Image caption: Eddy covariance tower deployed at a rice field in Arkansas.

Partitioning Rice Field Evapotranspiration into Evaporation and Transpiration Components

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Abstract: This project aimed to resolve uncertainties in the evapotranspiration (ET) portion of the water balance as rice farms transition from conventional to alternate wetting-drying (AWD) irrigation strategies. As 64% of regional precipitation is converted to ET, it is a dominant part of the surface water balance, and understanding its behavior is a key priority to determine the state's water resources situation. Our project's research work is performed at several scales. First, we directly monitor ET rates with the eddy covariance method at several rice production fields in Arkansas in concert with biometeorological measurements to detect underlying, predictive mechanisms. We interpret these measurements in a number of ways, including the Food and Agricultural Organization's implementation of the Penman-Monteith equation to partition ET into its transpiration and evaporation components. Here we find that AWD management does not significantly alter the surface water balance due to the high rates of transpiration during the growing season. Second, we have generated a regional network of research scientists focused on ET and related fluxes (e.g., land-atmosphere exchange of CO_2, which plays a major, interacting role in controlling plant water use). Further, we have connected to a USGS groundwater modeling team to enhance their representation of ET in their projections. Our local and regional results lay the groundwork for more nuanced experimental research in both ground observations and modeling strategies. The initial results will help to constrain the rate of ET in the region so that USGS-driven models more accurately anticipate changes in the region's water resources.

Key Points:

- Evapotranspiration (ET) is largely composed of transpiration during the growing season (74% over the season; up to 95% in the mid-summer)
- The transpiration signal is strong such that drying periods do not seem to show significant reductions in ET.
- The project team has expanded its spatial reach by developing a regional network of ET observation sites and will work with a USGS team to help constrain regional groundwater models.

Introduction

Rice agriculture uses 35% of Arkansas's irrigation water and contributes to the unsustainable depletion of the state's water resources (Reba et al., 2013; ANRC, 2014). A variety of new irrigation methods have been proposed to reduce water use, including alternate wetting and drying (AWD), which floods the soil and then allows a strategic dry down before reflooding to save water, reduce the risk of the straighthead disability on rice, and decrease field methane production. This method reduces greenhouse gas emissions by more than 70% (including from methane, which is produced under water-saturated conditions and is 20-30 times more potent as a greenhouse gas than CO_2) (Rogers et al., 2013; Linquist et al., 2015). Our 2015 project found that total evapotranspiration (ET) from an AWD field is similar or even slightly greater than a comparison, conventionally flooded field. This response may be due to the strong ability of rice roots to pull water from the soil matrix and from the relatively short length of the dry down period (approximately 11 days).

Therefore this project aimed to investigate further the relationships between evaporation and transpiration and to quantify a second growing season of ET rates in Arkansas rice production to test whether the initial results were robust over time. This project also aimed to generate broader interest through the creation of a regional network of measurement sites. While our eddy covariance datasets are still being developed, we have been able to compare initial findings with the Food and Agricultural Organization's Penman-Monteith method of reference ET (known as FAO56; Allen et al., 1998). The FAO56 method is also used to partition the total ET into contributing portions of evaporation and transpiration by applying a dual crop coefficient method.

Additionally, we recognize a need for a more regional perspective, and so sought out strategic partners who both collect and interpret ET observations. We generated the regional Delta-Flux observation network, established ties to South Korean researchers, and have begun working with a USGS team dedicated to improving groundwater modeling of the Mississippi Alluvial Aquifer. These efforts are described in more detail in the Results and Conclusions sections.

Methods

This research is situated within a larger project aimed to measure year-round land-atmosphere fluxes of energy, water vapor, CO_2 and CH_4 from two side-by-side pairs of rice fields near Humnoke and Burdette, AR, respectively (Figure 1). This larger project provides meteorological instrumentation, eddy covariance equipment to measure the fluxes, and associated environmental monitoring devices to capture terms such as the water level and soil temperature. Presented here are the water vapor fluxes measured by the eddy covariance method, for the Humnoke fields in 2015.

