Site Factors Related to Dry Farm Vegetable Productivity and Quality in the Willamette Valley of Oregon

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ABSTRACT. Dry farming has been defined as rainfed crop production in a climate with more than 20 inches of annual precipitation, but where most precipitation falls outside the growing season. Dry farming is garnering interest in the western United States because it allows farmers to produce crops despite a lack of access to irrigation or water rights or to eliminate the infrastructure, labor, and energy costs of irrigation systems. Sites have differing suitability for dry farming, and some sites that can be farmed with irrigation will perform poorly when dry-farmed. To determine site factors associated with dry farm yield and fruit quality, trials of 'Early Girl' tomato (*Solanum lycopersicum*) and 'North Georgia Candy Roaster' winter squash (*Cucurbita maxima*) were conducted at 17 participant farms in the Willamette Valley in Oregon, USA, in 2018 and 2019. The mean blossom-end rot (BER) incidence was higher in the Willamette Valley than in coastal California; this was probably because of the Willamette Valley's hotter and drier climate. Increasing the available water-holding capacity of soil, total available water (available water-holding capacity of the soil plus in-season rainfall), native productivity rating, soil pH (0–6 inches and 24–36 inches), soil nutrient concentrations (0–6 inches and 24–36 inches), and in-season rainfall were positively associated with at least one measure of tomato or winter squash yield, fruit number, or average fruit weight. An earlier planting date was positively associated with winter squash total yield and total fruit number in 2019. The water-limited yield potential (the total yield potential if water was the only limiting factor) for 20-ft^2/plant plots was estimated to be 2.2 tons/acre per inch for tomato and 2.8 tons/acre per inch for winter squash. In 2019, high-density plantings (20 ft^2/plant) had higher tomato and winter squash mean total yields, mean total fruit numbers, and mean tomato unblemished yield than low-density plantings (40 ft^2/plant). In 2019, planting tomato at 20 ft^2/plant decreased the mean BER incidence by 15.6% when compared with planting tomato at 40 ft^2/plant.

Dry farming is a type of rainfed (i.e., unirrigated) crop production that occurs in climates with at least 20 inches of annual rainfall, but where most precipitation falls outside the growing season (Garrett 2019; Leap et al. 2017). Garrett (2019) documented the production of dry-farmed vegetables in western Oregon, and Leap et al. (2017) wrote a commercial production manual for dry-farmed 'Early Girl' tomato (*Solanum lycopersicum*) as a specialty crop in coastal California. Dry farming as defined here is different from dryland farming, which is the production of crops in semi-arid climates (where annual precipitation is less than 50% of potential evapotranspiration) without irrigation (Stewart and Peterson 2015; Stewart and Thapa 2016). Both dry farming and dryland farming are forms of rainfed farming, and both produce crops under water-limited conditions, but they differ in the timing and amount of precipitation. The Willamette Valley of Oregon is an example of a place where dry farming is practiced (Garrett 2019). While annual precipitation is greater than 50% of potential evapotranspiration throughout the Willamette Valley of Oregon, the region has a dry summer climate. Thus, a lack of moisture limits rainfed crop production for summer-grown vegetables.

Dry farming is garnering interest in western Oregon and California because it allows farmers to produce crops despite a lack of access to irrigation or water rights or to eliminate the infrastructure, labor, and energy requirements of irrigation systems. While millennia of practice and decades of research in dryland cropping systems have described factors related to dryland performance and identified strategies to improve system sustainability (Johnson et al. 2021; Passioura and Angus 2010), there has been little research conducted in dry farming systems in the western US Mediterranean climates. Because both are water-limited, literature pertaining to dryland farming may help to inform our understanding of dry farming. The goal of this work was to identify site factors related to dry farmed winter squash (*Cucurbita maxima*) and tomato yield and quality in the Willamette Valley of Oregon, allowing farmers to understand the dry farm potential of their sites and ways they can improve site performance.

The effect that climate and weather variables (including precipitation, temperature, relative humidity, irradiance, and wind speed) have on dryland farming outcomes has long been recognized (Widtsoe 1911). Leap et al. (2017), working in coastal California, recommends that the climate for the commercial dry farming of tomato have at least 20 inches of winter rain and a maritime influence, resulting in early morning fog, mild afternoon temperatures, and an evapotranspiration rate of 0.15 inch/d during the growing season. In contrast, the Willamette Valley in Oregon is hotter and the air is drier in the summer than coastal California, as demonstrated by both temperature and vapor pressure deficit (VPD). One weather database, the PRISM Climate Data (PRISM Climate Group, Oregon State University 2020), reported that the 30-year normal for the mean maximum daily VPD during July from 1981 to 2010

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was 23.4 hPa in Corvallis, OR, USA, compared with 15.4 hPa in Santa Cruz, CA, USA. The higher VPD in the Willamette Valley should result in an increased evapotranspiration rate and decreased water-use efficiency (El-Sharkaway and Cock 1984). Increased VPD has also been associated with a high incidence of blossom-end rot (BER) for tomato (Bertin et al. 2000; Blanc 1985). BER is a physiological disorder that results in dark brown lesions on the blossom end of the fruit, making them unmarketable.

Dry farmers rely primarily on stored soil moisture for crop production. To access stored soil moisture, dry-farmed crop roots grow into deep layers of the soil profile (Garrett 2019; Leap et al. 2017). The water that is available to a dry-farmed crop depends on the available water-holding capacity (AWHC) of the soil as well as properties that influence the vertical and lateral extensions of the root system. Soil AWHC is the amount of plant-available water that the soil can store. It is related to the particle size distribution of the soil (for example, silt loams have higher AWHC than sandy loams and clays), organic matter content, structure, total pore volume, and bulk density (Chapin et al. 2002; da Silva et al. 1994). The development of the root system of a crop in soils can be measured directly with soil coring or indirectly by measuring changes in soil moisture or soil electrical resistivity (Maeght et al. 2013).

Productivity ratings offer another way of evaluating site suitability for dry farming. Huddleston (1982) developed a system for rating the agricultural productivity of Willamette Valley soils. Soils were assigned a native productivity rating (NPR) generated by subtracting points (from a maximum of 100) for characteristics that reduce productivity (e.g., depth, texture, drainage, moisture regime, fertility, and acidity). The most productive (highest NPR) soils identified by Huddleston's work in Willamette Valley are deep, fertile, well-drained, and have a medium texture.

Although maintaining soil fertility in the surface layer (top 6 inches) is critical to irrigated crop productivity, historically, it has not been considered as critical for dryland productivity (Widtsoe 1911). This bias can be explained, in part, by Liebig's law of the minimum: water, not fertility, is what limits dryland productivity. In addition, if dry-farmed crops root more deeply than irrigated crops, then they may scavenge soil nutrients at depth, offsetting nutrient deficits in the surface layer (Canadell et al. 1996; Leap et al. 2017; Maeght et al. 2013; McCulley et al. 2004). However, we expect that soil nutrient availability and soil pH will influence crop development. Root development can be impeded by low pH and soil nutrient deficiencies (Chapin et al. 2002; Hatfield and Stewart 1992; Kochian et al. 2015; Rahman et al. 2018). Alternatively, excess nutrients may negatively affect dry-farmed crops (van Herwaarden et al. 1998). BER in tomato has been associated with calcium deficiency (Ho and White 2005; Taylor and Locascio 2004), and also with excessive soil nutrients (Bouquet 1941; Saure 2001, 2014) however, there is currently no consensus regarding the direct cause of the development of BER (Hagassou et al. 2019).

In addition to site suitability, cropping system strategies may affect the outcomes of dry farming. Dryland farmers and dry farmers have historically used techniques such as early cover crop termination, early planting, low planting density, and weed control to maximize residual soil moisture for summer crop growth (Garrett 2019; Leap et al. 2017; Passioura and Angus 2010; Widtsoe 1911). Farmers growing dry-farmed tomato in coastal California use similar techniques; however, they also prune and stake tomato and grow them at a high planting density (9–12 ft^2/plant), similar to that of irrigated tomato (Leap et al. 2017). Tomato planting density recommendations for dry farming have yet to be proposed for the Willamette Valley. Wetzel and Stone (2019) reported that across all winter squash varieties tested in the Willamette Valley, planting density did not significantly affect yield (tons per acre) of irrigated or dry-farmed winter squash, although higher planting densities reduced the average fruit weight.

