1 The Impact of Expanding Flooded Land Area on the Annual Evaporation of Rice

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Abstract

The amount of published data on annual evaporation on rice remains extremely limited despite the role of rice as a key food source. We report on six years of rice evaporation measurements, based on the eddy covariance method. This rice was cultivated in the hot dry climate of California, where water is a scarce and precious resource. During the first year, we found that rice evaporation exceeded potential evaporation rates and summed to 1155 mm y^{-1} . In following years, we found that annual evaporation decreased yearly, yielding a 15% reduction (to 982 mm y^{-1}) by the sixth year. The remainder of the paper examined the how and why of this unexpected decreasing trend in annual evaporation occurred.

We inspected trends in variations in biophysical variables (net radiation, temperature, leaf area index) associated with evaporation and potential biases in the flux measurements using energy balance closure and co-spectral analysis. None of the biophysical variables varied enough to explain this observation.

What did change was the area of rice, and nearby flooded wetlands. During the first year, the flooded rice field was less than 1 km² in area and was relatively isolated. This situation promoted an ‘oasis effect’ that enabled warm dry air to be entrained from across the top of the planetary boundary layer; this contention was supported by the co-spectral analysis and analysis with a coupled surface energy balance-planetary boundary layer model. By the sixth year of this project, the area of flooded rice and wetlands approached 6 km², a horizontal scale that seemed to inhibit the ‘oasis effect’. We conclude that the amount of water used, on an area basis, by wetland restoration projects will depend upon the spatial extent of these projects.

46 **Introduction**

47 Natural solutions are needed to offset climate warming that is being attributed to increasing levels of
48 carbon dioxide in the atmosphere. Land use change and ecological restoration are integrated options
49 that are gaining growing interest due to their potential change the carbon balance favorably or offset
50 warming (Jackson et al., 2008; Suding, 2011). An increase in the carbon sink capacity of a landscape can
51 be achieved by ecological restoration of wetlands (Artigas et al., 2015; Audet et al., 2013; Knox et al.,
52 2015; Mitsch and Gosselink, 2000) or by re-forestation (Jackson et al., 2008). Alternatively, cooling of
53 the landscape is possible by introducing irrigated crops in deserts (Christy et al., 2006; Doran et al.,
54 1992; Sorooshian et al., 2011) or by replacing forests with grasslands, in the mid to higher latitude belts
55 (Jackson et al., 2008; Lee et al., 2011).

56 One of the concerns of ecological or geo-engineering is the introduction of unintended consequences
57 with the modification of the environment (Robock, 2008; Suding, 2011). Forests can be effective carbon
58 sinks, as long as they do not burn periodically (Malmsheimer et al., 2011). In other instances, forests
59 may be warmer than the short vegetation they replace because forests possess a darker albedo and
60 ingest more sensible heat into the atmosphere due to their aerodynamic roughness (Baldocchi and Ma,
61 2013; Lee et al., 2011). Only in the tropical regions, where forests play a role in sustaining convective
62 clouds and rain, do forests lead to cooling compared to deforestation (Dickinson and Henderson-Sellers,
63 1988).

64 With regards to increasing the carbon sink capacity of a landscape, there is the well-known 'cost of
65 water for carbon' through optimal control of stomata (Bierhuizen and Slatyer, 1965; Cowan and
66 Farquhar, 1977; Katul et al., 2010). In other words, increasing carbon uptake comes at the cost of
67 increasing the amount of water used (Law et al., 2002; Sinclair et al., 1984). In humid environments,
68 this extra cost of water may not be a concern, but growing vigorous vegetation in semi-arid

69 environments with irrigation can have negative implications as this is a very energy-intensive solution
70 involving the redistribution of a scarce and precious resource, water.

71 Restoration of wetlands or adoption of flooded rice, on drained peatland agricultural lands, provide
72 much promise for being strong carbon sinks (Bridgman et al., 2006; Hatala et al., 2012; Miller et al.,
73 2008; Mitsch et al., 2013), circumventing many of the perceived problems associated with reforestation.
74 The flooding produces anoxic conditions that inhibit heterotrophic respiration, thereby reproducing
75 conditions that can re-build layers of peat (Drexler et al., 2009a; Miller et al., 2008). Being wet and
76 flooded, wetlands tend not to burn. Wetlands are also ideal for fish and bird habitat. But we are
77 beginning to learn some of the unintended consequences of wetland restoration or the adoption of
78 flooded rice. This flooding causes high rates of methane production, a perfidious greenhouse gas
79 (Hatala et al., 2012; Knox et al., 2015; Petrescu et al., 2015). Flooding also promotes mosquito
80 populations and methyl mercury (Marvin-DiPasquale and Agee, 2003), both are menaces to people
81 living in the vicinities of wetlands.

82 In central California, we are working on a project that is introducing rice and restored wetlands to stop,
83 and possibly reverse, the soil subsidence of drained peatlands (Hatala et al., 2012; Knox et al., 2015).
84 However, the management of rice or wetlands in central California, which has a semi-arid
85 Mediterranean-type climate, may have additional ecological and environmental costs. Vegetation
86 growing in this region experiences high evaporation potential, reaching 1000 mm y⁻¹ (Drexler et al.,
87 2008; Falk et al., 2013; Ryu et al., 2008), and this region has a limited, variable, changing and contested
88 supply of water for irrigation, fish and wildlife and urban use (Hanak and Lund, 2012). What remains
89 unknown is amount of water lost, at annual and multi-year time scales, by transforming a drained or
90 upland agricultural landscape into one with flooded vegetation, be it rice or restored wetlands?

91 Rice supplies food for over three billion people world-wide (Nguyen and Ferrero, 2006). Yet, there is
92 only a modest number of studies that have reported direct eddy covariance measurements on water use
93 and energy exchange of rice, world-wide. Most of these reports are for case studies or seasonal water
94 budgets (Alberto et al., 2011; Alberto et al., 2009; Harazono et al., 1998; Hsieh et al., 2008; Lang et al.,
95 1983; Leuning et al., 2000; Ohtaki and Matsui, 1982; Ohtaki and Oikawa, 1991; Uchijima, 1976). The
96 number of studies that have measured annual water budgets of rice directly with eddy covariance is
97 paltry (Hatala et al., 2012; Hossen et al., 2012; Timm et al., 2014). And, fewer studies have reported on
98 interannual variations in rice evaporation, based on either direct measurements by eddy covariance
99 (Hatala et al., 2012) or inferential measurements based on surface renewal (Linguist et al., 2015a).

