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Research paper

Spatio-temporal salinity dynamics and yield response of rice in water-seeded rice fields

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ABSTRACT

The scarcity of high quality irrigation water is a global issue facing rice growers, forcing many to adopt water management systems that may result in increased salinity and yield reductions. While salt concentrations in field water have been shown to vary depending on water management, the distribution and build-up patterns of dissolved salts are unclear. This study was conducted to elucidate the within field spatial and temporal salinity dynamics in water-seeded rice cropping systems, and to assess current salinity thresholds for rice yield reduction. In this two-year study, water and soil salinity concentrations of eleven field sites were monitored weekly, with three sampling points being established in the top, middle and bottom basins of each field. There was a consistent spatio-temporal water salinity pattern among all fields: the maximum water salinity within a field occurred during week 2 to week 7 after planting, and was greatest farther from the irrigation inlet and where soil salinity was high. A model developed to predict water salinity within a field indicates that, averaged over an entire growing season, the position within a field contributed to 82% of the variation explained by the model, while preseason soil salinity contributed to 18%. Importantly, field water salinity was determined to be the most sensitive salinity metric for rice yield, as preseason soil salinity was a poor predictor of yield loss. The threshold field water salinity concentration was estimated at 0.88 dS m^{-1}, lower than the previous report of 1.9 dS m^{-1}. These results illustrate the ability to predict water salinity in a rice field with few parameters, while highlighting the importance of field water salinity as the main salinity metric for rice cropping systems.

1. Introduction

High quality water available for irrigated agriculture is currently scarce and is expected to become less available due to climate change and population growth (Hanak and Lund, 2012; Fraiture and Wichelns, 2010; Mirchi et al., 2013; Schewe et al., 2014; Wallace 2000). This will result in increased use of marginal water and decreased drainage, thereby resulting in increased secondary salinization (Connor et al., 2012; Molden et al., 2010). Rice, a globally important staple crop, is the most salt-sensitive cereal (Grieve et al., 2012; Munns and Tester, 2008). Additionally, when grown under irrigation, rice requires two to three times more water input than other cereals (Bouman et al., 2007; Kijne 2006). The current and projected decline in the quantity and quality of water for rice production, prompts the need to investigate salinity in rice cropping systems to avoid yield reductions.

In California, rice is the top agricultural water user based on application rate per hectare (USDA, 2013). Rice fields in California, which are typically divided into several hydrologically connected basins, are continuously flooded throughout the growing season, with irrigation water entering the topmost basin and cascading through to the bottommost basin. The primary water management system in California is a conventional flow-through system (hereafter referred to as “conventional-drainage”). Under conventional-drainage, tailwater discharges to a drainage ditch for much of the growing season; the exception being during water holding periods after pesticide applications, whereby tailwater drainage is temporary halted to allow for pesticide degradation in the field (Hill et al., 1991). Under conventional-drainage, the amount of tailwater drainage can be as high as 7.6 ML ha^{-1} (Hill et al., 2006) and 39% of the total water applied to a field (Linquist et al., 2015). Tailwater drainage helps remove salts that accumulate in the field water (Scardaci et al., 2002), thereby preventing

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the long term accumulation of salt in the soil (Lekakis et al., 2015). Recent drought conditions in California have reduced the water available for rice production (Howitt et al., 2015), forcing many growers to reduce the amount of water applied to a field. A common method to reduce the water applied to a field is to eliminate the tailwater drainage (hereafter referred to as "zero-drainage"). While zero-drainage can greatly reduce the total water applied to a field, it is likely to increase the salinity concentration, particularly in bottom basins. Nevertheless, the projected future of decreased water available for rice production in California (Hill et al., 2006) will likely increase the practice of zero-drainage. This, along with an increased reliance on groundwater for irrigation, which has a higher salt concentration than surface water (Grattan 2002), may lead to high salinity in rice fields and reductions in yield.

Crop yield response to salinity is most often displayed using a piecewise linear model (Ayers and Westcot 1985; Maas and Grattan 1999; Maas and Hoffman 1977), where the first segment is a tolerance plateau with a slope of zero, and the second segment is a concentration dependent line with a negative slope (Supplementary Fig. 1). The threshold salinity concentration, the concentration beyond which crop yields decline, is of utmost concern to both growers and regulators. In flooded rice systems, a confounding factor is the need to account for both field water salinity (i.e. salinity of the ponded water) and soil salinity. Traditionally, field water and soil salinity thresholds for rice have been developed from studies with limited observations over a wide salinity range, resulting in large distances between salinity treatments and a large uncertainty in threshold estimates (Grieve et al., 2012). Additionally, salinity threshold studies occur under steady-state conditions, whereby salinity stress is kept constant throughout the growing season (Maas and Grattan 1999). Conversely, field water and soil salinity in commercial rice fields lack temporal uniformity (Scardaci et al., 1996; Scardaci et al., 2002), and the range of observed salinity concentrations is narrower and lower than in salinity threshold studies. The lack of relatedness between field and study conditions, and the uncertainty of threshold estimates, has led some to question the applicability of current thresholds (Kijne 2006; Shalhevet 1994), especially in rice, as yield loss has been reported below the threshold value (Simmonds et al., 2013). These discrepancies have increased the focus on developing thresholds under realistic field conditions (Kijne, 2006), thereby increasing the applicability of threshold estimates.