Water vapor fluxes are both measured by the eddy covariance method to determine turbulent transport between the surface and atmosphere (Baldocchi, 2003) and they are modeled by the Penman-Monteith equation (Monteith, 1981). The eddy covariance measurements are generated from observations of vertical wind and water vapor recorded 20 Hz by using the EddyPro software, version 6.2 (Li-cor, USA), and are carefully quality controlled following standard protocols and an additional screen for outliers in the scalar statistics. The eddy covariance observations are gap-filled using an artificial neural network approach (Knox et al., 2015, 2016). These models use data equally apportioned into training, testing, and validating groups from natural data clustered identified using a k-means method. The procedure was replicated across 20 resampling runs and the median prediction was used for gap-filling. To estimate conservative uncertainty bounds from this procedure for the seasonal budget, we use the 95% confidence interval from the 20 extractions used to

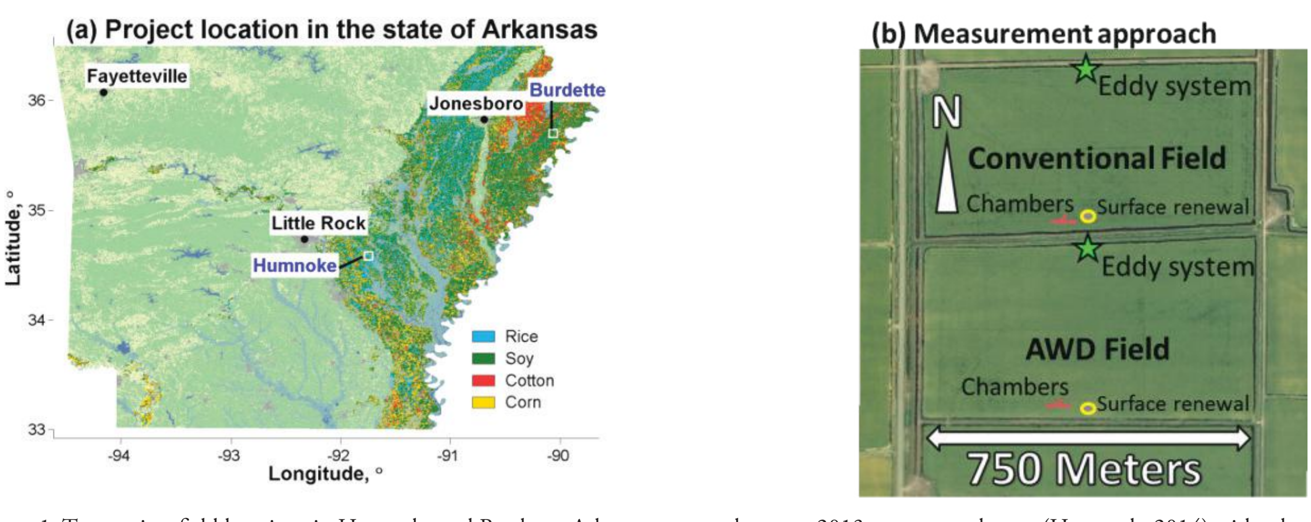

Figure 1: Two project field locations in Humnoke and Burdette, Arkansas, mapped upon a 2013 crop cover dataset (Han et al., 2014) with selected crops in legend. (b) Representative paired field site (Humnoke, AR farm) with measurement sites for the eddy covariance system (which includes soil and biometeorological measurements, closed chambers, and surface renewal system indicated).

fill each gap. The ANN model for ET was created with explanatory variables including decimal day since the start of the study period, leaf area index (LAI) and plant height interpolated using growing degree day, the friction velocity u*, air temperature, incoming solar radiation (Rg), vapor pressure deficit (VPD), and water table depth. The model also included representations of seasonality (spring, summer, and autumn) and the time of day (morning, afternoon, evening, and night), following the method of Papale and Valentini (2003).

Using observations of ET, meteorology, and assumptions about the roughness length and aerodynamic conductance, the Penman-Monteith equation can be inverted to estimate the canopy conductance gc. The model is inverted to create estimates of gc based on measured ET. This approach was previously used by the PI to determine canopy controls on ET in a Russian wetland (Runkle et al., 2014). The canopy conductance term is assessed during wet periods for both fields under the hypothesis that it should behave very similarly between fields under similar conditions. In the future, using the photosynthesis estimates derived from the simultaneous CO_2 flux measurements could enable a partition of ET into plant-controlled (transpiration) and water or soil controlled (evaporation) components. During dry down periods the hypothesis is that canopy conductance will become an increasingly important control on ET rates. The transpiration portion of ET should also increase during these periods even if the overall ET rate is similar to wetter periods. The dual crop coefficient method requires biometeorological and phenological inputs in order to calculate two separate crop coefficients used to convert reference evapotranspiration (ET_{ref}) into transpiration and evaporation:

$$ET=(K_{trans.}+K_{evap.})*ET_{ref}$$

where the part modified by K_{trans} is the estimated transpiration and the part modified by Kevap is the estimated evaporation. Each coefficient was calculated separately using guidelines presented in FAO56, including recommendations and considerations for different crops, management practices, and climate. These coefficients are also adjusted for the higher relatively humidi conditions present in the US Mid-South. The reference evapotranspiration rate was calculated using methods also outlined in FAO56 as part of the Penman-Monteith method for calculating reference evapotranspiration.

Site description

Two privately farmed, adjacent rice fields (34° 35' 8.58" N, 91° 44' 51.07" W) located just outside of Humnoke, Arkansas, were used for this research. Each field is approximately 350m wide from north to south and 750m long from east to west (i.e., 26 ha). One field was managed with continuous flooding (CF) during the rice growing season and the other with AWD management practice, facilitating a direct comparison of the two types of systems with minimal spatial separation. Both sites have been zero-graded and thus have approximately 0% slopes. Although only about 12.3% of total rice in Arkansas is grown on zero-graded land, this practice is growing due to the potential to save water in the fields (Hardke, 2015), to serve as a carbon-offset credit option (ACR, 2014) and to receive credit in the Natural Resources Conservation Service's Environmental Quality Incentives Program (EQIP). The sites are not tilled and are flooded for two months in winter for duck habitat and hunting. The dominant soil mapping unit in this area is a poorly-drained Perry silty clay. In 2015, the fields were drill-seed planted April 7 (AWD) and April 8 (CF), given an irrigation flush on May 3 (CF) and May 4 (AWD), and given a permanent flood on May 16 (CF) and May 18 (AWD). The AWD field dried on June 5 and received 3 more dry periods through the summer.

Results

Evapotranspiration observations and partition into evaporation and transpiration

Observed ET in each field in 2015 was similar, regardless of water management (Figure 2). Even during periods when the AWD field had a water table below the surface and the CF field had a standing water table, the daily observed ET was very similar (the AWD field ET was 1.07 ± 0.06 times the CF field ET, n=25 observed days; alternately, when both fields had a standing water table, the slope was 1.01 ± 0.03, n=63). In 2015 the fields also had similar yields, though the field under AWD treatment had higher peak LAI (approx. 5 vs 4.5). The contributions of modeled evaporation and transpiration to ET – both as observed and as modeled by the FAO56 method – for the entire 2015 growing season can be viewed in Figure 3. Transpiration was the highest contributing portion in both fields, composing 73-75% of total ET. Seasonal totals for each portion as well as eddy covariance observations can be found in Table 1. With these fields the modeled ET tended to overestimate the observed and gap-filled ET. Further work is being performed to test this finding by assessing the eddy covariance data for further corrections, including transducer shadowing on the sonic anemometer (Horst et al., 2015) and other possible causes for the well-known potential under-estimation bias of eddy covariance measurements (Foken et al., 2011).

Our initial investigation of surface conductance, looking at the noon-time value as representative of canopy characteristics, indicates that both fields were similar whether the two fields were under similar, ponded-water conditions or whether the AWD field was dry and the CF field was wet. In these cases the relationship between gc of the AWD field and gc of the CF field had a slope of 1.12 ± 0.01 (n=18) or 1.17 ± 0.004 (n=51), respectively (data not shown). Because these relationships look so similar, we cannot yet use surface conductance as a clear indicator of flooded or dried water flux source conditions, nor use it as a clear indicator by which to partition the flux into evaporation or transpiration components.