100 Rice has the potential to be a large user of water because rice is flooded and establishes a closed canopy
101 with a high leaf area index that absorbs much of the incoming radiation. This is especially true in
102 California, where flooded rice is grown in a hot, dry climate. Regarding the potential water use by rice,
103 some studies show that as much as 90% of available energy is consumed as evaporation through latent
104 heat exchange during the peak of the growing season in Japan and the Philippines (Alberto et al., 2011;
105 Uchijima, 1976). But this high evaporative fraction is not universal. Other studies show that lower
106 fractions of available energy are lost as latent heat exchange over flooded rice; about 60% for rice
107 growing in Brazil (Timm et al., 2014) and 70% for rice growing in Bangladesh (Hossen et al., 2012). So
108 there remains uncertainty about how much water is lost from a rice paddy during the growing season
109 and over the course of a year; in Asia, rice is often double cropped. Also uncertain is the degree
110 management affects the amount of water used. For example, can rice be manipulated to minimize
111 water use? In the Philippines, there are experiments on how much water is lost from flooded vs.
112 aerobic rice (Alberto et al., 2011). In California, investigators are looking at the effect of dry seeded vs
113 wet seeded rice on water budgets (Linguist et al., 2015a). Additional complicating factors revolve
114 around straw and wildlife management. In the region we are studying rice, the fields are flooded during

winter for water fowl, who help breakdown and degrade the rice straw, thereby reducing air pollution associated with rice straw burning, but extending the period by which water can freely evaporate from the land.

The null hypothesis we are testing in this paper is that flooded rice in California experiences little year to year variability in water use. One could expect this result because the crop is irrigated so it experiences no water deficits, the year to year differences in climate variables that drive evaporation (sunlight, air temperature, humidity deficits, wind) are relatively invariant in central California (Ryu et al., 2008) and the extensive size of the fetch ensures we have a well-developed internal boundary layer and constant flux layer. The basis for this null hypothesis stems from a recent study that inferred estimates of interannual evaporation (using surface renewal and residual energy budgets) of rice growing in the Sacramento Valley (Linguist et al., 2015a); they reported no change in rice evaporation over a 3 year period (862 mm y^{-1}).

Alternatively, we hypothesize that the amount of water lost by a flooded field of rice can vary with its spatial extent. Evaporation from an isolated paddock of flooded rice (even with a fetch with several hundred of meters) maybe enhanced by horizontal advection and by entrainment of warm dry air into the planetary boundary layer (Brakke et al., 1976; Lang et al., 1974; Lang et al., 1983; McNaughton, 1976a). This process would lead to a positive feedback where evaporative cooling causes the surface temperature to be less than the air temperature, which extracts more sensible heat from the atmosphere and thereby increases evaporation further. We propose this alternative hypothesis because we are studying rice in a region where rice cultivation is being introduced. During the first years of our study, the flooded rice field was relatively isolated, being surrounded by pasture and corn. In subsequent years, the area devoted to flooded rice or flooded wetlands grew progressively. If the alternative hypothesis is true, we expect that evaporation rates will decrease with time as the area

planted in rice and restored wetlands increase because the impact of advection, or 'oasis effect' diminishes. Furthermore, expanding area of rice and wetlands could humidify the region, which would impose negative feedback on latent heat exchange and reduce evaporation with time (McNaughton, 1976b; McNaughton and Jarvis, 1991).

Materials and Methods

Sites

The data reported here are from a meso-network of eddy covariance stations in the Sacramento-San Joaquin Delta of Central California. The central site is a rice (*Oryza sativa* L.) field; Ameriflux site US-Twt. Its latitude is 38.10875°, the longitude is -121.6530° and the elevation is 5 m below sea level. We have been making mass and energy flux measurements over the rice since April, 2009 (Hatala et al., 2012) and this paper contains data through April, 2015, yielding six site-years of data.

For comparison, we present evaporation data from an irrigated pasture, infested with pepper weed (*Lepidium latifolium*), an alfalfa (*Medicago sativa*, L.) field and a corn (*Zea mays*) field. The pasture site is on Sherman Island, about 12 km away (latitude, 38.0373; longitude, -121.7536); it is AmeriFlux site US-Snd. This study site was active between April, 2007 and April, 2015. Several studies describing the site, its carbon and water balance and turbulent exchange are available for more details (Detto et al., 2010; Hatala et al., 2012; Sonnentag et al., 2011a). The corn field was located about 700 m in the downwind from the rice site (latitude: 38.1047; longitude: -121.6433 and operated between May, 2012 and November, 2013; it is AmeriFlux site US-Tw2. The alfalfa field was about 900 m north-west of the rice (latitude: 38.1159 N; longitude: 121.64666W; elevation: -9 m); it is AmeriFlux site US-Tw3. Flux measurements at the alfalfa site started in May (day 144) 2013. The fetch was over 370 m. Addition information on the alfalfa study site was reported in a recent paper (Baldocchi et al., 2015).

The climate of the region is defined as Mediterranean-type, with cool, wet winters and hot, clear and dry summers. The climate of the area is defined by 295 +/- 134 mm of annual rainfall, a mean annual daily maximum temperature of 23.06 +/- 0.87 C and a mean annual daily minimum temperature of 9.11 +/- 1.23 C; these data came from the National Climatic Data Center (NCDC) coop climate station near Antioch, CA (USC00040232) and represent the period between 1956 and 2014.

