values observed in previous work (Kochendorfer and Paw U 2011).

**Calibration of surface renewal heat fluxes against eddy covariance**

Half-hourly measurements from station D5 were used to derive calibration coefficients relating sensible heat flux measured using eddy covariance and sensible heat flux measured using surface renewal. Separate coefficients were determined for positive and negative sensible heat fluxes (Figure A-SII-2). The high coefficients of determination ($R^2$) and the slope's being close to one indicate a close relationship between the two independent measurements when $H$ is positive (typical daytime conditions). When $H$ is negative (typical at night), the relationship is not as precise due to typically lower turbulence levels in these conditions. Sensible heat fluxes measured using surface renewal at all sites were multiplied by these calculated coefficients.
Methods for estimating ground heat flux

Ground heat flux, $G$, was measured at station D5 for a period of about nine days during the experiment using ground heat flux plates and soil temperature sensors as described earlier. It is necessary to account for $G$ at the other sites and at station D5 outside of the period of $G$ measurement. Two approaches were considered. The first was to assume the ground heat flux term negligible at the daily scale (i.e. set it equal to zero), with the assumption that the bulk-averaged soil temperatures did not vary greatly from day to day, such that theoretically, then $G$ would be close to zero. The second was to parameterize $G$ as a function of the net radiation. Parameterizing $G$ as a constant approximately 10% of $R_n$ is common for surfaces with a canopy, but for this study we empirically derived a parameterization from bare soil measurements we had that were based on an informal technique we piloted for other research at the UC Davis Campbell Tract Field Research Facility. This parameterization was based on an analysis during the current study and consisted of separating the ratio $G/R_n$ into a daytime and a nighttime value, using these data to form these ratios inspired by a previous fallow field experiment at Campbell Tract, described in Stephens (2013). Due to the rain event when the ground heat flux was being measured at station D5, to obtain a parameterized $G/R_n$ ratio representative of dry, summer field conditions, $G$ from dry period days only was used in the calculations. The result was a daytime $G/R_n$ ratio of 0.23 and a nighttime ratio of 0.70 (Figure A-SII-3). Similarly, measurements taken in bare soil at the Campbell Tract fields (see Stephens 2013 for details) over a longer period yielded corresponding ratios (0.24 during the day and 0.72 at night, not shown).
Figure A-SII-3. Top graph: Half-hourly mean values of measured Rn and G during the dry period at station D5. Bottom graph: Ratios of measured G to Rn at station D5 during the dry period. Labeled, solid black lines show the values used to parameterize G when only Rn (and not G) was measured. Extreme values of G/Rn, occurring near sunrise and sunset when Rn is near zero, were not considered in the parameterization averages and are not expected to affect the ETa estimates greatly, since the values of Rn, and therefore G, are small during these times.
APPENDIX A TECHNICAL SUPPLEMENT III: CIMIS STATION DATA SUMMARY (WIND ROSES, RELATIVE HUMIDITY, AND PRECIPITATION)

Data from the closest CIMIS station to each of the fallow fields was used to estimate hourly wind speed at the field and for reference ETo estimates to compare with the actual ETa we measured in the fields. The Manteca CIMIS station was located 8.4 miles to the east-southeast of station D5. The Modesto CIMIS station was located 4.3 miles to the east-southeast of stations D3 and D4. The Brentwood CIMIS station was located 2.7 miles to the southwest of stations D1 and D2. Historical hourly data from these three stations showed predominantly northwesterly winds during all hours of the day for the month of September during years 2000-2015. Wind directions over the period of this 2015 measurement campaign (Figure A-SIII-1-A-SIII-3) matched closely with the climatology. During October 1, 2015, starting just before midnight of the night before, all three CIMIS stations recorded precipitation: Manteca, 5.0 mm; Modesto, 5.1 mm, and Brentwood, 9.0 mm.

In between the 2015 field campaign and the 2016 field campaign, the three Delta Water Agencies funded the purchase and deployment of five new CIMIS stations within the Delta. Data from these new stations that were incorporated into the CIMIS network will be valuable in achieving improved correlation of local weather variations, particularly those associated with wind conditions, which are highly variable within different parts of the Delta.

![Wind rose diagram from Manteca CIMIS station]

Figure A-SIII-1. Wind direction, strength, and frequency shown from the Manteca CIMIS station during the experiment period. This CIMIS location was the closest in proximity to station D5.
Figure A-SIII-2. Wind direction strength, and frequency shown from the Modesto CIMIS station during the experiment period. This CIMIS location was the closest in proximity to stations D3 and D4.

Figure A-SIII-3. Wind direction, strength, and frequency shown from the Brentwood CIMIS station during the experiment period. This CIMIS location was the closest in proximity to stations D1 and D2.
Figure A-SIII-4. Relative humidity recorded by all three CIMIS stations during the experiment period was used in correlation to possibly explain the variation in ET from zero on a day-to-day basis.
Figure A-SIV-3. Stations D1 and D2 located off of Byron Hwy

Figure A-SIV-4. Stations D3 and D4 located off of S Kasson Rd
Figure A-SIV-5. Station 5 located off Crocker Rd. This map image was taken on 3/14/2016, months after our experiment period ended. A walnut orchard was planted here.
APPENDIX A TECHNICAL SUPPLEMENT V: STATION PHOTOGRAPHS

Figure A-SV-1. Station D1 (lite station) with station D2 seen in the distance to the left

Figure A-SV-2. Station D2 (lite station)
Figure A-SV-3. Station D3 (lite station)

Figure A-SV-4. Station D4 (lite station)
Figure A-SV-5. Station D5 (full station)