Agricultural and Forest Meteorology 256–257 (2018) 179–195

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

The effect of land cover type and structure on evapotranspiration from agricultural and wetland sites in the Sacramento–San Joaquin River Delta, California

Elke Eichelmann[a,*], Kyle S. Hemes[a], Sara H. Knox[a,d], Patricia Y. Oikawa[b], Samuel D. Chamberlain[a], Cove Sturtevant[c], Joseph Verfaillie[a], Dennis D. Baldocchi[a]

[a] Department of Environmental Science, Policy & Management, UC Berkeley, 130 Mulford Hall, Berkeley, CA 94720, United States
[b] Department of Earth and Environmental Sciences, California State University, East Bay, North Science Room 329, Hayward, CA 94542, United States
[c] National Ecological Observatory Network (NEON), Boulder, CO 80301, United States
[d] Department of Earth System Science, Stanford University, 473 Via Ortega, Stanford, CA 94305, United States

ARTICLE INFO

Keywords:
Evapotranspiration
Eddy covariance
Wetland
Alfalfa
Rice
Pasture

ABSTRACT

Water is a limited and valuable resource in California. A large proportion of the fresh water for southern California is supplied by the Sacramento and San Joaquin rivers. With recent efforts to restore large areas of land in the Sacramento–San Joaquin Delta region from farmland to managed wetlands, it is important to investigate the effect of wetland restoration on the local water cycle. We measured evapotranspiration using the eddy covariance method over six different sites in the Sacramento–San Joaquin Delta from 2013 to 2016. The three restored wetlands sites differed in time since restoration and wetland structure, i.e. the area of open water compared to closed vegetation. The three agricultural sites were a flooded rice field, an alfalfa field, and a grazed cattle pasture. In most years, annual evapotranspiration was significantly lower at the drained agricultural sites, with 652 ± 131 mm (2 year average ± standard deviation, SD) for the pasture and 901 ± 24 mm (3 year average ± SD) for the alfalfa field, compared to the two open water wetlands, with 1091 ± 144 mm (4 year average ± SD) for the Mayberry wetland and 1140 ± 67 mm (3 year average ± SD) at the East End wetland. Annual evapotranspiration at the flooded rice site (975 ± 50 mm, 4 year average ± SD) or the closed vegetation wetland (West Pond wetland, 996 ± 63 mm, 4 year average ± SD) was not significantly different from the drained alfalfa site across individual years. Our analysis showed that the structural difference between the wetlands, specifically the fraction of open water compared to closed vegetation, has a large impact on evapotranspiration dynamics. Through analysis of normalized equilibrium evaporation and nighttime evapotranspiration measurements we deduced that evapotranspiration at the wetland with a low fraction of open water surfaces was almost entirely dominated by plant transpiration with very little contribution from evaporation, despite the fact that the site was flooded and water was readily available. Both evaporation and transpiration contributed substantially to evapotranspiration at the two wetlands with larger fraction of open water surfaces. At the closed canopy site evaporation from subcanopy water seemed to be inhibited through two mechanisms: first, the closed canopy prevented heating of the water column and led to significantly cooler water temperatures, which reduced surface vapor pressure. Second, the closed canopy decoupled the water surface from the atmosphere and inhibited turbulent transport of water vapor away from the water surface. Our results provide valuable insights into the water use in California wetlands and can inform decisions on how to maximize water conservation during wetland restoration.

1. Introduction

With a global commitment to restore 350 million hectares of degraded lands by 2030 made at the 2014 United Nations Climate Summit (Suding et al., 2015), there is an urgent need to understand the climatic consequences of changes in ecosystem structure and function.