The soil at the site consists of a silt loam upper layer, overlaying a deep peat. The soil is characterized by low bulk density (0.65 and 0.57 g cm⁻³ at a depth of 0-30 cm and 30-45 cm below the soil surface, respectively) and high C content (15% and 31% at a depth of 0-30 cm and 30-45 cm below the soil surface, respectively) (Drexler et al., 2009b; Hatala et al., 2012).

Semi-dwarf rice cultivars adapted to the cooler summers of the Delta, varieties M104 or M206, were planted at a density of 140-168 kg ha⁻¹. Management details of the site are reported in Knox et al. 2016. Key cultivation information, including variety, planting and harvest dates and peak leaf area index, are shown in Table 1. In summary, the farmers planted rice between early to mid-April, except in 2012 when it was planted mid-May, due to a wet spring. The field was flooded throughout the growing season; the depth of water was generally between 0.10 and 0.20 m. Senescence occurred by late August and harvest generally occurred between late September and late October. With the exception of 2014, the rice straw was chopped and left on the field after harvesting of the grain. The paddy was flooded each winter to provide habitat for migrating birds and straw management.

Eddy covariance (EC) and Meteorological measurements

The eddy covariance method was used to measure flux densities of sensible and latent heat; carbon dioxide and methane flux densities were also measured, but they are not reported here. Three dimensional wind velocities (horizontal, u ; lateral, v ; vertical, w ; m s⁻¹) and temperature (T_{sonic}) were

measured with a sonic anemometer (Gill Wind Master Pro; Gill Instruments Ltd, Lymington, Hampshire, England). Fluctuations in CO₂ and H₂O molar density (ρ_{CO_2} and $\rho_{\text{H}_2\text{O}}$) were measured with an open-path infrared gas analyzer (LI-7500; LI-COR Biogeosciences, Lincoln, NE, USA). Before May 2012, analog outputs from the gas analyzer were digitized by the sonic anemometer and these digital streams were recorded with a Campbell CR1000 data logger (Campbell Scientific, Logan, UT, USA). In 2012, we started using a digital data logger system (LI-7550A; LI-COR Biogeosciences, Lincoln NE, USA) that was coupled to the infrared gas analyzer. This change in data acquisition required that we modify the output stream of the sonic anemometer. We needed send analog signals from the sonic anemometer and digitize them on the gas analyzer's digital data logger. This modification required a change in firmware and wiring. We recently found that the manufacturer had a firmware error caused systematic biases in vertical velocity. Consequently, we reprocessed these measurements by multiplying vertical velocity updrafts by 1.166 and vertical velocity downdrafts by 1.289, a recommended by the manufacturer.

At the rice field, the eddy covariance instrument system was mounted on a tower at an average height of 3.15 m. Depending upon the year, the preferred upwind fetch ranged between 450 and 2000 m. The field was flat and winds were typically brisk, bringing ideal conditions for eddy covariance measurements. Identical sets of instruments were mounted at 2.8 m over the alfalfa field, at 5.15 m over the corn and 3.0 m over the pasture. The rice, pasture, corn and alfalfa sites were ideal from the perspective of applying micrometeorological theory and the eddy covariance method in terms of their flatness, vigorous winds, their persistent westerly direction and extended fetches (Baldocchi, 2003; Detto et al., 2010).

Covariances between scalars (temperature, T , and humidity, q) and vertical velocity (w) were computed by sampling fluctuations from the mean 10 to 20 times per second and averaging for 30 minutes. The

software initially removed spikes in the high frequency data and diagnostic instrument values corresponding to bad readings due primarily to precipitation or fog. Next, coordinate rotations were applied to align the streamlines with the surface at the site resulting in zero mean w and v within each 30-min average. We applied a series of standard corrections using in-house software (Detto et al., 2011; Hatala et al., 2012; Knox et al., 2014). A variable time lag was calculated based on a maximum cross-correlation method, where lags outside of a chosen range were replaced by the mode of computed lags over the previous three days. When using open-path sensors, the effects of fluctuations in air density by temperature and moisture were considered (Webb et al., 1980). Sonic temperature, T_{sonic} fluctuations were calculated from fluctuations in the speed of sound after crosswind and humidity corrections were applied (Kaimal and Gaynor, 1991; Schotanus et al., 1983). No high frequency spectral corrections (Moore, 1986) were applied to fluxes computed using open-path sensors since co-spectral analysis indicated that flux losses were less than 5% (Knox et al., 2014), which are well within the accuracy of any spectral correction algorithm; we designed the system sampling rates, sensor placement (height and separation) to minimize such corrections.

Fluxes were also filtered for spikes in 30-min average densities, variances, covariances, and vertical rotation angles exceeding $\pm 7^\circ$. Fluxes were also flagged using the non-stationarity test of Foken and Wichura (1996). Lastly, fluxes from wind directions outside the footprint of the rice paddy (0° – 180°) were filtered and omitted from this analysis. During the active period, between typical planting and harvesting dates (days 100–300), we accepted 75% of the measurements. During the winter and autumn fallow periods, when fluxes were small, winds were often northerly and weather less ideal, we accepted a lower fraction of data (28%), yielding an overall acceptance rate of 55% over 6 years. We filled the missing data with neural network gap filling methods using meteorological variables as inputs (Moffat et al., 2010).

232

233 A suite of meteorological variables was measured in conjunction with the mass and energy flux
234 measurements. Air temperature and humidity was measured with an aspirated and shielded thermistor
235 and capacitance sensor (Vaisala HMP 45, Woburn, MA). Soil and water temperatures were measured
236 with a profile of copper-constantan thermocouples. Soil moisture was measured with a network of
237 capacitance (Theta Probe ML3, Delta-T Devices, Cambridge, UK) sensors. Water table was measured
238 with a pressure sensor (Druck CS420, Campbell Scientific, Logan, UT) immersed in a well, next to the
239 meteorological tower. A digital camera was pointed towards the west, the prevailing wind direction,
240 and monitored the status of the vegetation, through the computation of the greenness index, and field
241 management (Sonnentag et al., 2011b).