In 2018 and 2019, trials were conducted on 25 farms (17 farms each year) to determine the suitability of Willamette Valley sites for dry farming. We hypothesized that the soils of the Willamette Valley would have high soil AWHC, making them suitable for dry farming; however, the hotter, drier climate would make the Willamette Valley less suitable to dry farming than coastal California. We hypothesized that soil AWHC, total available water (TAW; the summation of in-season rainfall and soil AWHC), NPR, in-season rainfall, and soil pH and nutrient concentrations in the topsoil and subsoil would relate to dry farm yield and fruit quality. Finally, we hypothesized that yields in 2019 would be significantly higher in plots planted at 20 ft^2/plant compared with plots planted at 40 ft^2/plant.

Methods

Twenty-five farms participated in the study over the 2 years, with 17 farms participating each year. Nine farms participated in both years; however, six of them moved their plot to a different location for the second year (for these farms, the 2019 plots were on a different soil series than the 2018 plots). In both years, farmers prepared and fertilized their sites before planting, using their typical tomato and winter squash production soil management practices. In 2018, 15 participant farms planted plots of five 'Early Girl' tomato (Johnny's Selected Seeds, Winslow, ME, USA) and 13 participant farms planted plots with five 'North Georgia Candy Roaster' winter squash (Johnny's Selected Seeds). Plots were planted at a density of 20 ft^2/plant, with between-row spacing determined by the farmer and ranging between 4 ft and 6 ft 8 inches; in-row spacing was adjusted accordingly. Plots were installed from 10 May to 6 Jun 2018. In 2019, each farm hosted four plots: two high-density (20 ft^2/plant) plots and two low-density (40 ft^2/plant) plots. Each plot was planted with five winter squash or five tomato transplants. Between-row spacing was determined by the farmer and again ranged from 4 ft to 6 ft 8 inches, with in-row spacing adjusted accordingly. Plots were installed from 8 May to 4 Jun 2019.

Each year, tomato and winter squash transplants were grown in a certified organic greenhouse, with tomato seedlings produced in 2-inch pots and winter squash seedlings in 50-cell trays. Seedlings were thoroughly watered before planting and watered with 250 mL of water each after planting. The planting date was recorded. The perimeters of the plots were planted with 'Crown' winter squash seeds (High Mowing Organic Seeds, Wolcott, VT, USA), 'North Georgia Candy Roaster' winter squash transplants or crops provided by the farmer at an equivalent planting density to the experimental plants they bordered. In some cases, the border was simply a mowed grass path. Winter squash transplants and seeds at all locations were covered with row cover [Deluxe (0.5 oz); DeWitt Company, Sikeston, MO, USA] after planting to avoid damage by striped cucumber beetle (*Acalymma vittatum*), and the row cover was removed before anthesis when the plants were large enough to withstand some cucumber beetle damage. Tomato plants were allowed to sprawl or were trellised by the farmer. Trellising was not investigated as a variable.

The average daily maximum temperature, total rainfall, and average daily maximum VPD for each month of the growing season were collected from weather databases (AgriMet Cooperative Agricultural Weather Network and PRISM Climate Data) for Corvallis, OR, USA, in 2018 and 2019 (US Bureau of Reclamation 2020). In-season rainfall was estimated for each site from planting date to 31 Jul using data from that location from a weather database (PRISM Climate Data).

Soil pedons (3-inch-diameter cores sampled with a bucket auger to a depth of 5 ft) were collected on the day of planting. Soil profiles were described using standard US Department of Agriculture (USDA) methods and USDA Soil Taxonomy to classify soils to the series level (Schoeneberger et al. 2012; Soil Survey Staff 1999; Soil Survey Staff, Natural Resources Conservation Service, US Department of Agriculture 2019). Soils were hand-textured to estimate USDA soil texture. Soil AWHC was estimated for each horizon based on soil texture, soil structure pedotransfer functions, and National Cooperative Soil Survey laboratory data for water retention when available. The TAW was estimated for each site using the summation of in-season rainfall and soil AWHC. The NPRs were taken from Huddleston (1982) for soil series listed in that publication. For soil series not listed, the NPRs were calculated using Huddleston's method.

Two soil samples (depths of 0–6 and 24–36 inches) were collected on the day of planting from each soil pedon for soil nutrient analysis. These are referred to as topsoil and subsoil samples in this work. A&L Western Laboratories (Portland, OR, USA) analyzed the soil samples to determine the pH and phosphorus (weak Bray, parts per million), potassium (parts per million), and calcium (parts per million) concentrations.

In 2018, tomatoes were harvested when red ripe from 21 Jul to 30 Sep, with zero to five harvests each week, depending on the week and the farm. Winter squash were harvested from 6 Sep to 14 Oct, with only one harvest at each farm at crop maturity. In 2019, tomatoes were harvested when red ripe from 15 Jul to 27 Sep, with one to three harvests each week, depending on the week and the farm. Winter squash were harvested from 21 Aug to 24 Sep, with only one harvest at each farm at crop maturity. At each tomato harvest, total fruit weight, total fruit number, and total fruit with BER were recorded. These data were used to calculate tomato total yield (tons per acre), total fruit number (fruits per acre), average fruit weight (pounds per fruit), and proportion of fruit with BER. Tomato unblemished yield was estimated by multiplying tomato total yield by the proportion of fruit without BER for each harvest (tons per acre). At each winter squash harvest, the total fruit weight and number were recorded, and these data were used to calculate winter squash total yield (tons per acre), total fruit number (fruits per acre), and average fruit weight (pounds per fruit).

Soil moisture sensors (WATERMARK 200SS; Irrometer Company, Inc., Riverside, CA, USA) were installed at soil depths of 1, 2, 3, and 4 ft at each site on the day of planting. These sensors measure electrical resistance in a granular matrix. This electrical resistance is an indirect measurement of soil water tension, which is the force needed to remove water from the soil. Soil water tension reflects soil water content; the higher the soil water tension, the less water is available. Soil electrical resistivity has been considered as an indirect measure of root proliferation (Maeght et al. 2013). Soil moisture sensors (WATERMARK 200SS) were installed in the winter squash plots in 2018 (unless there was only a tomato plot) and in the 20-ft^2/plant tomato plots in 2019. They were placed in-row, with each sensor directly between two plants (thus, in-row spacing affected the distance between sensors and plants). Sensor data were collected manually using a portable meter (WATERMARK Handheld Meter; Irrometer Company, Inc.) once per week in 2018, starting on 25 Jun, and every other week in 2019, starting on 17 Jun. While data was collected across multiple weeks, only one week of data was used in the analysis for each depth. The week used in the analysis (for a given depth) was the week prior to one of the sites reaching the maximum reading of 199 cbars for these sensors. These were the only weeks used because they included the measurement with the largest variance between sites before one site reached the maximum possible reading. These were the weeks of 16 Jul, 23 Jul, 23 Jul, and 13 Aug in 2018, and 15 Jul, 29 Jul, 29 Jul, and 12 Aug in 2019, for the soil moisture sensors at depths of 1, 2, 3, and 4 ft (WATERMARK 200SS), respectively.

