

Floor Management and Amendment Applications Affected Dry-farmed Tomato Production during a 2020 Experiment in the Willamette Valley of Oregon

Matthew Davis¹, Andy Gallagher², and Amy Garrett³

KEYWORDS. blossom-end rot, compost, dust mulch, leaf mulch, *Solanum lycopersicum*, weed management

ABSTRACT. ‘Early Girl’ tomato (*Solanum lycopersicum*) was dry-farmed during 2020 to determine the effects of floor management and amendment treatments on the total and unblemished yields, average fruit weight, blossom-end rot (BER) incidence, sunscald incidence, plant size, soil water tension, predawn leaf water potential (PDLWP), and leaf and soil nutrient concentrations. Floor management treatments included leaf mulching (4 inches of semi-composted leaf mulch), dust mulching (mechanical tillage to a depth of 6 to 8 inches after rain events), and a weedy treatment (weeds were not controlled). Amendment treatments included high compost (additional 73.5 wet tons/acre), high nitrogen (N) (160 lb/acre N applied as composted chicken manure and feather meal), low N (40 lb/acre N), and gypsum (2075 lb/acre gypsum). All these treatments were compared with a clean-cultivated control fertilized at 100 lb/acre N. No floor management treatment performed better (referring to total yield, unblemished yield, fruit count, fruit weight, BER incidence, sunscald incidence, and PDLWP) than the clean-cultivated control, and the leaf mulch and weedy treatments performed significantly worse. The leaf mulch treatment decreased the average fruit weight (30%), increased the BER incidence (34%), and increased the necrotic BER incidence (88%) when compared with the control. However, the leaf mulch treatment also used soil moisture more slowly than the control did. The weedy treatment decreased total yields (65%) and unblemished yields (88%), decreased the total fruit count (53%), decreased the average fruit weight (25%), increased the BER incidence (53%) and necrotic BER incidence (82%), decreased PDLWP (suggesting that the plants were more drought-stressed) on 20 Jul (27%) and 3 Aug (44%), and resulted in smaller plants when compared with those treated with the control. No amendment treatment performed better than the control, and the high compost treatment performed significantly worse. When compared with the control, the high compost treatment decreased the average fruit weight (15%), increased the BER incidence (39%), increased the necrotic BER incidence (67%), and increased plant aboveground biomass at the end of the experiment (34%). Increasing applications of organic fertilizers increased the BER incidence, with 48% BER at 40 lb/acre N and 62% BER at 160 lb/acre N. These data suggest that excess fertilizer applications and factors that increase drought stress (e.g., weeds) induce BER in dry-farmed tomato. Dust mulching may not be necessary, and shallow cultivation can be used instead for weed management. Dry farmers in the Willamette Valley must control weeds and avoid excess soil fertility and leaf mulches because they can result in large plants with a large fruit set; however, these fruit are more susceptible to BER.

Dry farming is the production of crops without the use of irrigation during a dry growing season in regions with at least 20 inches of annual rainfall (Davis et al. 2023; Garrett 2019; Leap et al. 2017). Instead of irrigating, dry farmers rely on residual soil moisture and limited in-season rainfall to meet the water needs of their crops. This differs from dryland farming, which involves the production of crops without irrigation in semi-arid regions where annual precipitation is less than half of the annual potential

evapotranspiration (Stewart and Thapa 2016). On the west coast of the United States, there is increasing interest in using dry farming for tomato (*Solanum lycopersicum*) production because it can allow for crops to be grown despite irrigation water scarcity or a lack of water rights, and because it may improve crop flavor (Garrett 2019; Leap et al. 2017; Patanè and Cosentino 2010). However, there have been few studies of the effects of floor management and soil amendments on this agricultural system (Gill et al. 2024; Keller 2022; Socolar et al. 2024).