242

243 A common measure of sensor and system performance is a test of the surface energy balance closure
244 (Figure 1). Over six years, the mean daily sum of net radiation was 8.366 MJ m⁻² d⁻¹. In comparison, the
245 daily sum of sensible and latent heat exchange, soil heat flux, energy stored in the water column and
246 energy fixed as photosynthesis was 7.788 MJ m⁻² d⁻¹, yielding an agreement within 7% of one another.
247 The degree of energy balance was closed on a year by year basis is further summarized in Table 2. On a
248 year by year basis, the slope between net radiation and the residual of the energy balance ranged
249 between 0.81 and 0.89 and the relative difference in energy balance closure ranged between -2 and
250 15%.

251 The degree of energy balance closure falls within the range typically observed at sites within the
252 FLUXNET network (Stoy et al., 2013; Wilson et al., 2002), and is acceptable given the fact that the spatial
253 footprint of latent and sensible heat fluxes differs greatly from the spatial sampling of net radiation and
254 soil heat terms (Leuning et al., 2012).

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256

257 *Mapping rice extent from remote sensing data*

258 Spatial extent of rice was estimated using satellite and aerial remote sensing data processed by a
259 combination of automated and knowledge-based classification methods. First, we compiled a time
260 series of Landsat satellite images at 30m resolution and 16-day revisit frequency and selected scenes
261 with no cloud cover over the Twitchell Island (11-16 scenes per year). The images were acquired by
262 Landsat 5 TM missions for years 2009-2011, by Landsat 7 ETM+ for 2012 and by Landsat 8 OLI for 2013-
263 2014. They were accessed and processed on the new Google Earth Engine applied programming
264 interface (Google Inc.) as L1T terrain-corrected products converted to the top-of-atmosphere
265 reflectance. Due to the end of operational imaging of Landsat 5 in late fall 2011, Landsat 7 ETM+ was
266 the only operational Landsat mission 2012; its images have striped gaps since 2003 due to the scan line
267 correction mirror failure; consequently, we applied a gap-filling correction to 2012 Landsat images using
268 pixels from the closest temporally matching images from 2011 or 2013.

269

270 Next, for each scene we estimated Normalized Difference Vegetation Index (NDVI) as the normalized
271 difference between Landsat's near-infrared and red electromagnetic bands and Land Surface Water
272 Index (LSWI) as the normalized difference between near- and the first shortwave-infrared bands, and
273 several other indices previously used in remote sensing-based monitoring of rice paddies. We then
274 constructed seasonal profiles of their values for designated polygons representing samples of known
275 locations of rice, alfalfa, pastures, wetlands, water and bare soil to assess the contrasts between rice
276 and other surface types. These assessments were performed separately for each year because of

variability in specific dates of available cloud-free imagery.

We found that the most effective spectral features to discriminate between rice fields and other surfaces in the study area were: 1) LSWI from the scenes taken at late fall or winter flooded stages, 2) its ratio to standard deviation of NDVI values from the whole years and in 3) spectral difference between either NDVI or LSWI values of the maximum greenness summer stage and flooded winter stage. The corresponding indices were extracted as raster datasets for each year and overlaid with the overall extent of agricultural areas digitized manually from the National Agricultural Imagery Program (NAIP) aerial photo product (1-m spatial resolution) from June 2012. Then pixels with the flooded-stage LSWI values greater than 0 were assigned as 'seed' units for rice classification, and an iterative region-growing procedure was applied to the neighboring pixels to fill paddy boundaries with "rice" pixels if those paddies contained 'seeds', constrained by a limit on maximum allowable contrast in spectral index values between seed and neighbor pixels. This operation was performed to account for the higher intrinsic heterogeneity of rice plant density and hence spectral features within newer paddies compared to more homogeneous older fields. Total spatial extent of the mapped paddies was estimated as the sum of areas of their allocated pixels and further corrected to account for the pixels falling on field edges or non-rice elements such as parking grounds using high-resolution field boundary digitized from the NAIP aerial image.

Independent data for verification of the field boundaries were available for 2009-2010 from the paddy maps in the progress report document for Twitchell Island Rice Project by Hydrofocus Inc.; all of the mapped fields matched the paddy areas from the report in these two years. In 2013 and 2014, several non-rice crop fields on the island were also flooded in the winter, leading to similar single-date and seasonal differences in LSWI values with rice paddies. To avoid the over-prediction of rice, mapping results for 2013 and 2014 were compared with high-resolution summer Google Earth imagery and any

non-rice elements mislabeled of rice were corrected.

Results

The first question we address is whether sums of annual rice evaporation varied across years, and if so why? Figure 2a compares the cumulative sums of evaporation by year, starting at day 93, when this study started in 2009. Summing the daily evaporation fluxes we found that the rice system evaporated 1155 mm of water during the first study year, 2009-10 (Table 2). In subsequent study years, we observed a steady decrease in annual evaporation. By 2014-15, the rice field evaporated 982 mm, a 15% decrease compared to 2009-10.

Figure 2a also informs us about the trajectories by which the different annual sums of rice evaporation accumulated. Within the first 30 days there was little differences in evaporation, as the fields were drained, cultivated and recently seeded; summer flooding started typically around day 159, or 66 days into the accumulation period. The greatest divergence in cumulative evaporation occurred between about 50 and 150 days after the start of each accumulation period (day 93), with the temporal trends in evaporation during 2009-10 outpacing all the other years; the respective slopes in the cumulative evaporation sums with time were 6.95, 6.08, 5.55, 6.00, 6.01, 6.05 mm d⁻¹, for 2009 through 2015. Afterward, the slopes of accumulated evaporation with time plateaued and were approximately parallel to one another. This suggests that year to year differences in planting and harvest dates and the state of the fallow periods (flooded or drained) had a secondary effect on annual sums of evaporation.