Elucidating the spatial and temporal salinity dynamics is vital to ameliorate salinity stress in rice fields, especially since rice is more sensitive to salinity from tillering to flowering (Castillo et al., 2007; Heenan et al., 1988; Fraga et al., 2010; Pearson and Bernstein 1959; Zeng et al., 2001). Additionally, there have been reports of decreased stand establishment in commercial rice fields due to high salinity early in the season (Scardaci et al., 2002; Shannon et al., 1998). Previous studies in commercial fields under conventional-drainage, have found that water salinity increased in bottom basins of fields (Scardaci et al., 2002 & Simmonds et al., 2013), likely due to evapo-concentration. Simmonds et al. (2013) also found water salinity to be higher in areas of the field away from the primary water flow path (i.e. low flow areas). Results from Simmonds et al. (2013) and Scardaci et al. (2002), suggest that location in a field, relative to the irrigation inlet and primary water flow path, largely determines the field water salinity concentration; though, it is unclear how applicable these results are in fields under zero-drainage. A complete understanding of the spatio-temporal salinity dynamics in rice fields, however, is essential to being able to properly manage salinity in rice fields. Therefore, the objectives of this study were to: 1) reassess salinity thresholds using commercial rice fields, 2) quantify spatial and temporal variation of water and soil salinity in commercial rice fields and 3) develop a model to predict water salinity in fields under zero-drainage.

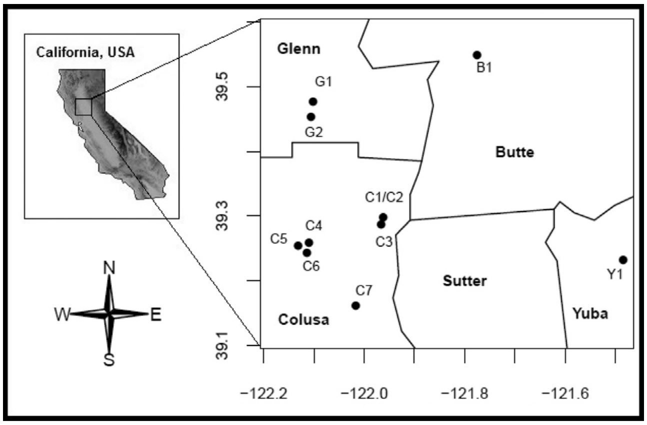

Fig. 1. A map illustrating the location of field sites for the study. Field names refer to the first letter of the counties they are in.

2. Materials and methods

2.1. Study area and site descriptions

This experiment was carried out in commercial rice fields throughout the Upper Sacramento Valley of California (Fig. 1) during the 2014 and 2015 rice growing seasons. Eleven field sites with zero tailwater drainage or conventional tailwater drainage, and a wide range of soil salinity, were chosen for this study. There were seven field sites in Colusa county (C1, C2, C3, C4, C5, C6, and C7), two in Glenn county, (G1 and G2), one in Butte county, (B1), and one in Yuba county, (Y1). This region has a Mediterranean climate, characterized by warm, dry conditions during the rice growing season. The mean air temperature during the 2014 and 2015 growing seasons was 22.7 °C, while the mean precipitation during the growing seasons was 15 mm (CIMIS, 2016). All field sites have fine-textured soils with minimal slope, which is typical for rice fields in the region. Soil taxonomic classifications, soil characteristics, irrigation practices and variety sown are shown in Table 1. Field-specific pesticide regimens were employed to combat weeds and insect pests.

2.2. Experimental design

Each field site contained 9 plots (2 m × 2m) that were split between the top (A), middle (B) and bottom(C) basins (Fig. 2). Within each basin, three sampling plots were established and numbered (1, 2, 3) based on their proximity to the primary water flow path (plot 1 being closest and plot 3 being farthest from the primary water flow path). For basins B and C, if water flowed down from both sides of the field, then plot 3 was in the middle of the basin (as shown in Fig. 2). If water flowed from only one side of the field, then plots in the B and C basins were spaced similar to the A basin. All plots were established 15 m in from the edge of the field to avoid border effects. Fig. 2 is a representation of the plot design within a field; however, field sites varied in dimension and number of basins. The position of each plot was determined in each field, with the position within a field being considered as the combination of the longitudinal distance down the field and the lateral distance across a basin (as shown in Fig. 2).

2.3. Sampling and measurements

After spring land preparation, but before fertilizer application and flooding, soil samples were taken from each plot at a depth of