Among the sites, three in 2018 and six in 2019 had at least one plot that was considered an outlier for certain response variables, and these outlier plots were removed from the analysis for these response variables. The rationale for their removal are described here. In 2018, one site had their winter squash plot removed from the analysis because of crop failure caused by crown and foot rot disease (*Fusarium solani* f. sp. *cucurbitae*). One site did not collect tomato number data or BER incidence data. Another site had their tomato plot removed from analysis because the crop was lost to herbivory. One site had crop failure for an unknown reason. Thus, in 2018, 13 farms were used in the analysis of tomato total yield; 12 farms were used in the analysis of tomato unblemished yield, total fruit number, average fruit size, and BER incidence; and 11 farms were used in the analysis of winter squash total yield, total fruit number, and average fruit size. Some farms did not measure soil water tension every week. Therefore, 11 farms were used in the analysis of the soil moisture sensors at the 1-ft depth, 12 were used in the analysis of the soil moisture sensors at the 2- and 3-ft depths, and 13 were used in the analysis of the soil moisture sensors at the 4-ft depth. In 2019, two sites had complete crop failures, one caused by an infestation of symphylans (*Scutigerella immaculate*) and the other caused by an unknown reason. Irrigating with drip tape after planting also resulted in high yields at two sites, one irrigating their winter squash and the other irrigating both winter squash and tomato. One site had no border next to its 40-ft^2/plant tomato plot. Finally, one plot was located adjacent to an irrigation pivot that frequently misted the plot. This also resulted in high yields of tomato and no BER incidence, probably because of either increased soil water availability and/or decreased evapotranspiration rate. Thus, in 2019, for the 20-ft^2/plant plots, 13 farms were used in the analysis of tomato total yield, total fruit number, and unblemished yield; 14 farms were used in the analysis of tomato average fruit weight and BER incidence; and 12 farms were used in the analysis of winter squash total yield, total fruit number, and average fruit weight. For the 40-ft^2/plant plots, 12 farms were used in the analysis of tomato total yield, total fruit number, and unblemished yield; 13 farms were used in the analysis of tomato average fruit weight and BER incidence; and 12 farms were used in the analysis of winter squash total yield, total fruit number, and average fruit weight. Fourteen farms were used in the analysis of soil water tension.

Data analysis

Data analysis was performed using statistical software (R version 4.1.3) (R Core Team 2022; RStudio Team 2018). Means, minimums, maximums, and coefficients of variation (*CV*) were determined for each site variable across all sites. Means and *SEM*s were determined for response variables across all sites. Pearson correlation coefficients (*r*) were calculated between the site variables across all sites and reported and between the site variables and response variables across all sites; if they were significant, then they were reported ($\alpha = 0.1$). The relationship between site variables and BER incidence was tested using a logistic regression analysis with a binomial distribution and relationships were tested for significance ($\alpha = 0.1$) using drop-in-deviance tests with F-distributions, with the number of fruit included in the model as weights. Mixed-effects models were constructed to test the effect of planting density on total and unblemished yield, fruit number, and average fruit weight for winter squash and tomato, with farm included as a random intercept (Pinheiro et al. 2022). The effect of planting density was tested for significance ($\alpha = 0.05$) using likelihood ratio tests. Estimated marginal means and *SE*s were reported (Lenth 2020). The effects of planting density on the proportion of fruit with BER were tested using generalized linear mixed models with a beta-binomial distribution, with farm included as a random intercept and number of fruit included in the model as weights (Brooks et al. 2017). Longitudinal harvest data are presented for tomato total yield, total fruit count, unblemished yield, BER incidence, and average fruit weight using data from 2019 (separated by 20-ft^2/plant and 40-ft^2/plant plots) (Auguie 2017; Wickham and Sievert 2016). For each plot, weekly averages were calculated and plotted. The relationship between the TAW and tomato and winter squash total yields are presented in graphs with linear regressions plotted for each year and for both years combined (Auguie 2017; Wickham and Sievert 2016). An arbitrary line was added to the plot to represent the water limited yield potential (French and Schultz 1984). For the line, we used the same x-intercept as the linear regression for both years combined (Grassini et al. 2011). The line was drawn from this x-intercept to include all plots below the line (French and Schultz 1984; Grassini et al. 2011).

Results

Summary of site variables. The two growing seasons differed in their average daily maximum temperature, total rainfall, and average daily maximum VPD in Corvallis, OR, USA; in summary, 2018 was a hotter and drier year than 2019 (Fig. 1). Soil AWHC ranged from 3.0 to 12.6 inches in 2018, and from 5.9 to 12.7 inches in 2019 (Table 1). In-season rainfall ranged from 0.7 to 1.9 inches in 2018, and from 1.0 to 3.7 inches in 2019. The NPR ranged from 0 to 69 in 2018, and from 10 to 75 in 2019. The average soil pH and nutrient concentrations were lower in 2019 than in 2018.

Collinearity between site variables. Correlation coefficients between the site variables are reported in Tables 2 and 3. Soil AWHC was positively correlated with the TAW in both years. In 2018, the soil AWHC was positively correlated with the NPR, but this relationship was not statistically significant in 2019. The TAW and NPR were positively correlated in both years. In-season rainfall was negatively correlated with planting day in 2019 (later planting associated with less in-season rainfall), but not in 2018; there was less rain during the 2018 planting window. In 2019, the TAW was negatively correlated with the planting day; however, in 2018, the TAW was positively correlated with the winter squash planting day. In 2018, soil AWHC and TAW were negatively correlated with topsoil potassium concentration and subsoil pH, and NPR was negatively correlated with subsoil pH, potentially confounding the relationship between these soil physical properties and yield. In 2019, NPR was negatively correlated with planting day (sites with a lower NPR were planted later). In 2018, the topsoil phosphorus concentration was negatively correlated with planting day; however, in 2019, topsoil pH and calcium concentration were negatively correlated with planting day. Soil pH and nutrient concentrations were often correlated.

Summary statistics for response variables. Summary statistics for yield and fruit quality data are presented in Table 4. In 2019, tomato and winter squash plots planted at a density of 20 ft^2/plant had significantly higher mean total yields and mean total fruit counts than plots planted at 40 ft^2/plant. Planting at 20 ft^2/plant also increased the mean tomato unblemished yield and reduced the mean BER incidence ($\alpha = 0.1$). Tomato and winter squash mean average fruit weights were unaffected by planting density. Sites had higher yields and larger fruit in 2019 than in 2018. The BER incidence was lower in 2018 than in 2019.

Longitudinal data from 2019. Longitudinal data from 2019 showed that the first 4 weeks of harvests had relatively low yields; averaged across all sites, these harvests comprised approximately 11% and 8% of the total yield for the 20-ft^2/plant and 40-ft^2/plant plots, respectively (Fig. 2A and B). Yields began to increase at week 5, and they peaked from weeks 6 to 8. During this 3-week-long peak, ~50% of the total yield was harvested, on average. Yields began to decline across weeks 9 to 11, although this period still had an average of 29% of the yield for the 20-ft^2/plant plots and 32% of the yield for the 40-ft^2/plant plots. Total fruit number followed a similar trend as that of total yield (Fig. 2C and D). Although total yield peaked from weeks 6 to 8, the tomato unblemished yield peaked earlier, with ~20% of the tomato unblemished yield harvested on week 6 for both