Figure 2b shows the seasonality of daily-integrated evaporation over the 6-year study period; for clarity of presentation we averaged sets of data points on a weekly basis. During the autumnal and winter fallow periods, at the beginning and end of each calendar year, daily evaporation totals from among years overlapped with one another; respective daily sums during the winter (days 1 to 100) and autumn (days 301-365) fallow periods for years 2009 to 2015 were 1.23 +/- 0.9189 mm, 1.28 +/- 1.06 mm, 1.30

+/- 1.06, 1.03 +/- 0.70 mm, 1.26 +/- 1.01 mm, and 1.13 +/- 1.00 mm. The largest values in daily evaporation occurred during the heart of the growing season, between days 150 and 250, when the fields were flooded, the vegetation covered most of the land and the plants were actively transpiring. This was also when there were significant differences in the maximum rates achieved among years. In 2009, peak daily sums of evaporation exceeded 8 mm d⁻¹. During the other years, peak daily evaporation ranged between 6 and 7 mm d⁻¹. Also notable were elevated rates of daily evaporation during the spring of 2012. This was a wet spring and the rice was flooded when it was planted. This difference in weather and management enabled evaporation in 2012-2013 to achieve sums nearly as high as in 2009-2010.

Alone or in combination, none of the expected biophysical drivers of evaporation (solar and net radiation, air temperature, vapor pressure deficit, or leaf area index) experienced enough variation or trends in time to account for the 15% reduction in annual evaporation (Table 3). Similar amounts of net radiation were available at the beginning (3.127 GJ m⁻² y⁻¹) and end (3.179 GJ m⁻² y⁻¹) of the study. Mean annual air temperature was warmer and the mean annual vapor pressure deficit was greater, indicative of a drier atmosphere, during the last year of the study; these factors would have promoted greater, not less, evaporation. And, peak leaf area index was always greater than the threshold value (about 3 m² m⁻²) upon which evaporation is sensitive to changes in leaf area index (Baldocchi and Meyers, 1998; Ritchie, 1972). Nor did we observe distinct trends in gross photosynthesis (Knox et al, submitted to JGR Biogeosciences).

The temporal reduction in annual evaporation of this magnitude for a flooded landscape was unexpected and unprecedented given the fact that a rice system should evaporate near potential rates, as identified by the Priestley-Taylor equation (Priestley and Taylor, 1972):

$$\lambda E = 1.26 \lambda E_{eq} = 1.26 \frac{s}{s + \gamma} A \quad (1);$$

In Equation 1, E_{eq} is the rate of equilibrium evaporation, λ is the latent heat of evaporation, 1.26 is the Priestley-Taylor constant, s is the slope of the saturation vapor pressure-temperature function, γ is the psychrometric constant, and A is available energy; A is defined as net radiation (R_n) minus soil heat flux (G) minus heat storage in the water column (G_{h2o}) minus energy used in photosynthesis (P).

Normalizing λE by equilibrium evaporation ($\frac{\lambda E}{\lambda E_{eq}}$) gives us a way of looking at trends in evaporation that are normalized for differences in available energy, or evaporation potential. Figure 3 shows a marked trend in the ratio, $\lambda E / \lambda E_{eq}$ among years. In the earliest year (2009), this ratio equaled 1.79. This value is much greater than the ideal value of 1.26, that is expected for vegetation evaporating near potential rates (McNaughton and Spriggs, 1986; Priestley and Taylor, 1972). Growth of the planetary boundary layer, due to the input of sensible heat by the surface, and its entrainment of warmer and drier air from above, have proven to be explanations for why the Priestley-Taylor coefficient is 1.26, and not one, for freely evaporating vegetated surfaces, that exert some stomatal control on transpiration (McNaughton and Spriggs, 1986). Wet surfaces, on the other hand, can experience conditions when the ratio between $\frac{\lambda E}{\lambda E_{eq}}$ exceeds 1.26 (Shuttleworth and Calder, 1979). Ratios of $\lambda E / \lambda E_{eq}$ greater than 1.26, as shown here, may be indicative of an enhancement in local evaporation by the 'oasis effect' (Lang et al., 1974; McIlroy and Angus, 1964) if the foliage is not wet. In following years, the ratio

between $\lambda E/\lambda E_{eq}$ experienced an asymptotic decline toward 1.26 by 2014. This ratio indicates that the rice canopy evaporated at rates close to potential evaporation in most of the latter years of this study. The exception to this trend was 2012-13 when the $\lambda E/\lambda E_{eq}$ ratio was anomalously large (1.71); this large value is attributed to, in part, to the fact that the field was flooded prior to planting. In the following section we investigate why annual sums evaporation over rice, and evaporation rates normalized by available energy, experienced such a decline over this 6-year period, in a relatively steady environment.

Discussion

An 'Oasis Effect' by Horizontal or Vertical Advection?

Because rice is not grown widely south of Sacramento, CA, we were working on flooded experimental fields that were relatively isolated during the first years of our experiment. Figure 4 shows the progressive increase in the size of the rice fields and surrounding wetlands with time. During the first year, the east-west fetch, in the yellow area was less than 500 m. This fetch doubled in 2010. And, by 2012 we had about 2 km of upwind fetch, dedicated to rice.

Quantification of this change in area of flooded rice and wetlands is shown in Figure 5. During the first year, rice occupied less than a square kilometer of land. With time there was a gradual expansion in the area of rice. And in later years, wetlands were planted in the vicinity. By 2014, rice covered 2.44 km² of land and the total area of flooded vegetation reached 5.7 km². At this scale, the extent of flooded vegetation is expected to influence the regional condition of the atmosphere (humidity and depth of the planetary boundary layer), and vice versa (fluxes of mass and energy exchange of the vegetation and soil).

While we generally had enough fetch to establish a constant flux layer, the size of the flooded rice during the early years may have been small enough to allow an 'oasis effect' (Lang et al., 1974; McIlroy and Angus, 1964). Quantification of the flux footprint using the analytical model of Hsieh et al (2000) revealed that 90% of the cumulative flux footprint was within 450 m of the tower for neutral thermal stratification, which is at the limit of the horizontal domain of the rice field in 2009. Thereby, any advection of warm, dry air from the surrounding area and or by entrainment from above the planetary boundary layer will cause evaporation rates of well-watered surfaces to exceed net radiation (McIlroy and Angus, 1964). If true, we posit that this 'oasis effect' would diminish as the areal expansion of rice and wetlands occurs, as suggested in Figure 3. In the following figures we explore this hypothesis further.

