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Coastal low cloudiness and fog enhance crop water use efficiency in a California agricultural system

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ABSTRACT

Impacts of climate change threaten California farmers in a number of ways, most importantly through a decline in freshwater availability, concurrent with a rise in water demand. In coastal California, the growing season of economically important crops, such as strawberries, overlap with the occurrence of summertime coastal fog, which buffers the summer dry season through shading effects and direct water inputs. The impacts of coastal fog on plant physiology have been extensively studied in natural ecosystems. Yet, very few studies have evaluated its direct effects on crop water use and demand, which has potential to curtail groundwater use. We established two sites on large, conventional strawberry farms along a coastal-inland gradient in the Salinas Valley, California, where we monitored variation in microclimate conditions and measured strawberry plant physiological responses to foggy and non-foggy conditions between June–September 2015. Spatial analysis of coastal low clouds and fog from satellite imagery was preformed to quantify and characterize fog events at seasonal and diel time scales. We found strong agreement between field and satellite-derived observations of coastal fog events. Canopy-level conductance and whole-plant carbon uptake were reduced by 60% and 30%, respectively, on foggy compared to clear-sky days. Leaf-level photosynthesis and stomatal conductance were 30% lower on foggy compared to clear-sky days, which was driven by reduced photosynthetically active radiation and cooler temperatures during fog events. Taken together, we found that whole-plant water use efficiency increased significantly during foggy periods, and these patterns were driven by changes in the radiation balance and atmospheric water stress. Our results provide evidence that the shading effect by fog is a primary influence on crop water use efficiency in coastal agricultural fields during summer. The outcome of our research can inform estimates of how much irrigation water may be reduced during foggy periods without sacrificing crop yields on coastal agricultural lands.

1. Introduction

California agriculture is a US$47 billion industry and consumes 80% of freshwater resources in the state (California Department of Food and Agriculture, 2015). Availability of freshwater resources is threatened by climate change and drought, in particular (Postel 1998; Green et al., 2011). The economic, social, and ecological impacts of drought are widespread, especially for the agricultural sector which is highly vulnerable to water scarcity and climate variability (Tanaka et al., 2006; Connell-Buck et al., 2011; Howitt et al., 2015). Between 2012–2015, California experienced the most severe drought in the past 1200 years (Griffin and Anchukaitis, 2014). While precipitation deficit is the primary driver of drought conditions, anthropogenic warming of the atmosphere increases the likelihood of more extreme droughts in California (Diffenbaugh et al., 2015; Williams et al., 2015a), which is a direct threat to water availability in agriculture (AghaKouchak et al., 2014; Thomas et al., 2017). Because freshwater utilization by agriculture far outpaces usage by any other sector, agricultural irrigation practices should be more water efficient for food production to be sustainable in the future (Marques et al., 2005; Schaible and Aillery, 2012).

Coastal California supports production of many economically important crops (i.e., strawberries, lettuce, and broccoli) that contribute significantly to the state's multibillion-dollar agricultural industry. For example, in crop-year 2015–16, strawberry production was valued at US$1.8 billion dollars and ranked fifth in agricultural commodities in the state (California Department of Food and Agriculture, 2015). Strawberry crops occupy nearly 20,000 hectares of coastal California farmland and are also one of the most water-intensive crops to grow. Coastal farms are threatened not only by water scarcity, but also by

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saltwater intrusion that contaminates groundwater supply, which effectively reduces the amount of arable land in this region. To curtail groundwater use, support tools have been developed to inform irrigation practices (amount and timing) based on daily estimates of evapotranspiration (ET) rates, known as 'ET-based irrigation' (Snyder and Pruitt, 1992; Melton et al., 2012; Snyder et al., 2015). Despite scientific evidence that ET-based irrigation would not negatively impact crop yield (Johnson et al., 2016), the pervasive narrative among farmers is that the economic risk of crop loss by reducing irrigation application is too great. However, the recently enacted Sustainable Groundwater Management Act (SGMA) requires that groundwater be regulated for the first time in California's history (Kiparsky et al. 2017), which incentivizes farmers to implement sustainable water use plans and rely more on ET-based irrigation systems.