While we observed a second rice growing season, in 2016,

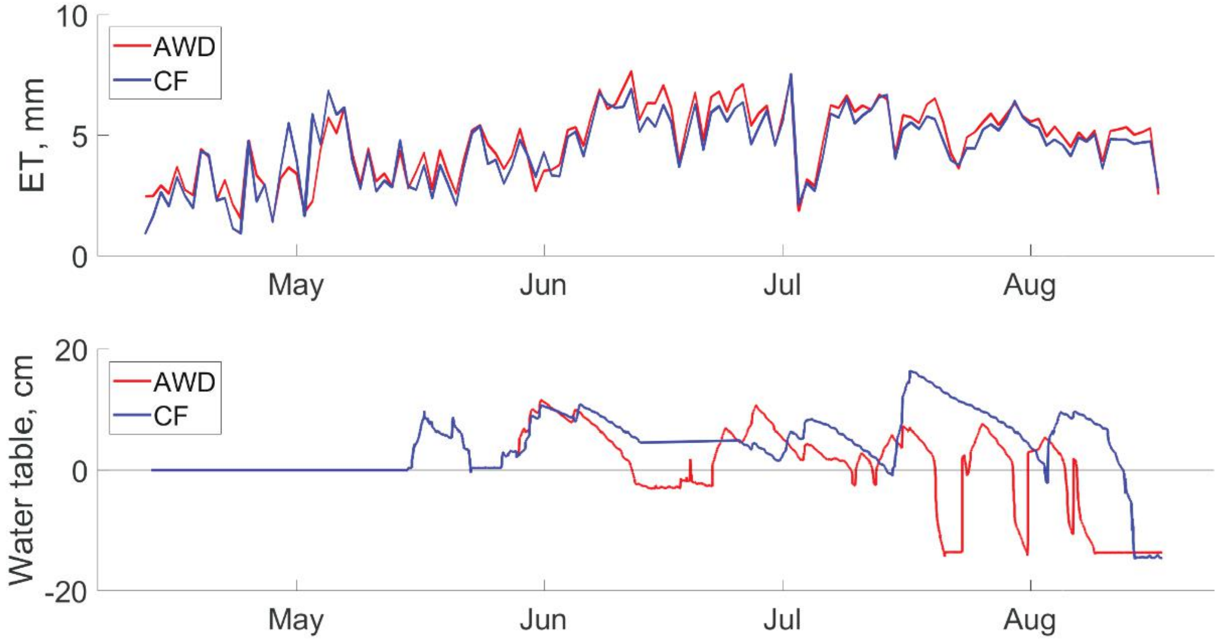

Figure 2: Daily ET estimates for both CF and AWD fields using eddy covariance, gap-filled with a neural network model, and presented with 30-min water table measurements throughout the 2015 growing season.

and expanded our efforts to include measurements near Burdette, Arkansas, those results are not yet ready for release. They are being quality-controlled and checked for accuracy, and they were delayed in part through re-coding for the transducer shadowing effect as described above. An initial look at this data suggests that the findings are consistent with the 2015 growing season. These results will be published as soon as possible and then widely shared through the AmeriFlux website.

Network generation and project expansion

A major result of this project was an effort to generate several regional networks. Networked research sites are increasingly used to study regional land management impacts on carbon and water fluxes. However, key national networks lack contributions from the Lower Mississippi River Basin (LMRB), whose highly productive agricultural areas have potential for soil carbon sequestration through conservation practices. Therefore, we established the new Delta-Flux network to coordinate efforts to quantify carbon and water budgets and their interactions at seventeen eddy covariance flux tower sites in Arkansas, Mississippi, and Louisiana (Runkle et al., 2017). We are also working with USGS researchers to improve the water budget of the Mississippi Embayment Regional Aquifer System (MERAS) groundwater model (Clark and Hart, 2009) which is being used to provide projections on groundwater supply under various scenarios of climate and land use changes for the MAP. However, this modeling group lacks ground-based observations of ET, and we hope to integrate the MERAS model with the Delta-Flux network.

Beyond these regional networks, we also expanded our international network to build on work funded through the USGS 104(b) project. We leveraged the 104(b) project to seek funding from the AsiaRice Foundation for a travel grant for project graduate student Colby Reavis. In January, 2017, he visited Youngryel Ryu's research group at Seoul National University in South Korea. There, he learned how to use the Breathing Earth System Simulator (BESS) product, based on remote sensing products and ecophysiological relationships and built by Ryu's group (Ryu et al., 2011; Jiang and Ryu, 2016). The visit to Korea also involved a visit to a rice research site with an eddy covariance tower and discussions about how to better parameterize and clarify the role of rice phenology as an important factor in field ET. Together the site visit and rice phenology discussion highlighted the need to take advantage of cutting edge site-monitoring tools such as drone-based imagery and solar-induced fluorescence.