One of the signatures of the 'oasis effect' is an enhancement of evaporation by sensible heat exchange (H) directed towards the surface (H has a negative sign). Negative values of sensible heat initiate a positive feedback loop that promotes excess evaporation. As the surface cools, this inverts the temperature profile over the surface and enables more sensible heat to be extracted from the atmosphere, especially under daytime conditions when turbulent mixing is vigorous. This positive feedback drives more evaporation, which cools the surface further, extracting even more sensible heat from overhead (Brakke et al., 1976; Lang et al., 1983); over irrigated alfalfa in Nebraska, these positive feedbacks have been known to promote evaporation rates up to 14 mm d^{-1} (Rosenberg and Verma, 1978).

To investigate if there was an augmentation of evaporation from sensible heat, we inspected the mean diel pattern of sensible heat flux (H) for the 100-day period (days 150 to 250) during the heart of the growing season when **daily** evaporation fluxes were greatest (Figure 6). There is clearly a ranking of the diel pattern of H among years, with H most negative during 2009. Daily maximum values of sensible

410 heat flux were the least (near 20 W m^{-2}) and most negative (as low as -76 W m^{-2}) during 2009. By 2014,
411 the mean daily maximum was on the order of 60 W m^{-2} and the lowest value was near -60 W m^{-2} . We
412 also note that sensible heat fluxes crossed over from positive to negative values at 13 hours during 2009
413 and after 15 hours during 2014, giving the rice canopy an extra 3 hours to extract sensible heat from the
414 atmosphere. Adding these data up over a day we find that daily integrated sensible heat ranged
415 between $-2.88 \text{ MJ m}^{-2} \text{ d}^{-1}$ during this period in 2009 to $-0.98 \text{ MJ m}^{-2} \text{ d}^{-1}$ by 2014, which can yield almost
416 another millimeter per day of evaporation. These differences indicate the differential the degree to
417 which sensible heat was extracted from the atmosphere to promote higher rates of evaporation during
418 the early years when the rice field was smallest, compared to the later years when the area of rice and
419 wetlands had expanded.

420 While we have established the role of sensible heat advection on enhancing rice evaporation, what is
421 the source of this energy? Was it due to horizontal advection or vertical entrainment from above the
422 planetary boundary layer, or some combination of both? One signature of advection is a shift in the co-
423 spectrum between vertical velocity (w) and either temperature (T) or humidity (q) towards lower
424 frequencies, or longer wavelengths (Motha et al., 1979). In Figure 7a we observe that the co-spectral
425 densities for $\overline{w'T'}$ overlapped one another during 2009 and 2014; we confined the data set between
426 days 150 and 250 and the hours between 12 and 18 hours when sensible heat exchange was directed
427 toward the surface and the atmosphere's stratification was stable. These results, thereby, suggest that
428 the enhancement of evaporation during 2009, relative to 2014, was not from the differential advection
429 of warmer air at long wavelengths, as associated with the lowest frequencies.

430 What about the advection of drier air? Figure 7b compares the spectral transfer function, defined as the
431 ratio between the humidity ($\overline{w'q'}$) and temperature ($\overline{w'T'}$) co-spectral densities, for turbulence
432 measurements collected during 2009 vs 2014. The transfer function was close to one in 2009 for

frequencies ranging between 0.02 and 0.5, while in 2014, the transfer function was close to one for frequencies ranging between 0.01 and 0.5. This behavior suggests that suggesting that eddies in this frequency range transferred both heat and water equally across these scales. These are the frequencies that transfer most mass and energy between land and the atmosphere, and because heat and moisture exchange have similar sources and sinks, this unity was expected (Kaimal et al., 1972; Motha et al., 1979). The spectral transfer functions diverged at lower frequencies, suggesting that long wave length contributions augmented the transfer of moisture relative to heat more 2009 than in 2014; during 2009 the co-spectral densities of $\overline{w'q'}$ ($S_{wq}(n)$) at normalized frequencies less than 0.01 were up to 1.5 times greater than that for the co-spectral densities of $\overline{w'T'}$ ($S_{wT}(n)$). This spectral enhancement could be accomplished by either a greater downward flux of dry air, entrained from above the planetary boundary, or a by greater upward flux of moisture from upwind surfaces. Since the upwind fields were drier than the flooded rice (Figure 4), we favor the entrainment interpretation.

In 2014, we observed a filtering of water vapor exchange at the lowest frequencies compared to heat exchange; at frequencies below 0.002 the transfer function was less than one. It is possible that humidification of the boundary layer by a larger wetland complex would lessen the 'oasis effect' and dampen the entrainment of dry air from above. This contention is plausible given mean vapor pressure deficit between days 150 and 250 was 1141+/- 486 Pa during 2009 and was 946 +/- 549 Pa during 2014 (Table 3) (these two populations were significantly different from one another, $t = 2.85$; $P = 0.005$).

Given the potential of additional sources of energy for evaporation from the atmosphere, the surface conductance determines how well this energy is partitioned into latent heat exchange. Could it be possible that the conditions of the surface exerted different levels of control on evaporation over time?

To answer this question we computed canopy surface conductance by inverting the Penman-Monteith equation for latent heat exchange (Monteith, 1981):

$$G_{sfc} = \frac{\gamma G_{a,H} \lambda E}{sA + \rho_a C_p D G_{a,H} - \lambda E(s + \gamma)} \quad (2)$$

Undefined terms in Equation 2 include air density (ρ_a), the boundary layer conductance for heat transfer ($G_{a,H}$), the specific heat of air at constant pressure (C_p), vapor pressure deficit (D), and available energy (A). Figure 8 shows the mean diel pattern in canopy conductance during the heart of the growing season (days 150 to 250) for each year. We find that G_{sfc} was generally ranged between 0.01 and 0.02 m s^{-1} , except in 2009 when it reached 0.03 m s^{-1} late in the afternoon.