In California, crop productivity peaks during the summer months (June-August) when the photoperiod is longest; however, this is also when rates of potential evapotranspiration (PET) are highest. Heat loading and evaporative demand in coastal California are partially relieved during summer due to the occurrence of low-level coastal stratus clouds and ground fog, which is when the cloud interacts with the land surface (hereafter, grouped together as "coastal fog"). Coastal fog forms when warm subsiding air interacts with cool air over the ocean that is driven by coastal upwelling. Water vapor condenses on condensation nuclei, such as salt spray, forming the marine layer offshore. Inland temperature drives a gradient that causes the marine layer to advect onshore (Koračin et al., 2005). Coastal fog influences the water and energy balance of ecosystems in a number of ways. Shading by fog reduces PET, which improves plant water status, supporting plant growth, especially during the otherwise dry time of year in Mediterranean climates (Williams et al., 2008; Fischer et al., 2009). Plants immersed in fog can benefit from direct water inputs because water droplets drip to the ground and increase soil moisture (Azevedo and Morgan, 1974; Harr 1982; Ingraham and Matthews, 1995; Dawson 1998; Corbin et al., 2005; Williams et al., 2008; Carbone et al., 2013; Fischer et al., 2016; Baguskas et al., 2016). Several studies have also demonstrated that transpiration rates decline during fog events across a wide-variety of plant species in natural ecosystems (Burgess and Dawson, 2004; Ritter et al., 2009; Berry and Smith, 2013; Alvarado-Barrientos et al., 2014; Gotsch et al., 2016) due to lower vapor pressure deficit and leaf-wetting events. Direct foliar absorption of fog water can reduce leaf water deficit and increase leaf gas-exchange rates (Burgess and Dawson 2004; Simonin et al., 2009; Limm et al., 2009; Goldsmith et al., 2013; Berry et al., 2014; Baguskas et al., 2016) and contribute to whole-plant rehydration (Eller et al., 2013). There are also potential tradeoffs between reduced plant water stress and reduced solar radiation on foggy days (Bai et al., 2012). Cloud shading can reduce plant productivity by reducing the total amount of light available to drive photosynthesis and growth (Knapp and Smith, 1990; Larcher, 2003). Alternatively, cloudy conditions can increase whole-plant productivity because diffuse, cloud-scattered light can irradiate otherwise shaded leaves in the plant canopy (Gu et al., 1999; Gu et al., 2002; Min 2005; Alton et al., 2007; Still et al., 2009; Mercado et al., 2009; Bai et al., 2012). Associated changes in atmospheric conditions (temperature, relative humidity, and vapor pressure deficit) during fog events can also have a significant impact on plant water use and productivity (Williams et al., 2008; Ritter et al., 2008, 2009; Still et al., 2009).

While the impacts of coastal fog on plant biology have been extensively studied in natural ecosystems, only a few studies have evaluated its direct effects on the water, carbon, and energy budgets of agroecosystems (Hunt et al., 2008; Moratiel et al., 2013). Moratiel et al. (2013) found that the deposition of water on leaves from dew, fog, and light rain increases the accuracy of modeled crop-ET in California farmlands because leaf-wetting from these events results in a discrepancy between soil water balance and crop-ET estimates. Similarly, Hunt et al. (2008) found that summertime coastal fog decreases actual ET from blueberry farms on the east coast of the U.S., which was attributed to the effects of both shading and direct water inputs through fog-drip to the soil. These studies provide evidence that coastal fog can significantly offset water loss from farms. Because peak growing season of highly valued crops in California overlaps with the occurrence of coastal fog, improving estimates of crop-scale ET rates based on mechanistic relationships between coastal fog and crop physiology has potential to increase irrigation efficiency on farms.

Characterizing fog events in ways that are ecologically significant has been a challenge because there are many ways to define fog, and these definitions vary in space and time (Torregrosa et al., 2014; Weathers et al., 2014; Piso et al., 2016). In the field, measuring fog-drip using passive or active fog collectors is a common method used to identify and quantify fog events (e.g., Ingraham and Matthews, 1995; Dawson 1998; Fischer and Still, 2007; Hiatt et al., 2012); however, relying on fog-drip alone to identify fog events can be problematic because often overcast conditions do not generate fog-drip, as in low elevation agricultural areas where ground fog is less common. Yet, fog shading and associated reduction in atmospheric water stress during fog events have significant effects on ecosystem function (Williams et al., 2008). Local micrometeorological conditions are usually monitored to assess the effect of fog on incoming solar radiation, leaf wetness, and vapor pressure deficit that impact plant function (Fischer et al., 2016). A limitation to field-based approaches for characterizing fog events is that they are spatially-limited; therefore, the more robust evaluations of fog on ecosystem function characterize the fog events at multiple spatial and temporal scales. Spatiotemporal patterns of coastal fog can be quantified using satellite imagery (Williams et al., 2008, Clemesha et al., 2016, Torregrosa et al., 2016, Rastogi et al., 2016), which is necessary for assessing landscape scale spatial patterns of fog inundation and frequency. Expanding our understanding of fog at landscape scales has many ecologically-relevant applications. For example, Baguskas et al. (2014) found that satellite-derived summertime cloud frequency was a significant predictor of the spatial extent of drought-induced tree mortality in a California coastal forest ecosystem. Parameterization of regional climate models with fog climatologies can advance our understanding of physical controls on fog formation (O'Brien et al., 2013). Integrating fog climatologies into water balance models can improve predictions of how climate change may impact water budgets of ecosystems, and to help identify suitable habitat for species (Johnstone and Dawson 2010; Fernández et al., 2015; McLaughlin et al., 2017). Developing mechanistic relationships between field and satellite observations of coastal fog is essential for scaling our ecological understanding of fog, especially for land managers and decision makers in government, industrial, and agricultural sectors of society.

The objectives of our study were to: 1) characterize fog events at an inland and coastal farm site by combining field and satellite observations, and 2) develop a mechanistic understanding of the relationships between coastal fog and the water and carbon balance of croplands. We hypothesized that: 1) Coastal fog decreases from the coast inland; therefore, the effects of fog on reducing crop transpiration rates will be stronger closer to the coast; 2) Through the effects of shading and reduced evaporative demand, coastal fog will increase water use efficiency of crops at the leaf and canopy scales.

2. Materials and methods

2.1. Study sites

We conducted a field investigation at two conventional strawberry farms located at the coastal and inland extent of the fog gradient in the Salinas Valley, California. The coastal farm was located approximately 1.5 km from the coastline while the inland farm was 30 km from the coast, and both sites were at sea level. The strawberry crops (*Albion* var.) were grown using conventional methods, and similar farming practices were applied at each farm. The peak strawberry growing and