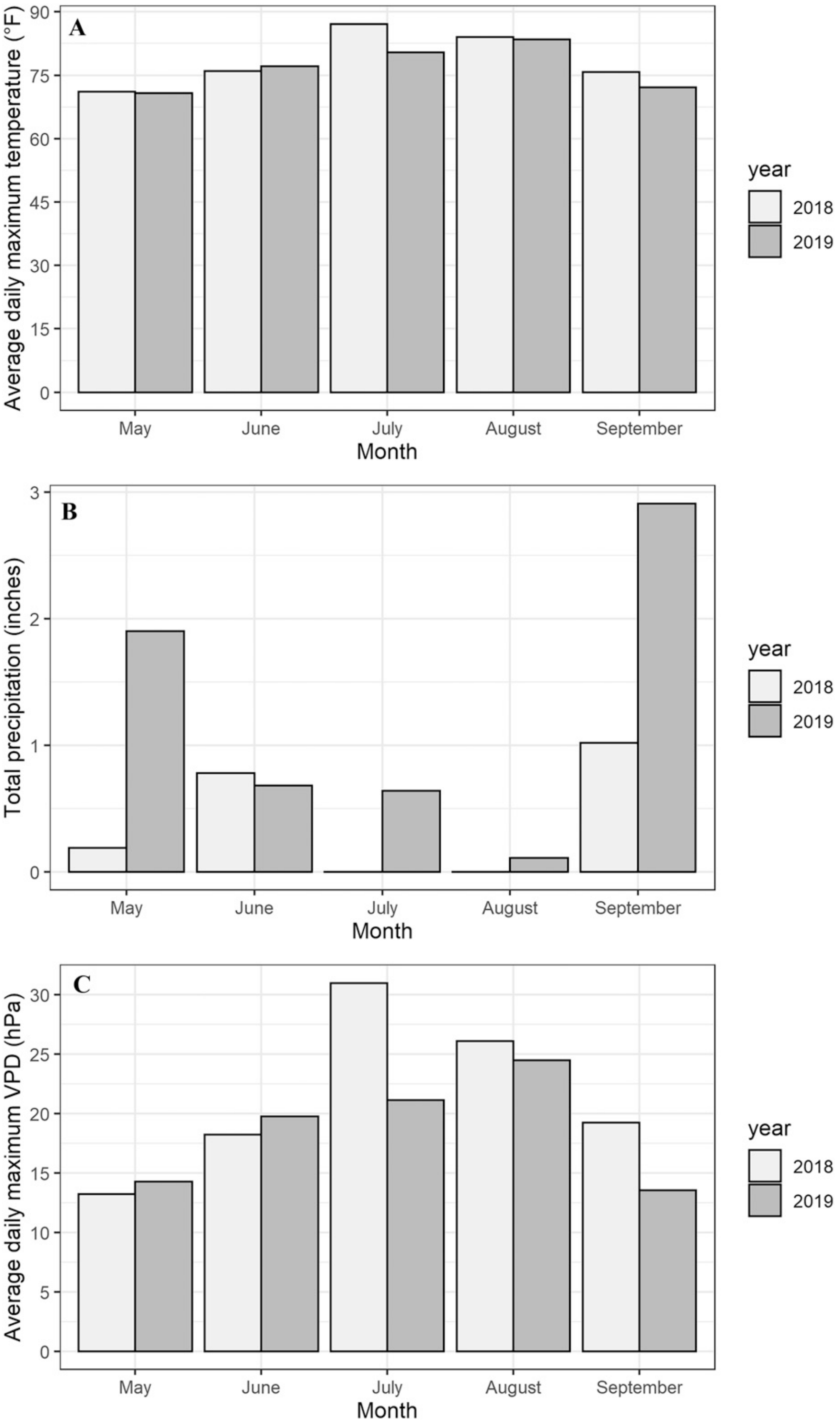

Fig. 1. Average daily maximum temperature (A), total precipitation (B), and average daily maximum vapor pressure deficit (C) during each month of the growing season in Corvallis, OR, USA, for 2018 (light gray bars) and 2019 (dark gray bars). Data from weather databases AgriMet Cooperative Agricultural Weather Network (US Bureau of Reclamation 2020) and PRISM Climate Data (PRISM Climate Group, Oregon State University 2020). (°F − 32) ÷ 1.8 = °C; 1 inch = 2.54 cm; 1 hPa = 0.0145 psi.

20-ft^2/plant and 40-ft^2/plant plots (Fig. 2E and F). This is because of an increase in the BER incidence over the course of the season (Fig. 2G and H). The BER incidence increased rapidly from weeks 5 to 7, and then peaked at week 9 (averages of 52% for the 20-ft^2/plant plots and 62% for the 40-ft^2/plant plots); therefore, it began to decline. The increasing BER was not the only way that fruit quality diminished over time; the average fruit weight decreased over the course of the growing season (Fig. 2I and J). The average fruit weight during the peak harvest window (weeks 6–8) in the 20-ft^2/plant plots decreased from an average of 0.2 lb/fruit to 0.16 lb/fruit, and the average fruit weight of the 40-ft^2/plant plots decreased from 0.2 lb/fruit to 0.15 lb/fruit.

Relationships between site variables and response variables. Correlation coefficients between site and response variables are presented in Table 5. Soil AWHC was positively correlated with tomato total yield and tomato unblemished yield in the 40-ft^2/plant plots in 2019, and with the tomato average fruit weight and winter squash total yield in 2018. The TAW had a similar relationship with these response variables and was positively correlated with tomato total fruit number and winter squash average fruit weight in the 40-ft^2/plant plots in 2019. The NPR rating was not correlated with any measures of tomato yield and fruit quality, but it was frequently positively correlated with measures of winter squash total yield and total fruit number. Surface and subsoil pH and nutrient concentrations were occasionally positively correlated with tomato and winter squash yield and fruit quality metrics. Subsoil calcium concentration was negatively correlated with winter squash total yield, total fruit number, and average fruit weight in the 2019 20-ft^2/plant plots. In 2019, in-season rainfall was positively correlated with tomato total fruit number in the 40-ft^2/plant plots, and it was correlated with winter squash average fruit size in the 20-ft^2/plant plots. Planting day was negatively correlated with winter squash total yield and average fruit weight in the 20-ft^2/plant plots in 2019. Generalized linear modeling did not find any relationship between site variables and BER incidence.

Soil water tension at the depths of 1, 2, 3, and 4 ft were included as indirect measurements of root proliferation (Maeght et al. 2013). In 2018, soil water tension at a depth of 1 ft was positively correlated with NPR, topsoil phosphorus and potassium concentrations, and subsoil potassium concentration (sites with high NPR and soil nutrient

Table 1. Summary statistics [number of farms where data were collected (*N*), average value (Avg), minimum value (Min), maximum value (Max), and coefficient of variation (*CV*)] for site data [soil available water-holding capacity, in-season rainfall, total available water, native productivity rating, topsoil (0–6 inches) and subsoil (24–36 inches) pH and nutrient concentrations, and planting day] collected in the Willamette Valley of Oregon, USA, on 17 dry farms in 2018 and 17 dry farms in 2019.

		2018					2019				
Variable		***N***	**Avg**	**Min**	**Max**	***CV***	***N***	**Avg**	**Min**	**Max**	***CV***
	Soil available water-holding capacity (inches)[i]	17	9.2	3.0	12.6	0.28	17	10.5	5.9	12.7	0.17
	In-season rainfall (inches)[i]	17	1.0	0.7	1.9	0.32	17	2.5	1.0	3.7	0.32
	Total available water (inches)[i]	17	10.2	4.3	14.5	0.24	17	13.0	9.6	16.3	0.15
	Native productivity rating	17	50	0	69	0.35	16	57	10	75	0.37
0–6 inches[i]	Soil pH	17	5.8	4.8	6.5	0.08	17	5.6	4.6	6.6	0.11
	Soil phosphorus concentration (weak Bray, ppm)[i]	17	64	1	174	0.80	17	52	5	150	0.87
	Soil potassium concentration (ppm)[i]	17	293	62	828	0.77	17	246	76	1170	1.05
	Soil calcium concentration (ppm)[i]	17	2070	940	3915	0.40	17	1725	572	3300	0.49
24–36 inches[i]	Soil pH	17	5.9	5.4	6.5	0.05	17	5.9	5.2	6.4	0.06
	Soil phosphorus concentration (weak Bray, ppm)[i]	17	8	0	35	1.18	17	12	1	41	1.14
	Soil potassium concentration (ppm)[i]	17	155	23	720	1.27	17	134	41	707	1.17
	Soil calcium concentration (ppm)[i]	17	2382	896	3569	0.28	17	2233	723	3415	0.30
	Day of planting tomato[ii]	15	7	0	16	0.82	17	10.5	0	27	0.69
	Day of planting winter squash[ii]	14	9.6	0	23	0.75	17	10.5	0	27	0.69

[i] 1 inch = 2.54 cm; 1 ppm = 1 mg·kg^{-1}.

[ii] Day of planting since the start of the experiment (10 May 2018 and 8 May 2019) for tomato (*Solanum lycopersicum*) and winter squash (*Cucurbita maxima*).

concentrations used water more quickly), and negatively correlated with planting day (later planting delayed roots reaching a depth of 1 ft). In 2019, soil water tension at a depth of 1 ft was positively correlated with soil AWHC and TAW. In 2018, soil water tension at a depth of 2 ft was positively correlated with topsoil and subsoil phosphorus concentration, whereas in 2019, it was positively correlated with soil AWHC, TAW, and topsoil calcium concentration, and negatively correlated with planting day. In 2018, soil water tension at the 3-ft depth was again positively correlated with topsoil and subsoil phosphorus concentration, whereas in 2019, it was positively correlated with TAW, topsoil pH and calcium concentration, and subsoil pH, and negatively correlated with planting day. In 2018, soil water tension at the 4-ft depth was positively correlated with NPR and topsoil and subsoil phosphorus concentrations, whereas in 2019, it was positively correlated with TAW, NPR, and topsoil pH and calcium concentration and negatively correlated with planting day.