To provide perspective and a theoretical explanation for how these surface conductances may have affected evaporation, we plotted theoretical values of $\lambda E / \lambda E_{eq}$ vs surface conductance, G_{sfc} , using a coupled surface energy balance and planetary boundary layer model (McNaughton and Spriggs, 1986) (Figure 9). We find that theoretical values of $\lambda E / \lambda E_{eq}$ are close to 1.26 as long as the surface is freely evaporating, as when canopy conductance, G_{sfc} , is greater than 0.01 m s^{-1} . In other words, variations in G_{sfc} between 0.01 and 0.03 m s^{-1} are expected to have little impact on $\lambda E / \lambda E_{eq}$ for uniform values of canopy aerodynamic conductance. This result is consistent with our finding that measured values of $\lambda E / \lambda E_{eq}$ which were close to 1.26 during the later years when fetch was most extensive. Re-visiting data

on canopy aerodynamic resistance, in Table 4, we conclude that wind and turbulence did not vary enough to have a significant effect on latent heat exchange. Based on the relation between $\lambda E/\lambda E_{eq}$ and G_{sfc} , we conclude that ‘oasis effect’ through the entrainment of warm dry air from above the planetary boundary layer must have contributed to $\lambda E/\lambda E_{eq}$ exceeding 1.26 in 2009 and 2010 because the one dimensional model computations would have assumed an infinite fetch.

Skeptics may argue that the differences in annual evaporation may have been an artifact of differential energy balance closure (Table 2). If we force energy balance closure and assume we measure the Bowen ratio (β) without bias, we can compute evaporation with the Bowen Ratio equation and measurements of available energy:

$$\lambda E = \frac{A}{1 + \beta} \quad (3)$$

In performing this exercise, we compute that annual evaporation was 1234, 1073, 11124, 1148, 1195 and 1055 mm y^{-1} , respectively between 2009 and 2015. This analysis suggests that evaporation in 2009-10 was 15% greater than during 2014-15. While these computations support the conclusion drawn from our eddy covariance measurements—evaporation of rice decreased with time as the fields got larger—we must admit that forced energy balance closure has its own set of problems. First, the size of the footprint sampled by the radiometer and soil sensors is much, much smaller and less representative than the footprint sensed by the eddy covariance system. Second, there is uncertainty in how well we compute storage in the water column based on measurements of water table depth and time rate of change of temperature.

Comparison with other Studies

How do sums of evaporation from these rice fields compare with other evaporation measurements in this region? Figure 10 compares annual sums of evaporation from rice with those from our meso-network of eddy covariance towers in the region. The longest comparative record came from the pasture that was sub-irrigated; the water table was about 0.60 m deep. We see marked year to year variation in pasture evaporation ($698 \pm 117 \text{ mm y}^{-1}$), but there was not any trend in evaporation, like the one observed over the rice. Annual evaporation from the pasture peaked at 900 mm y^{-1} during the 2010-11 study period and was at its lowest (564 mm y^{-1}) during the year with the highest rice evaporation (2009-10). The alfalfa crop evaporated about **920 mm per year** between 2013 and 2015. Corn, with its C_4 photosynthetic pathway, lost 697 mm of water over the 2012-13 study year.

While rice grown in California experiences relatively high amounts of evaporation, they do not use as much water as orchards in the San Joaquin Valley, which reach and exceed 1000 mm (Falk et al., 2013). **In addition**, we find that evaporative water use by rice in California is more comparable with evaporative water use of alfalfa, a perennial crop, with a longer growing season.

How well do sums of evaporation from rice grown in California compare with other rice studies? Only a few eddy covariance studies exist for comparison. We found that rice growing in Brazil used about 998 mm y^{-1} of water and achieved peak rates of 7 mm d^{-1} (Timm et al., 2014). A doubled rice system in Bangladesh used 997 mm of water over a year, it achieved peak rates of about 6 mm d^{-1} and it consumed about 71 to 74% of net radiation as latent heat (Hossen et al., 2012). In the Philippines, the most tropical site with year round cultivation, an aerobic rice system used 1301 mm y^{-1} of water while a flooded system used 1440 mm y^{-1} (Alberto et al., 2011). Inferential estimates of rice evaporation in the Sacramento Valley, north of our field site, using surface renewal and energy balance residual method, reported that rice lost 885 mm y^{-1} of water (Linguist et al., 2015a), with little year to year variability.

520 Conclusion

521 We reported a strong (15%) decrease in annual evaporation of rice grown in the delta over a six-year
522 period. The focus of this study was on how and why rice evaporation decreased so much with time.
523 First, we found that the year to year variability of climate variables that drive evaporation could not
524 explain the decline, as their variability was low, and if anything trended toward increasing evaporation.
525 Nor did we observe a strong decline in measured evaporation at a nearby irrigated pasture in the same
526 climate region. Using geographical information methods and remote sensing we found that the area of
527 flooded rice and wetlands increased from less than 1 km² to over 5 km². This led us to test if there was
528 an oasis effect and that it may have declined with time.

529 We found that evaporation rates during the first years, when normalized by available energy, exceeded
530 potential rates, defined by the Priestley-Taylor (1.26). This suggests that evaporation was enhanced by
531 either horizontal advection or vertical entrainment of from above the planetary boundary layer of warm
532 dry air. Additional analysis and interpretation of our data was based on co-spectral analysis and use of
533 a coupled surface energy balance-planetary boundary layer model. Our evidence supports the claim of
534 entrainment of warm dry air from above the planetary boundary layer was an agent causing evaporation
535 of rice to exceed rates of potential evaporation when the size of the fields was smallest.

536 We conclude that the amount of water lost by rice, per unit area will be a function of the size of the
537 surrounding fields, given similar environmental conditions. The explanation is best explained by
538 McIlroy and Angus (1964):

539 *'The resulting enhancement of evaporation rate and reduction or reversal of*
540 *upward sensible heat flux is greatest at the upwind boundary, but decreases*
541 *with distance downwind, rapidly at first and then more gradually, due to the air*
542 *becoming moister and cooler as it flows further into the oasis. If the latter is*

large enough and the weather is steady enough, the evaporation rate should eventually tend to a finite lower limit which can be shown to depend partly on temperature but mainly on net radiation input'

Therefore, this study provides a lesson on the loss of water from rice and restored wetlands in semi-arid regions like the California Delta and river deltas in Mediterranean regions of Europe, like the Rhone in southern France and the Rio Guadalquivir in Spain, and gives guidelines on the optimal size these systems should be.