Conclusions, Recommendations and Benefits

The project findings that ET is largely composed of transpiration during the peak growing season highlight that water savings from AWD are not derived from reduced ET. They are instead derived from a mixture of reduced over-application of water, AWD's ability to capture mid-summer rainfall that would otherwise have drained off the field edge, and reductions in other end-of-field drainage and soil percolation. The ET rates of the fields in this study are very similar to modeled ET using the Penman-Monteith method. This finding lends confidence to regional modeling initiatives that they can constrain this term's uncertainties and reduce uncertainty in projections of the region's full water balance,

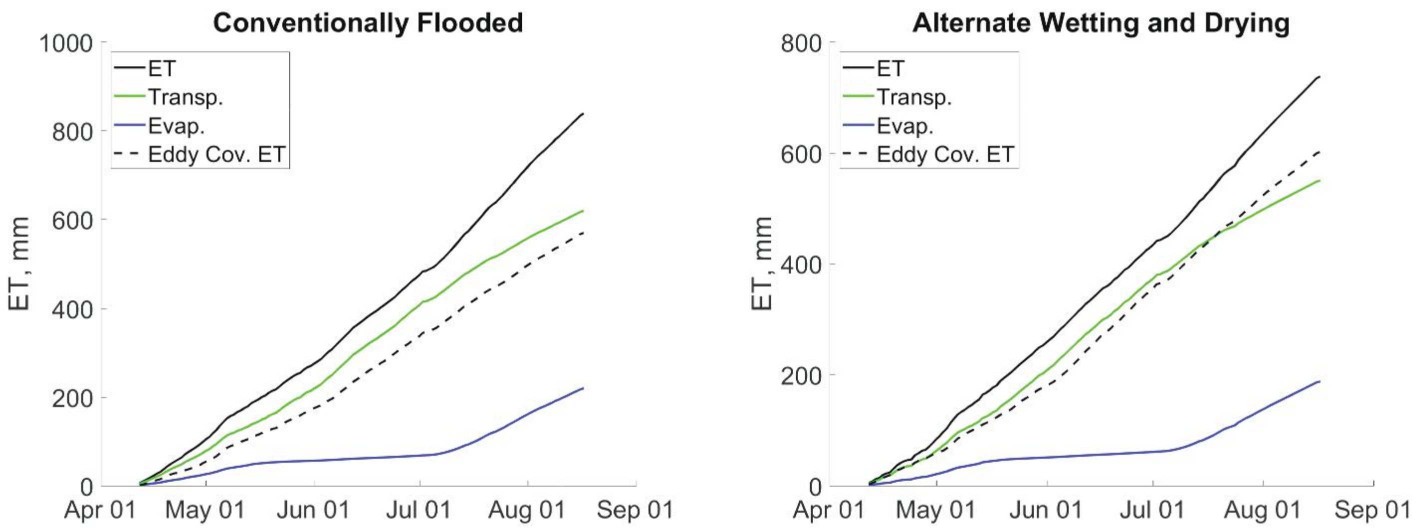

Figure 3. Cumulative transpiration (green) and evaporation (blue) for the 2015 growing season with both portions summing to total evapotranspiration (black) as predicted from the dual crop coefficient model. Eddy covariance observations (dashed) are also included for reference.

including its groundwater levels. To enhance partitioning efforts between evaporation and transpiration, we encourage more field-based techniques such as leaf photosynthesis measurements, analysis of water table fluctuations, or the use of lysimeters or isotopic methods. Coupling an analysis of ET rates with landscape CO_2 exchange may also prove fruitful for helping differentiate the two water flux pathways.

Local, regional, and national benefits

Local measurements of the ET terms will help in managing water demand and irrigation scheduling. Increased knowledge of how the components of rice field evapotranspiration respond to different weather conditions will enable two types of upscaling: (1) temporally, these relationships can be used to expand and improve on models of crop water use in different future climate scenarios, (2) spatially, changes in weather patterns across the state can generate a mosaic pattern of ET. The project outcome will therefore constrain estimates of groundwater recharge, the regional meteorological energy balance, and downstream water quality. We have begun collaborating with USGS partners on the MERAS groundwater model to contribute our ET datasets to their regional modeling initiatives. In addition to providing quantitative data on the magnitude of ET we also hope to generate locally-calibrated mechanistic relationships to place within their modeling framework.

Table 1. Seasonal totals for each contributing portion of evapotranspiration for the 2015 growing season (April 13 to August 17) in Humnoke, Arkansas, based on the dual crop coefficient model.

	Seasonal Total, mm	
	AWD	CF
Transpiration	550	619
Evaporation	188	220
Total ET	738	839

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