Schematics (adapted from French and Schultz 1984) of the relationships between the TAW and yields of tomato and winter squash are presented in Fig. 3. For tomato, the linear regression between TAW and total yield for 2018 had a slope of 0.6 ton/acre per inch (*SE* = 0.5) and an x-intercept at −3.4 inches; those for 2019 had a slope of 1.1 tons/acre per inch (*SE* = 0.6) and an x-intercept at −0.1 inch. The slope for the linear regression for the combined analysis (2018 and 2019 data) was 1.2 tons/acre per inch (*SE* = 0.3) and the x-intercept was at 2.2 inches. The slope for the water limited yield potential for dry-farmed 'Early Girl' tomato was estimated to be 2.1 tons/acre per inch and the

Table 2. Correlation coefficients across 17 dry farms in Willamette Valley, OR, USA, for site variables [soil available water-holding capacity (AWHC); total available water (TAW); native productivity rating (NPR); topsoil and subsoil pH; weak Bray phosphorus concentration (P), potassium concentration (K), and calcium concentration (Ca); in-season rainfall; and planting day] in 2018.

					0–6 inches[i]				24–36 inches[i]				
		AWHC (inches)[i]	**TAW (inches)[i]**	**NPR**	**pH**	**P (ppm)[i]**	**K (ppm)[i]**	**Ca (ppm)[i]**	**pH**	**P (ppm)[i]**	**K (ppm)[i]**	**Ca (ppm)[i]**	**In-season rainfall (inches)[i]**
	TAW (inches)[i]	0.99***[ii]											
	NPR	0.67***	0.64***										
0–6 inches[i]	pH	−0.10	−0.09	0.14									
	P (ppm)[i]	−0.16	−0.16	0.14	0.37								
	K (ppm)[i]	−0.53**	−0.52**	−0.15	0.32	0.75***							
	Ca (ppm)[i]	−0.06	−0.11	0.20	0.52**	0.30	0.46*						
24–36 inches[i]	pH	−0.49**	−0.45*	−0.49**	0.16	0.08	0.28	0.14					
	P (ppm)[i]	0.16	0.18	0.31	0.04	0.58**	0.18	−0.21	−0.07				
	K (ppm)[i]	−0.26	−0.26	0.01	0.02	0.51**	0.83***	0.48**	0.13	0.04			
	Ca (ppm)[i]	−0.11	−0.17	−0.02	−0.06	−0.07	0.19	0.56**	0.15	−0.32	0.34		
	In-season rainfall (inches)[i]	−0.30	−0.18	−0.39	0.11	0.03	0.19	−0.34	0.40	0.11	0.05	−0.43*	
	Planting day (tomato)[iii]	0.37	0.37	0.07	−0.26	−0.18	−0.38	0.19	−0.46	−0.09	−0.19	0.25	−0.32
	Planting day (winter squash)[iii]	0.46	0.47*	0.11	−0.14	−0.56**	−0.34	0.05	−0.17	−0.43	−0.16	−0.11	0.03

[i] 1 inch = 2.54 cm; 1 ppm = 1 mg·kg^{-1}.

[ii] Significance of the correlation coefficient between two site variables indicated within cells. *, **, *** significant at $P < 0.1$, 0.05, and 0.01, respectively.

[iii] Day of tomato (*Solanum lycopersicum*) and winter squash (*Cucurbita maxima*) planting since the start of the experiment (10 May).

Table 3. Correlation coefficients across 17 dry farms in Willamette Valley, OR, USA, for site variables [soil available water-holding capacity (AWHC); total available water (TAW); native productivity rating (NPR); topsoil and subsoil pH; weak Bray phosphorus concentration (P), potassium concentration (K), and calcium concentration (Ca); in-season rainfall; and planting day] in 2019.

					0–6 inches[i]				24–36 inches[i]				
		AWHC (inches)[i]	TAW (inches)[i]	NPR	pH	P (ppm)[i]	K (ppm)[i]	Ca (ppm)[i]	pH	P (ppm)[i]	K (ppm)[i]	Ca (ppm)[i]	In-season rainfall (inches)[i]
	TAW (inches)[i]	0.91***[ii]											
	NPR	0.41	0.46*										
0–6 inches[i]	pH	0.34	0.39	0.39									
	P (ppm)[i]	0.25	0.27	0.03	0.44*								
	K (ppm)[i]	0.17	0.13	0.27	0.56**	0.72***							
	Ca (ppm)[i]	0.26	0.27	0.26	0.73***	0.03	0.28						
24–36 inches[i]	pH	0.05	0.05	–0.16	0.57**	0.16	0.27	0.42*					
	P (ppm)[i]	0.39	0.32	0.47*	–0.07	0.48*	0.25	–0.28	–0.40				
	K (ppm)[i]	0.21	0.15	0.26	0.27	0.66***	0.91***	0.02	0.04	0.38			
	Ca (ppm)[i]	0.12	–0.01	–0.41	0.22	–0.11	0.03	0.66***	0.21	–0.34	–0.11		
	In-season rainfall (inches)[i]	–0.09	0.34	0.19	0.16	0.06	–0.08	0.07	–0.00	–0.11	–0.13	–0.29	
	Planting day[iii]	–0.11	–0.45*	–0.45*	–0.51**	–0.05	–0.06	–0.50**	–0.06	0.10	0.10	–0.03	–0.82***

[i] 1 inch = 2.54 cm; 1 ppm = 1 mg·kg^{-1}.

[ii] Significance of correlation coefficient between two site variables indicated within cells. *, **, *** significant at $P < 0.1$, 0.05, and 0.01, respectively.

[iii] Day of tomato (*Solanum lycopersicum*) and winter squash (*Cucurbita maxima*) planting since the start of the experiment (8 May).

x-intercept was estimated at 2.2 inches. For winter squash, the linear regression for 2018 had a slope of 1.0 ton/acre per inch (*SE* = 0.7) and an x-intercept at –0.9 inch; that for 2019 had a slope of 1.5 tons/acre per inch (*SE* = 0.8) and an x-intercept at 0.8 inch. The slope for the linear regression for the combined analysis (2018 and 2019 data) was 1.5 tons/acre per inch (*SE* = 0.4) and the x-intercept was at 2.0 inches. The slope for water limited yield potential for dry-farmed 'North Georgia Candy Roaster' winter squash was estimated to be 2.8 tons/acre per inch and the x-intercept was estimated at 2.0 inches.

Discussion

Impacts of year and planting density on yield and fruit quality. Weather differed between the years of this study; 2018 was a hot and dry year, whereas 2019 was cooler, more humid, and had higher in-season rainfall. These differences in temperature,

Table 4. Summary statistics for response variables (total yield, total fruit, average fruit weight, blossom-end rot (BER) incidence, and unblemished yield) of tomato (*Solanum lycopersicum*) and winter squash (*Cucurbita maxima*) dry-farmed in the Willamette Valley, OR, USA, separated by year and planting density, with likelihood ratio tests for the effect of planting density (20 ft^2/plant compared with 40 ft^2/plant) in 2019 on mean response.