Floor management involves activities that control soil health, weeds, soil nutrients, and soil moisture through tillage, herbicides, cover cropping, and mulches (Guerra and Steenwerth 2012). One floor management practice that has been recommended for dry-farmed tomato production is dust mulching, which is described as shallow soil tillage (to a depth of 4–6 inches) using a rototiller, rolling cultivator, or disk harrow applied every 2 or 3 weeks until the plants are too large to cultivate (Leap et al. 2017). Dust mulching controls weeds, and some believe that it also conserves soil moisture by disrupting capillary action that would wick soil moisture to the surface (Leap et al. 2017). In dryland farming systems, dust mulching is no longer promoted because of its negative environmental consequences, including diminished soil organic content, poor soil structure, reduced infiltration, reduced soil water holding capacity, and wind erosion (Stewart and Thapa 2016). Many dryland farmers now practice no-till farming, and tillage has been shown to increase evaporation to the depth of tillage (Greb et al. 1979; Sarkar and Singh 2007; Stewart and Thapa 2016; Zentner et al. 2002). Other floor management strategies that may conserve water for crops include deep mulching with organic materials, which can decrease soil temperatures, increase nutrient availability, and suppress weeds (Díaz-Pérez et al. 2004; Schonbeck and Evanylo 1998; Youssef et al. 2021). Organic mulches have increased tomato yields under rain-fed conditions in Bangladesh (Kayum et al. 2008). Controlling weeds is an important consideration when planning floor management; in southern Italy, the relative effect of weed biomass on tomato yield losses increases under dry-farmed conditions compared with those under irrigated conditions (Valerio et al. 2013).

Soil amendments are used to improve soil chemical properties, such as fertility, pH, and organic matter, and soil physical properties, including infiltration, structure, aggregate stability, and available water holding capacity (Dorado et al. 2003). The current amendment recommendation for dry-farmed tomato production is fall-applied compost; however, it has been reported that compost applied at cover crop incorporation will not benefit the crop (Leap et al. 2017). This is because the

topsoil, where most nutrients are located, is rapidly depleted of water, leaving nutrients unavailable to the crop. Therefore, it was suggested that dry-farmed tomato scavenges nutrients from deep in the soil profile, and that nutrients from fall-applied compost are leached into the subsoil (Leap et al. 2017). Socolar et al. (2024) found that only soil nutrients below a depth of 30 cm were correlated with the tomato marketable yield, blossom-end rot (BER) incidence, and fruit percent dry weight. However, others have found a relationship between surface phosphorus concentrations and dry-farmed tomato total yields, but not unblemished yields (Davis et al. 2023). In addition to improving soil nutrient concentrations, compost and other organic amendments can also increase soil organic matter and improve soil available water holding capacity, which may improve dry farm productivity (Brown and Cotton 2011; Hernando et al. 1989). Available water holding capacity, which is the amount of plant available water that the soil can store, is of particular interest to dry farmers because it has been correlated with dry-farmed tomato yields (Davis et al. 2023).

Floor management and amendment applications may affect BER rates; BER is a physiological disorder that causes significant fruit loss for dry-farmed tomato (Bouquet 1922; Davis et al. 2023; Leap et al. 2017). However, BER remains poorly understood, with two different

theories explaining its direct causes (Hagassou et al. 2019). One theory is that BER is induced by calcium deficiency in the fruit, and that this deficiency is caused by environmental factors that either reduce calcium uptake or affect calcium partitioning (Ho and White 2005; Taylor and Locascio 2004). The other theory is that rapid growth, followed by abiotic stress, induces reactive oxygen species accumulation in the plant, leading to membrane disintegration and loss of cell turgor (Saure 2001, 2014). According to each theory, interactions between genetic, physiological, and environmental factors contribute to the BER occurrence (Hagassou et al. 2019). If calcium deficiency in the fruit causes BER, then treatments that increase soil calcium availability and uptake or that affect calcium partitioning should reduce the BER incidence. This could result from increasing soil calcium concentrations by applying calcium-based fertilizers (e.g., gypsum), reducing relative concentrations of other soil cations, or reducing soil water loss (Geraldson 1956; Taylor and Locascio 2004; Taylor et al. 2004). If BER is induced by a sequence of rapid growth followed by abiotic stress, then treatments that reduce the growth rate of the crop and/or reduce drought stress (or other abiotic stresses) should reduce the BER incidence. Socolar et al. (2024) found that the BER incidence in dry-farmed tomato decreased as soil ammonium concentrations increased at a depth of 30 to 60 cm, but the marketable yields decreased as ammonium concentrations at a depth of 60 to 100 cm increased.

