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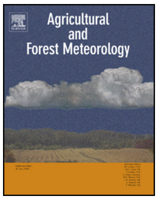

The impact of expanding flooded land area on the annual evaporation of rice

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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 km^2 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 km^2, 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.

1. Introduction

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

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

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

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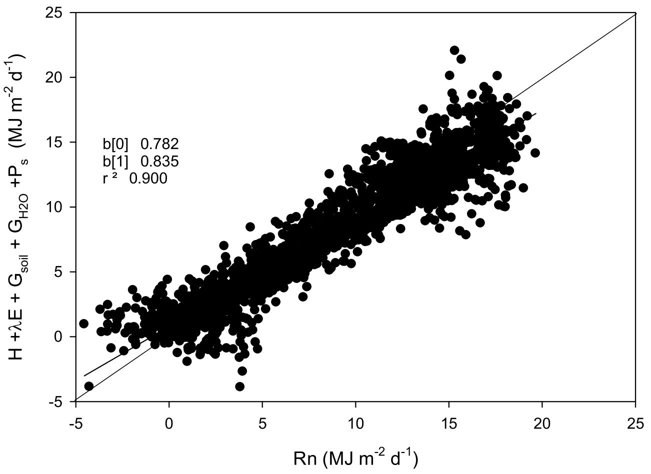

Fig. 1. Surface energy balance at the rice field site, using daily integrated values. Net radiation (Rn) is compared with the sum of sensible (H), latent (λE), and soil heat flux (G_{soil}), heat stored in the water column (G_{h2o}) and energy used to drive carbon assimilation (P_s). The slope of the regression is 0.835, the intercept is 0.782 MJ m^{-2} d^{-1} and the coefficient of determination (r^2) is 0.900.

vigorous vegetation in semi-arid environments with irrigation can have negative implications as this is a very energy-intensive solution involving the redistribution of a scarce and precious resource, water.

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

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

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

Rice has the potential to be a large user of water because rice is flooded and establishes a closed canopy with a high leaf area index that absorbs much of the incoming radiation. This is especially true in California, where flooded rice is grown in a hot, dry climate. Regarding the potential water use by rice, some studies show that as much as 90% of available energy is consumed as evaporation through latent heat exchange during the peak of the growing season in Japan and the Philippines (Alberto et al., 2011; Uchijima, 1976). But this high evaporative fraction is not universal. Other studies show that lower fractions of available energy are lost as latent heat exchange over flooded rice; about 60% for rice growing in Brazil (Timm et al., 2014) and 70% for rice growing in Bangladesh (Hossen et al., 2012). So there remains uncertainty about how much water is lost from a rice paddy during the growing season and over the course of a year; in Asia, rice is often double cropped. Also uncertain is the degree management affects the amount of water used. For example, can rice be manipulated to minimize water use? In the Philippines, there are experiments on how much water is lost from flooded vs aerobic rice (Alberto et al., 2011). In California, investigators are looking at the effect of dry seeded vs wet seeded rice on water budgets (Linquist et al., 2015a). Additional complicating factors revolve 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 (Linquist 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., 1978; 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