	Mean (*SE*)[i]			
	2018	2019		Likelihood ratio test for effect of density in 2019[iii]
Response variable	20 ft^2/plant[ii]	20 ft^2/plant[ii]	40 ft^2/plant[ii]	
	Tomato			
Total yield (tons/acre)[ii, iv]	7.9 (1.2)	14.1 (1.3) A[v]	10.1 (1.4) B	*L* = 8.54, *df* = 1, *P* = 0.004***
Total fruit (no./acre)[ii, iv]	114,000 (14,000)	166,000 (17,000) A	120,000 (17,000) B	*L* = 9.17, *df* = 1, *P* = 0.003***
Average fruit wt (lb/fruit)[ii]	0.15 (0.01)	0.17 (0.01)	0.18 (0.01)	*L* = 0.52, *df* = 1, *P* = 0.471
BER incidence (proportion)	0.35 (0.06)	0.38 (0.07)	0.45 (0.07)	*L* = 2.77, *df* = 1, *P* = 0.096*
Unblemished yield (tons/acre)[ii, iv]	5.6 (1.1)	8.9 (1.2) A	5.5 (1.2) B	*L* = 9.14, *df* = 1, *P* = 0.003***
	Winter squash			
Total yield (tons/acre)[ii, iv]	10.6 (1.6)	18.0 (2.0) A	14.2 (2.0) B	*L* = 7.01, *df* = 1, *P* = 0.008***
Total fruit (no./acre)[ii, iv]	4,480 (520)	5,260 (450) A	3,870 (450) B	*L* = 8.46, *df* = 1, *P* = 0.004***
Average fruit wt (lb/fruit)[ii]	4.6 (0.4)	6.7 (0.4)	7.2 (0.4)	*L* = 2.35, *df* = 1, *P* = 0.126

[i] Values are means (2018 data) or estimated marginal means (2019 data) ± *SE*.

[ii] 1 ft^2 = 0.0929 m^2; 1 tons/acre = 2.2417 Mg·ha^{-1}; 1 fruit/acre = 2.4711 fruit/ha; 1 lb = 0.4536 kg.

[iii] Statistical significance of likelihood ratio test is indicated in this column. *, **, *** significant at $P < 0.1$, 0.05, and 0.01, respectively.

[iv] Per-acre yields were extrapolated from five-plant plot data (not shown) based on the area of each plot.

[v] Values for densities in 2019 not sharing a common letter within row are significantly different (Tukey's honest significant difference; $P < 0.05$).

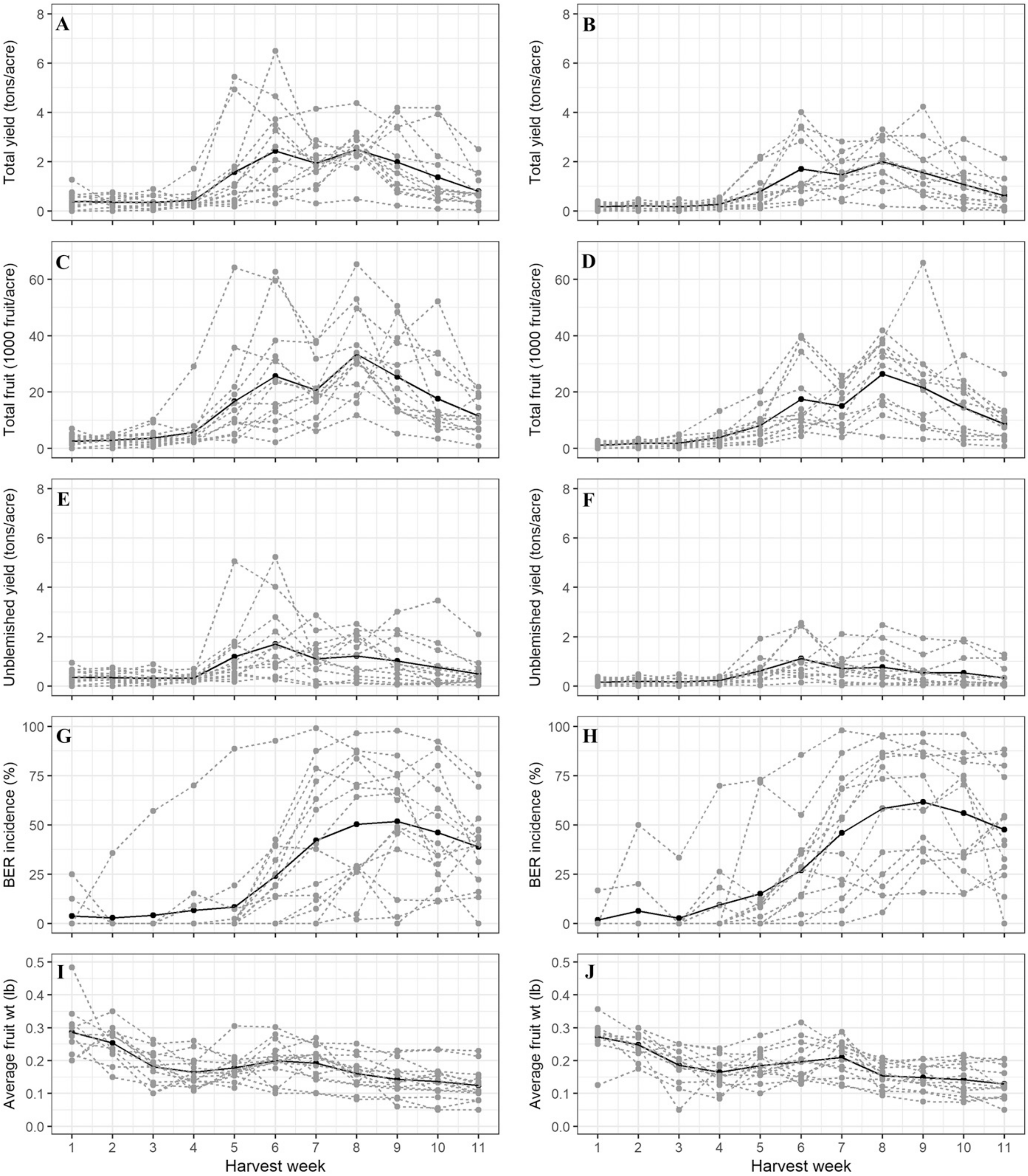

Fig. 2. Longitudinal data for dry-farmed tomato (*Solanum lycopersicum*) variables across the 2019 harvest season in Willamette Valley, OR, USA, for 20-ft^2/plant (A, C, E, G, I) and 40-ft^2/plant (B, D, F, H, J) plots. Tomato total yield (A, B), total fruit number (C, D), unblemished yield (E, F), blossom-end rot (BER) incidence (G, H), and average fruit weight (I, J) changed over the course of the growing season. Solid black lines and points represent averages for each harvest. Dashed gray lines and points represent individual farms. Per-acre yields were extrapolated from five-plant plot data (not shown) based on the area of each plot. 1 ft^2 = 0.0929 m^2; 1 tons/acre = 2.2417 Mg/ha; 1000 fruit/acre = 2471.0538 fruit/ha; 1 lb = 0.4536 kg.

VPD, and rainfall were likely responsible for the increased yield in 2019 when compared with that in 2018. Wetzel (2018) found a similar difference in yield for 'North Georgia Candy Roaster' winter squash between the years of their study, with 16.6 tons/acre in cool and humid 2016 and 11.9 and 12.5 tons/acre in hot and dry 2017. Sites

Table 5. Correlation coefficients between site variables [soil available water-holding capacity (AWHC); total available water (TAW); native productivity rating (NPR); topsoil and subsoil pH; weak Bray phosphorus concentration (P), potassium concentration (K), and calcium concentration (Ca); in-season rainfall; and planting day] and response variables (total yield; total fruit; average fruit weight; unblemished yield; and soil water tension at depths of 1, 2, 3, and 4 feet) for dry-farmed tomato (*Solanum lycopersicum*) and winter squash (*Cucurbita maxima*) in Willamette Valley, OR, USA, in 2018 and 2019, with data separated by planting density and year.