Abbreviations: ANN, artificial neural network; DOY, day of year; EBC, energy balance closure; EC, eddy covariance; ET, evapotranspiration; *G*, ground heat flux; GHG, green house gas; GPP, gross photosynthetic production; H, sensible heat flux; VPD, vapour pressure deficit; λE, latent heat flux; λE_{eq}, equilibrium evaporation

* Corresponding author.
E-mail address: eeichelm@berkeley.edu (E. Eichelmann).

https://doi.org/10.1016/j.agrformet.2018.03.007
Received 10 May 2017; Received in revised form 9 March 2018; Accepted 10 March 2018
0168-1923/

Land use change intended to restore ecosystems can have wide ranging consequences on the local and regional climate beyond intended benefits, such as wildlife habitat and carbon sequestration. Trade-offs between linked cycles, like the water and carbon cycles, are challenging to fully disentangle (Foley et al., 2005; Goldstein et al., 2012). While carbon dioxide (CO_2) assimilation is mediated at the leaf scale by diffusion of CO_2 into the stomata, the stomata are simultaneously the pores from which water is released into the atmosphere through evapotranspiration (Katul et al., 2009). Hence carbon and water cycles are inextricably linked and present a trade-off between ecosystem carbon sequestration and water loss through evapotranspiration. Understanding this link is critical when restoring ecosystems in water limited or drought-prone environments such as California.

Like many major river deltas around the world (Syvitski et al., 2009), the Sacramento–San Joaquin Delta (hereafter, Delta) of northern California is subsiding at a rapid rate, having lost up to 8 m of soil since the mid 19th century due in large part to agriculture-induced oxidation of the peat soils (Deverel et al., 2016; Drexler et al., 2009). Many of the islands are now 4–8 m below sea level and are threatened by saltwater intrusion and levee failure. In response to this widespread degradation, wetland restoration is being pursued for a suite of benefits, including those related to climate, habitat, levee stability, and recreation. California's Air Resources Board (CARB), mandated by Assembly Bill 32 (California Global Warming Solutions Act, 2006) to reduce greenhouse gas (GHG) emissions, has outlined how natural and working lands can play an integral role in climate change mitigation strategies, including wetland restoration (Air Resource Board, 2014).

The Delta peatlands play a complex role in a changing climate; while degraded or drained peatlands lose large amounts of soil organic carbon to the atmosphere through oxidation and have been shown to be strong sources of nitrous oxide (N_2O), intact flooded peatlands are a significant source of methane (CH_4) emissions caused by the anaerobic microbial breakdown of organic matter (Petrescu et al., 2015; Teh et al., 2011; Wang et al., 2004). Despite high CH_4 emissions, measurements over various restored wetlands in the Delta have shown that conversion of drained peatlands to wetlands (wetland restoration) can yield a GHG benefit predominantly due to reduced rates of respiration under flooded conditions (Knox et al., 2015).

The Delta also plays a critical role in California's water system. Expanses of irrigated farmland in California's central valley and large metropolises of southern California are reliant on water transported from the Delta via a system of canals and pumps (Deverel and Rojstaczer, 1996). Maintaining a high quality supply of freshwater from the Delta is, therefore, extremely important for all of California.

Past research has focused mostly on the direct biogeochemical effects of land use change in the Delta through increased or reduced greenhouse gas emissions (Detto et al., 2010; Hatala et al., 2012; Knox et al., 2016, 2015; Matthes et al., 2014; Sonnentag et al., 2011a). There is compelling evidence, however, that the biophysical impacts of land use management and land use change can play an equally important role in local- to regional-scale climate forcing (Baldocchi and Ma, 2013; Bonan, 2008; Juang et al., 2007; Lee et al., 2011; Luyssaert et al., 2014). Future changes in evapotranspiration, for example, could have far-reaching effects on precipitation, runoff, and irrigation, and could also affect partitioning of sensible and latent heat and drive regional climate feedbacks (Keenan et al., 2013; Sacks et al., 2009; Sellers et al., 1996).

