Technical Appendix

Field Methods and Measurements

For the Davis experiment, groundwater was pumped from a nearby well, allowing detailed measurement of the applied water. To assess the effect of winter water application on crop production, stem and plant counts were determined in each treatment area before the recharge events (Nov. 2014) and alfalfa yield was measured after completion of the winter recharge experiments. Yield was measured on April 23, 2015 (first cutting) by harvesting the biomass by hand from three 0.5-m^2 quadrats in each plot and oven drying the biomass to determine dry matter yield. A second cutting was not taken due to poor stand density.

In the Scott Valley, surface water was diverted from the Scott River through the district's irrigation ditch. The total amount of applied winter water was measured with a Doppler flow meter (Greyline Instruments Inc., fig. 1a) at 15-min intervals and changes in groundwater level were recorded with a Hobo U-20 pressure transducer (Onset Computers Inc.) deployed in a nearby groundwater well (fig. 1a). In 2015, yield was measured at the Scott Valley site on May 27, 2015 (first cutting) and July 15, 2015 (second cutting) by harvesting plant biomass by hand in randomly chosen quadrats of 5.5 sq ft (0.5 m^2) in size (eight per treatment).

In fall of 2015, the alfalfa field was overseeded with orchardgrass. In 2016, plant biomass was harvested on May 24, 2016 (first cutting) and July 20, 2016 (second cutting) using a flail-type forage harvester (Carter Mfg. Co., Brookston, IN) from an approximately 25 ft by 3 ft area section from each of the 11 checks. A small subsample was taken from the cut biomass to determine the dry matter of the forage. Subsamples were also collected by hand clipping areas adjacent to the mowed area to determine the relative proportion of alfalfa, orchardgrass and weed biomass.

Water Balance Analysis

A water balance model based on the Thornthwaite-Mather (TM) procedure (Steenhuis and Van der Molen 1986) was set up for each site to estimate the fraction of the applied winter water going to deep percolation or groundwater recharge. Recharge, $\boldsymbol{R}$, was estimated using the following water balance equation:

$$\boldsymbol{R_t = I_t + P_t - ET_t - \Delta S_t - Q_t} \qquad (1)$$

Where $\boldsymbol{I_t}$ is the amount of applied winter water (in) at time t, $\boldsymbol{P}$ is precipitation (in), **ET** is evapotranspiration (in), **ΔS** the change in soil storage (in) (dependent on the available water capacity (AWC) of the soil), and $\boldsymbol{Q}$ is surface runoff (in). Q was considered to be negligible since all applied water infiltrated in the recharge plots. For each treatment, I was estimated from water application rates divided by the application area. The TM model was run for the entire hydrologic year (Oct. 1 to Sep. 30 of following year) at an hourly time step for the Davis site and at a daily time step for the Scott Valley site. Potential evapotranspiration (CIMIS ET_o) was obtained as hourly data from the CIMIS station in Davis (station 6) and as daily data for the Scott Valley (station 225) (CIMIS 2011). Data gaps in CIMIS ET observed for the Scott Valley station were filled using the Hargreaves-Samani ET equation (Jensen et al. 1990; Walden & Haith 2003) and daily temperature data from the Ft. Jones Ranger Station. In the TM water balance model the change in available soil water (ΔS) is dependent on the total available water capacity (AWC) (in) of the soil. For both sites the total plant available water reported in the SSURGO database was used, resulting in 11 in (28 cm) for the Yolo soil and 4.9 in (12.5 cm) for the Stoner soil (http://casoilresource.lawr.ucdavis.edu/soil_web, Soil Survey Staff, 2016). The TM model was initiated by assuming that the soil water content was at 50% of field capacity at the beginning of the simulation period (10/1/2014). Besides rainfall and winter recharge no additional water, such as growing season irrigation, was considered in the water balance.

The TM model was only applied to the root zone (upper 2 ft) where evaporation takes place and plant roots extract water. In order to simulate attenuation of the applied winter water in the deeper soil profile the TM model was extended to a 5-ft soil profile, consisting of the upper evapotranspiration zone (0-2 ft) and a transmission zone below the root zone (2-5 ft) (fig. 2). In the transmission zone, water movement during the recharge events can be modelled by assuming that gravity forces dominate over matric forces, thus, allowing application of Darcy's equation. For a soil profile near field capacity of length L the downward movement of soil water and deep percolation can be estimated as follows:

$$\theta_t = \theta_d - \frac{\theta_s - \theta_d}{\kappa} ln\left[\frac{\kappa K_{sat} \Delta t \exp(-\kappa)}{L(\theta_s - \theta_d)} + \exp\left(-\kappa \frac{\theta_{t-\Delta t} - \theta_d}{\theta_s - \theta_d}\right)\right] \quad (2)$$

Where θ_t is the volumetric water content (volume fraction) at time t, θ_s and θ_d are the volumetric water contents at field capacity and wilting point (volume fraction), κ is a constant (positive), K_{sat} is the saturated hydraulic conductivity, and Δt is the time step (Steenhuis et al. 1984). Since Eq. 2 does not take water input from the root zone into account, the percolation from the TM root zone was distributed evenly over the transmission zone (2-5 ft) at the beginning of each time step.

For the Davis site, κ was estimated from soil hydraulic parameters (i.e., van Genuchten parameters) derived from 15-min tensiometer data and soil texture and bulk density data generated with the ROSETTA hierarchical pedotransfer function (Schaap et al. 2001; http://cals.arizona.edu/research/rosetta/). ROSETTA defines the available water capacity as the difference between the water content at field capacity (θ_s) and wilting point (θ_d). For the Davis site, duplicate tensiometers (Irrometer model RSU-S, Irrometer Inc.) were installed in plots 9 to 13 (fig. 1b) at 2 ft and 5 ft depth, representative of the upper loamy layer and deeper coarse textured layer of the soil profile. Soil texture was determined by the pipette method and bulk density from undisturbed soil samples, respectively (USDA-NRCS 2004). Due to the high rock fragment content of the gravelly coarse loamy soil in the Scott Valley, tensiometers could not be installed and soil texture and bulk density data was too uncertain to reliable determine the van Genuchten parameter from field sampled soil cores. Here we used two sets of water content reflectometers (CS655, Campbell Scientific Inc.) installed at 8 and 28 in depth. Soil hydraulic properties and estimated van Genuchten parameters are summarized in table 1 for both sites.

Statistical Analysis

For the Davis site a mixed-model analysis of covariance (ANCOVA) was used to test for the effect of the experimental factors (water application quantity times timing) on alfalfa yield after including the initial plant count for each measurement location as a covariate. Blocks and plots were treated as random effects by allowing for random intercepts at each level. This allowed the within-plot and within-block variability to be accounted for separately from the overall between-plot (treatment-induced) variability. For the Scott Valley site, a one sample t-test for correlation between total applied winter water and alfalfa yield in each treatment was conducted to determine whether the observed alfalfa yield showed any response to the total applied winter water. The t-test effectively tests the null hypothesis that the slope of the linear regression between the two variables is zero (e.g., no trend or correlation). The t-test was performed at a significance level of $\alpha = 0.05$. A p-value of < 0.05 would therefore allow rejection of the null hypothesis and indicate a significant relationship between yield and amount of applied winter water.

References

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