							Soil chemical properties (0–6 inches)[i]				Soil chemical properties (24–36 inches)[i]					
Response	Yr	Density (ft^2/plant)[i]	Farms used in analysis (no.)	AWHC (inches)[i]	TAW (inches)[i]	NPR	pH	P (ppm)[i]	K (ppm)[i]	Ca (ppm)[i]	pH	P (ppm)[i]	K (ppm)[i]	Ca (ppm)[i]	In-season rainfall (inches)[i]	Planting day[ii]
Tomato																
Total yield (tons/acre)[i, iii]	2018	20	13													
	2019	20	13								0.56*,[iv]					
	2019	40	12	0.66**	0.72***		0.52*	0.62**								
Total fruit (no./acre)[i, iii]	2018	20	12								0.52*					
	2019	20	13													
	2019	40	12		0.61**			0.57*							0.51*	
Average fruit wt (lb/fruit)[i]	2018	20	12	0.58**	0.61**											
	2019	20	14													
	2019	40	13													
Unblemished yield (tons/acre)[i, iii]	2018	20	12													
	2019	20	13													
	2019	40	12	0.59**	0.56*											
Winter squash																
Total yield (tons/acre)[i, iii]	2018	20	11	0.54*	0.52*	0.56*										
	2019	20	12											−0.61**		−0.53*
	2019	40	12			0.68**										
Total fruit (no./acre)[i, iii]	2018	20	11													
	2019	20	12			0.54*						0.59**		−0.58**		
	2019	40	12			0.63**			0.55*				0.54*			
Average fruit wt (lb/fruit)[i]	2018	20	11													
	2019	20	12											−0.56*	0.68**	−0.58**
	2019	40	12		0.59**											
Soil water tension																
Soil water tension at 1 ft (cbars)[i]	2018	20	11			0.61**		0.73**	0.77***				0.84***			−0.56*
	2019	20	14	0.46*	0.51*											
Soil water tension at 2 ft (cbars)[i]	2018	20	12					0.58**				0.56*				
	2019	20	14	0.54**	0.69***					0.51*						−0.65**
Soil water tension at 3 ft (cbars)[i]	2018	20	12					0.65**				0.72***				
	2019	20	14		0.52*		0.63**			0.66***	0.57**					−0.59**
Soil water tension at 4 ft (cbars)[i]	2018	20	13			0.51*		0.77***				0.70***				
	2019	20	14		0.49*	0.55**	0.53*			0.50*						−0.51*

[i] 1 ft^2 = 0.0929 m^2; 1 inch = 2.54 cm; 1 ppm = 1 $mg \cdot kg^{-1}$; 1 tons/acre = 2.2417 $Mg \cdot ha^{-1}$; 1 fruit/acre = 0.4047 fruit/ha; 1 lb = 0.4536 kg; 1 ft = 0.3048 m; 1 cbar = 1 kPa.

[ii] Day of planting since the start of the experiment (10 May 2018 and 8 May 2019).

[iii] Per-acre yields were extrapolated from five-plant plot data (not shown) based on the area of each plot.

[iv] Significance of correlation coefficient between site and response variables indicated within cells. *, **, *** significant at $P < 0.1$, 0.05, and 0.01, respectively.

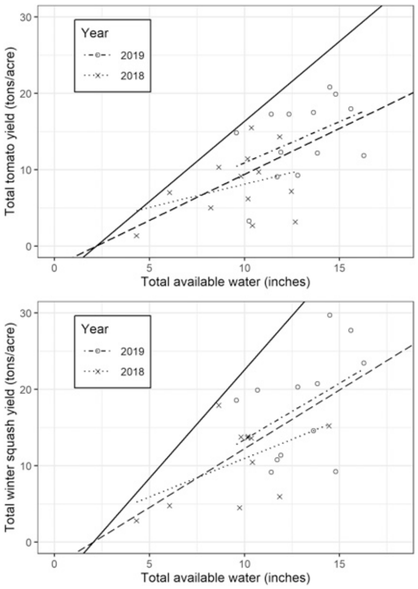

Fig. 3. Schematics of the relationships between total available water and yields of dry-farmed tomato (*Solanum lycopersicum*) and winter squash (*Cucurbita maxima*) for 20-ft^2/plant plots in Willamette Valley, OR, USA. Each data point represents one project site in 2018 (circle) or 2019 (cross). The dash-dotted line represents the conditional mean for the linear regressions for 2018 and the dotted line represents that for 2019. The dashed line represents the conditional mean for the linear regression for both years. The solid line represents water-limited yield potential and was estimated arbitrarily to include all points. Estimated slopes for water-limited yield potential are 2.2 tons/acre per inch for tomato and 2.8 tons/acre per inch for winter squash. Per-acre yields were extrapolated from five-plant plot data (not shown) based on the area of each plot. 1 ft^2 = 0.0929 m^2; 1 tons/acre = 2.2417 Mg/ha; 1 inch = 2.54 cm; 1 tons/acre per inch = 0.8826 Mg·ha^{-1}·cm^{-1}.

also had slightly higher measurements of soil AWHC and NPR in 2019, which may have contributed to this trend. Increased VPD reduces productivity and yield in crops because of decreased stomatal conductance and increased drought stress (Hsiao et al. 2019; Yuan et al. 2019). In-season precipitation increases yield for dryland crops (Lu et al. 2018). Interactions between VPD and precipitation show greater yield declines from increased temperature and VPD in years with lower precipitation (Hsiao et al. 2019). These factors suggest that dry farming in the Willamette Valley will be less productive in hotter and drier years. Climate change is expected to result in hotter and drier summer in the Willamette Valley (Jung and Chang 2012; Mote and Salathé 2010) and may make dry-farmed crops less productive and increase the risk of crop failure without the proper mitigation strategies.

Leap et al. (2017) reported an expected marketable tomato yield of 9.71 tons/acre in coastal California with one harvest per week for 9 weeks. If this yield estimate accounts for an expected 10% to 20% loss in marketable yield caused by BER (Leap et al. 2017), then the expected total tomato yield for California can be estimated to be 11.17 tons/acre. A comparison of expected coastal California and project yields suggested that in cooler and more humid years, western Oregon total tomato yield should be similar to coastal California (e.g., 14.1 tons/acre in 2019); however, in hot and dry years, the yield could be considerably lower (e.g., 7.9 tons/acre in 2018). The tomato harvest season across all sites in 2019 was short, with ~50% of the total yield harvested during a 3-week period. This temporal yield pattern is not unlike that reported by Leap et al. (2017), who described a 4-week peak comprising 70% of the total harvest. Leap et al. (2017) recommends planting multiple successions to increase the duration of the harvest season.

Although the 2019 tomato mean total yield was greater than the yield reported by Leap et al. (2017) for coastal California, the 2019 tomato mean unblemished yield was lower during this project than in California (9.71 tons/acre compared with 8.9 tons/acre for 20-ft^2/plant plots) (Table 4). This is because of this project's higher BER incidence (~40% in the 2019 20-ft^2/plant plots compared with 10% to 20% reported in coastal California). A higher BER incidence in the hotter and drier Willamette Valley is not surprising considering that BER is reported to be positively associated with VPD (Bertin et al. 2000; Blanc 1985). However, the BER incidence was slightly higher in the cooler and wetter 2019 growing season than in the hotter and drier 2018 growing season. It is possible that in 2019, increased precipitation in May produced greater early season vegetative growth and higher fruit set, and this increased the BER incidence, as predicted by Saure (2014, 2001).

Dry farm tomato and winter squash fruit weight fell below the range provided by the seed company. ‘Early Girl’ tomato is reported to have a fruit weight of 1/4 to 3/8 lb and ‘North Georgia Candy Roaster’ winter squash is reported to have a fruit weight of 8 to 15 lb (Johnny’s Selected Seeds). Previous work found that dry-farmed winter squash fruit weight was smaller than irrigated winter squash fruit weight during the hot and dry 2017 growing season; however, in the cool and humid 2016 growing season, there was little difference (Wetzel and Stone 2019). Tomato average fruit weight across all sites decreased over the course of the growing season, probably resulting from decreasing water availability (Giardini et al. 1985). Lower average fruit weight, along with high incidence of BER, may make many of the late season tomatoes unmarketable. Pruning and staking dry-farmed tomato may help to increase tomato average fruit weight and wholesale value (Davis and Estes 1993).