Although past investigations of evapotranspiration from peatlands in the Delta included studies of agricultural fields as well as restored wetlands, there are still large uncertainties associated with estimates of water loss through evapotranspiration in the Delta (Baldocchi et al., 2016; Drexler et al., 2008; Hatala et al., 2012). Baldocchi et al. (2016) found that increases in the areal extent of flooded rice and wetlands in the Delta reduced evaporation by preventing warm air entrainment from the planetary boundary layer. Despite these reductions, flooded rice evapotranspiration was significantly higher than the non-flooded Delta land uses, losing between 1155 and 982 mm yr^{-1}, with peak growing season evapotranspiration rates between 6 and 8 mm d^{-1} (Baldocchi et al., 2016). Drexler et al. (2008) measured an average growing season evapotranspiration of 6 mm d^{-1} for a restored freshwater marsh in the Delta using the surface renewal technique. These growing season evapotranspiration estimates were higher than literature values for similar emergent wetlands (Drexler et al., 2008). Orang et al. (2013) established that evapotranspiration from tule and cattail wetlands in the Delta was 16–22% larger compared to drained cropland; however, these estimates were based on model calculations rather than direct measurements (Orang et al., 2013). Goulden et al. (2007), on the other hand, determined low summer evapotranspiration rates of 3–4 mm d^{-1} for a freshwater *Typha* marsh in Southern California, concluding that a thick layer of litter acted as a barrier to evaporation from subcanopy water. As more land is converted back to restored wetlands from agricultural use in the Delta, it is important to quantify the effects this conversion has on the regional water budget (Anderson et al., 2003).

The process of wetland restoration involves complex decisions on creating vegetation-free water channels and ponds to provide habitat diversity for wildlife. The resulting structural differences between wetlands can have important implications for greenhouse gas emissions and carbon sequestration modeling efforts (Matthes et al., 2014; McNicol et al., 2017; Oikawa et al., 2016). In a review of methods for wetland evapotranspiration estimates, Drexler et al. (2004) stated that large structural differences between wetlands, such as the extent of open water areas or water temperature differences, greatly affect wetland evapotranspiration. The effect of open water structures on the latent energy exchange from restored wetlands and subsequent effects on the local water budget have, to date, largely been overlooked in evapotranspiration estimates for wetland restoration in the Delta. To design the optimal structure for a restored wetland which balances the benefits of open water surfaces (e.g. providing wildlife habitat) with their drawbacks (e.g. increasing water loss through evaporation), it is important to investigate the impact of wetland structure on evapotranspiration of restored wetlands.

Local and regional climate and weather models rely on predictions of evapotranspiration for accurate predictions of precipitation and cloud formation patterns (Skamarock et al., 2008). Being able to identify the effects of structural driver variables, such as fraction of open water, water table depth, or aerodynamic properties, on evapotranspiration will improve the ability to accurately predict and upscale evapotranspiration from complex landscapes with multiple and diverse land uses, such as the Delta.

Knox et al. (2016) found that evapotranspiration was an important driver for CH_4 emissions during the fallow period for a Delta rice field. Other studies have shown that CH_4 emissions from wetlands are highly dependent on evapotranspiration rates across multiple timescales (Morin et al., 2014; Sturtevant et al., 2016). Improving evapotranspiration estimates and predictions for these sites by identifying drivers of evapotranspiration on multiple timescales will help improve model estimates for emissions of other greenhouse gases, such as CH_4, which are dependent on evapotranspiration and heat exchange from water bodies for gas transport (Poindexter et al., 2016; Poindexter and Variano, 2013).

Eddy covariance measurements, which continuously measure the integrated mass flux of greenhouse gases and water between the biosphere and atmosphere, are particularly appropriate for understanding field and ecosystem-level water and climate trade-offs (Baldocchi, 2014, 2003). This study used an expanding network of eddy covariance flux towers across the Delta, where a long-term wetland restoration experiment has been underway since 1997. Continuous eddy covariance measurements were available for the past three to seven years over drained peatlands and wetlands of various maturity and structure. This study aims to demonstrate how wetland restoration affects the water cycle and associated ecological benefits.