The daily and annual evaporation from our rice field during the last few years of the experiment were on par with the literature, especially comparable with water use by rice in the Sacramento Valley (Linguist et al., 2015b). We also note that our greatest evaporation sums did not reach the greatest evaporation sums in the world, as may be occurring in the Philippines (Alberto et al., 2011).

And while rice is a large user of water, its water usage remains less than some of the perennial orchards being cultivated in the central valley of California, **and its water use is on par with that of alfalfa.** Because rice is grown on soils not suitable for other types of agricultural, it remains to be an integral component of California's diverse agricultural mix.

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Figure 1 Surface energy balance at the rice field site, using daily integrated values. Net radiation (Rn) is compared with the sum of sensible (H), latent (λE), and soil heat flux (G_{soil}), heat stored in the water column ($G_{\text{H}_2\text{O}}$) and energy used to drive carbon assimilation (P_s). The slope of the regression is 0.835, the intercept is $0.782 \text{ MJ m}^{-2} \text{ d}^{-1}$ and the coefficient of determination (r^2) is 0.900.

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Figure 2 a) cumulative sum of rice evaporation starting on day 93 of each year; b) seasonal pattern in

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daily-integrated, and weekly averaged, evaporation over rice.

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762 Figure 3 Temporal variation in the ratio between latent heat exchange and equilibrium evaporation.

763 Ratios are based on daily sums and averaged over the year.

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Figure 4 Map showing the increase area of rice and wetlands on Twitchell Island between 2009 and 2015. Predominant winds are from the westerly sector, or from the left on this figure.

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770 Figure 5 The change in area of rice and restored wetlands on Twitchell island

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Figure 6 Mean diel patterns of sensible heat exchange over rice on a year by year basis. Data are averaged by hour for a hundred day period, between days 150 and 250.

Rice, stable stratification, days 150 to 250

Figure 7 a) Comparison of the co-spectral densities of heat transfer during 2009 and 2014; b) the ratio of co-spectral densities of moisture and heat transfer during 2009 and 2014; These data were selected between days 150 and 250, between the hours of 12 and 18 when the atmosphere was stably stratified.

Figure 8 Mean diel pattern of canopy conductance, computed by inverting the Penman Monteith Equation. Data were confined to the period between days 150 and 250 for each year.

Figure 9 Theoretical computations between the ratio of latent heat and equilibrium evaporation and canopy conductance. Computations were derived using a coupled surface energy balance and one dimensional planetary boundary layer model, following McNaughton and Spriggs.

Figure 10 Year by year differences in annual evaporation at the rice, pasture, corn and alfalfa sites in the Sacramento-San Joaquin Delta.

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797 **Table 1 Cultivation information for the rice field.**

	2009-2010	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015
Variety	M104	M206	M104	M104	M206	M206
Plant date	15 Apr	16 Apr	22 Apr	17 May	2 Apr	28 Apr
	(day 105)	(day 106)	(day 112)	(day 138)	(day 92)	(day 118)
Harvest	20-25 Oct	28-29 Oct	12-14 Oct	13-15 Nov	20 Sep	2 Oct
date	Day 293-298	Day 301-302	Day 285-287	Day 317-319	Day 263	Day 275
Peak Leaf	6.7	7	6.2	4.1	4.6	5
Area						
Index						

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802 **Table 2** Energy balance closure by year. Net radiation (x) was regressed against the sum of latent,
803 sensible, and soil heat exchange, plus energy stored in the water column and used for carbon
804 assimilation (y). Regressions were based on daily integrals of these energy fluxes. The relative energy
805 balance difference is defined as (x-y)/x.

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year	Intercept (MJ m ⁻² d ⁻¹)	slope	R ²	Relative Energy Balance Difference (%)
2009-10	1.035	0.847	0.944	2.12
2010-11	1.08	0.887	0.919	-1.71
2011-12	0.918	0.811	0.900	7.72
2012-13	0.646	0.829	0.871	10.0
2013-14	0.258	0.828	0.915	14.6
2014-15	0.679	0.821	0.892	10.2

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809 **Table 3**

810 Mean or summed annual climate conditions for the study years. Variables include evaporation (E), solar
 811 radiation (R_g), net radiation (R_n), available energy (A), air temperature (T_a) and vapor pressure deficit
 812 (vpd).

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year	E, mm y ⁻¹	R_g , GJ m ⁻² y ⁻¹	R_n , GJ m ⁻² y ⁻¹	A, GJ m ⁻² y ⁻¹	T_a , C	vpd, Pa
2009-10	1155	6.42	3.126	3.120	14.45	700
2010-11	1054	6.44	2.875	2.730	13.84	608
2011-12	1019	6.72	2.961	2.830	14.02	648
2012-13	1126	7.13	3.108	3.211	14.68	727
2013-14	1052	6.87	3.081	3.005	15.36	839
2014-15	982	6.84	3.179	3.019	15.84	805

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818 Table 4 Average meteorological conditions between days 150 and 250. VPD is vapor pressure deficit, R_{am}

819 is the aerodynamic resistance for momentum and U is wind speed

year	VPD, Pa	$R_{a,m}$, $s\ m^{-1}$	U , $m\ s^{-1}$
2009	1141+/- 486	38.6 +/- 3.8	4.45 +/- 0.51
2010	598 +/- 339	32.6 +/- 3.6	4.41 +/- 0.47
2011	561+/- 368	34.8 +/- 6.6	3.71 +/- 0.71
2012	735 +/- 456	41.7 +/- 5.2	4.13 +/- 0.58
2013	982 +/- 542	31.1 +/- 2.3	4.10 +/- 0.37
2014	946 +/- 549	35.5 +/- 4.5	3.64 +/- 0.50

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