Historically, dry farmers have been encouraged to grow crops at a low density to improve productivity (Garrett 2019; Widtsoe 1911). As planting density decreases, the average volume of soil (and therefore soil moisture) available to each plant should increase. Alternatively, Leap et al. (2017) recommends managing the plants by pruning and staking and planting them at 16- to 24-inch in-row spacing and 6-ft between-row spacing, which are not that different from the recommendations for irrigated tomato spacing. Our results suggest that 20-ft^2/plant plantings have higher tomato and winter squash yield and fruit number than 40-ft^2/plant plantings. However, we only trialed 40-ft^2/plant plots in 2019; it is possible that during hotter and drier years, 40-ft^2/plant plantings may outperform 20-ft^2/plant plantings. Dry farm crops may prevent evaporation and increase water use efficiency at higher planting densities if the canopy is able to cover the soil more quickly (Cooper et al. 1987; Sadras and Rodriguez 2007). There was no effect of planting density on average fruit weight for tomato or winter squash. This contradicts Wetzel and Stone (2019), who found that the dry farm winter squash yield was unaffected by planting density, and that average fruit weight decreased as planting density increased. Higher-density planting also resulted in slightly less BER for tomato. Higher-density plantings may reduce early-season growth, preventing BER in tomato (Saure 2014, 2001). By planting in high-density clumps, dryland sorghum farmers conserve soil moisture for later in the growing season, resulting in increased yields, and decrease the chance of crop failure (Bandaru et al. 2006).

Site factors. The results presented here suggest that dry farm crop productivity is associated soil AWHC. This aligns with previous scholarship of dry farm vegetable production by Garrett (2019) and Leap et al. (2017). Soil AWHC may be an especially reliable determinant of dry farm yield in the Willamette Valley because of precipitation patterns. In dryland systems, higher soil AWHC tends to improve yields, but this relationship is dependent on both the total amount and timing of precipitation, especially for soils with high AWHC (He and Wang 2019; Lawes et al. 2009; Wang et al. 2009). Soil AWHC has the biggest impact on yield when there are high amounts of precipitation before planting, and it has the smallest impact when there is little precipitation or if the precipitation falls mainly during the growing season. Western Oregon receives abundant precipitation before the growing season and has a dry summer climate; therefore, a strong correlation between soil AWHC and yield should be expected.

The TAW is defined here as the summation of soil AWHC and in-season rainfall from planting to 31 Jul. Including in-season rainfall often improved the relationship between soil AWHC and response variables (Table 5), suggesting that in-season rainfall contributes to the total water available for crop production. This may be partially confounded by collinearity between the planting date and in-season rainfall in 2019. However, TAW does not explain all of the yield differences between sites. A regression analysis using data from both years showed that TAW predicts 35% of the variation in tomato total yield and 39% of the variation in winter squash total yield. Other factors that may influence yields include subsoil constraints, poor transplant quality, low soil pH, low soil nutrient contents, weeds, insect damage, disease damage, and/or increased evapotranspiration (Passioura and Angus 2010).

Water-limited yield potential is a concern of many studying wheat and maize production (French and Schultz 1984; Grassini et al. 2011; Sadras and Angus 2006). Our attempt to reproduce this relationship for dry-farmed tomato and winter squash grown in the Willamette Valley is presented in Fig. 2. The x-intercept for the lines propose that 2.2 inches of soil moisture is lost to evaporation under tomato whereas 2.0 inches of water is lost to evaporation under winter squash. These are lower than the soil evaporation values proposed for wheat and maize (4.3 inches and 3.9 inches, respectively) (French and Schultz 1984; Grassini et al. 2011). The slopes represent a hypothetical maximum yield if water is the only limiting resource, with 2.2 tons/acre per inch for tomato and 2.8 tons/acre per inch for winter squash. These are much higher than the water limited yield potentials proposed for wheat and maize (0.23 ton/acre per inch and 0.22 ton/acre per inch, respectively) (French and Schultz 1984; Grassini et al. 2011). This difference can be explained in part by the high water content of tomatoes and winter squash compared with grains. We only included soil AWHC to 5 ft in our estimate of TAW; however, it is possible that soil moisture below 5 ft is available to the plants at certain sites.

The NPR offers an alternative means by which farmers can evaluate their soil's suitability for dry-farmed vegetable production. The NPR was correlated with soil AWHC in 2018, but not in 2019. During 2019, NPR was more strongly correlated with winter squash yield, fruit count, and average fruit size than soil AWHC. Perhaps the NPR accounts for subsoil constraints to winter squash root growth that are missed in a simple soil AWHC measurement. Two soils with high AWHC and low NPR that may have contributed to this trend were both classified as Dayton series soils, and these soils have an abrupt textural contrast between the topsoil and subsoil (Bockheim 2016). Winter squash roots may struggle to grow into the subsoil of these soils. These soils also tend to be waterlogged, which may explain collinearity between NPR and planting day in 2019.

The results showed that topsoil and subsoil fertility were related to measures of yield and soil water tension, suggesting that crops grown in soils with sufficient nutrient concentrations and appropriate pH yield more and develop roots and uptake water more quickly than crops grown in soils with insufficient nutrient concentrations and low pH. Low pH decreases phosphorus availability, increases aluminum toxicity, and makes soil inhospitable to root growth (Chapin et al. 2002; Kochian et al. 2015; Rahman et al. 2018). Soil nutrient deficiencies, including phosphorus and calcium deficiency, also limit root growth (Hatfield and Stewart 1992). There was a high degree of collinearity between variables relating to soil fertility and pH, probably reflecting the overall quality of soil management on individual farms, and this confounds our ability to determine the relative importance of topsoil and subsoil nutrients. Additionally, subsoil nutrients may be correlated with subsoil texture; sites with high subsoil clay should also have high cation exchange capacity. This difference in soil texture potentially affected our soil water tension measurements in the subsoil.

The subsoil calcium concentration was negatively correlated with winter squash total yield, total fruit number, and average fruit weight for the 20-ft^2/plant plots in 2019. The subsoil calcium concentration may be related to the clay content of the subsoil, and subsoils with a higher clay content may impede root development (Bonomelli et al. 2019). This relationship may reflect unaccounted for collinearity between subsoil calcium and subsoil clay content. The subsoil calcium concentration was not correlated with soil water tension at any depth in 2019; however, the probes were installed in the tomato plots and not the winter squash plots.

Many authors have related excessive soil nutrients to BER in tomato; however, this relationship was not present in the data (Bouquet 1941; Saure 2001, 2014; Taylor and Locascio 2004). Considering the diversity of potential direct and indirect causes of BER, it is not surprising that we have not accounted for BER with simple correlations. Although BER was not correlated with any site variables, the BER incidence was related to total fruit number in the 20-ft^2/plant plots in 2019 ($F = 5.24$; $P = 0.041$).

In 2019, earlier plantings correlated with higher winter squash total yield and average fruit weight. It is not surprising that crops planted earlier would perform better because dry-farmed crops rely on stored soil water. Crops planted early in the spring may receive additional water from rain and establish at a time when VPD and, thus, water use are low. Planting day was not related to crop performance in 2018. Collinearity between planting day and soil AWHC in 2018 may have confounded this relationship; sites with higher soil AWHC tended to be planted later.

Conclusions

Dry farming tomato and winter squash has the potential to be a useful climate resilience strategy in regions like the Willamette Valley that have ample winter and spring precipitation to refill the deep soil profiles with high quantities of available water each year but have little summer growing season precipitation. The Willamette Valley's deep soils with silt loam and silty clay loam textures are well-suited to dry farming. Some soils are more suitable than others; therefore, soil assessment is critical to dry farming success. We recommend farming on soils with high AWHC. The NPR developed by Huddleston (1982) can also be used to evaluate sites and may account for subsoil constraints that are missed in soil AWHC estimations. Planting early may help generate higher winter squash yield, but it may not help with generating high yields of unblemished tomatoes. Although winter squash and tomato can be dry-farmed in this region, lower yields are expected during unusually hot dry summers, and they will occur more frequently if recent trends in climate change continue. Future studies of the dry farm site suitability should include measures of microclimate, especially windrun, because windbreaks may improve dry farm productivity (Campi et al. 2009; de Vries et al. 2012). In addition, the effect of subsoil constraints like abrupt textural contrast on rooting depth, water availability, and site suitability should be further explored. Dry-farmed tomato and winter squash performed better in the 20-ft^2/plant plots in 2019. More data are needed to determine if this trend holds true in hotter and drier years.

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