The objective of this study was to evaluate the effects of different amendment and floor management treatments on the yield, fruit quality, plant size, soil water tension, predawn leaf water potential (PDLWP), and leaf and soil nutrient concentrations for dry-farmed 'Early Girl' tomato at a site in the Willamette Valley. More succinctly, the aim was to experimentally test the conventional wisdom that is often shared between dry farmers and extension specialists along the west coast of the United States. The tested amendments included compost, organic fertilizers, and gypsum. The tested floor management methods included dust mulching, deep mulching, and abstaining from weed management altogether. Yield and fruit quality are the highest concerns for farmers, but

other measurements may help to elucidate reasons for changes in yield and fruit quality. Plant size may be important. It has been hypothesized that rapid plant growth may be associated with the BER incidence (Saure 2001, 2014). The soil water tension and PDLWP are measures of soil moisture availability and rooting, which are important for determining how plant water use is affected by the treatments in dry-farmed conditions.

Methods

The field experiment was conducted at the Oregon State University Vegetable Research Farm in Corvallis, OR, USA (lat. 44.5714°N, long. 123.2434°W) from Apr to Oct 2020. The Köppen climate classification for this region is Csb, which is characterized by a warm and dry summer climate. Local weather data during the experiment collected by the Hyslop Weather Station (AgriMet Weather Station, Corvallis, OR, USA), which is located approximately 4.8 miles from the field site (US Bureau of Reclamation 2024), are shown in Table 1. The soil series of the experimental area is a Chehalis silty clay loam, with approximately 12 inches of available water holding capacity in the first 5 ft of soil (analysis by Red Hill Soils, Corvallis, OR, USA).

The experimental design was a randomized complete block design with eight treatments and four replications. Individual plots contained three rows that were 5 ft apart, each comprised seven plants. In-row spacing was 4 ft. The outer 16 plants in each plot were border plants that surrounded five data plants; however, their data were not collected because they were planted to mitigate edge effects from the surrounding treatments. Plots were 420 ft² in size, with 100 ft² for the data plants. Treatments tested included four soil amendment treatments [named high compost (HC), gypsum (GY), high nitrogen (HN), and low nitrogen (LN)], three floor management treatments [dust mulch (DM), leaf mulch (LM), and weedy (WY)], and a control. Combinations of these treatments were not tested. A picture of the trial is presented in Fig. 1, and the treatments are summarized in Table 2.

The experimental site was seeded with a cover crop of common vetch (*Vicia sativa*), triticale (*×Triticosecale*),

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¹Department of Horticulture, Oregon State University, 2750 SW Campus Way, ALS #4017, Corvallis, OR 97331, USA

²Red Hill Soils, PO Box 2233, Corvallis, OR 97339, USA

³Dry Farming Institute, PO Box 2558, Corvallis, OR 97339, USA

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M.D. is the corresponding author. E-mail: davisma3@oregonstate.edu.

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Table 1. AgriMET data from the Hyslop Weather Station (Corvallis, OR, USA) for the 2020 growing season (US Bureau of Reclamation 2024).

	Avg daily minimum temp (°F) ⁱ	Avg daily maximum temp (°F) ⁱ	Avg daily mean temp (°F) ⁱ	Total monthly precipitation (inches) ⁱ	Total monthly evapotranspiration (inches) ^{i,ii}	Total monthly wind run (miles) ⁱ
April	39.95	63.64	51.75	1.73	3.94	3055.78
May	46.78	68.32	57.13	3.09	5.25	3063.48
June	50.68	73.01	61.56	1.85	6.30	3107.45
July	52.68	82.85	67.47	0.00	8.82	3387.38
August	52.62	84.25	68.26	0.12	8.75	3725.58
September	52.32	76.97	64.06	2.09	5.02	3098.75
October	43.40	65.16	53.56	1.69	2.39	2947.36

ⁱ (°F - 32) ÷ 1.8 = °C; 1 inch = 2.54 cm; 1 mile = 1.6093 km.

ⁱⁱ Calculated using the Kimberly Penman equation.

and annual fescue (*Vulpia myuros*) at a rate of 50 lb/acre on 15 Sep 2019 (240 d before transplanting). A cover crop sample was taken for analysis (%N, %P, %K, and %moisture) on

6 Apr 2020, 36 d before transplanting (Table 3); the analysis was performed at A&L Western Agricultural Laboratories (Modesto, CA, USA). The cover crop was flail mowed on 7 Apr (35 d before

transplanting). The field was prepared for planting on 13 Apr (29 d before transplanting) by spreading compost (4.5 wet tons/acre), subsoiling to 24 to 30 inches (910 5 Shank Ripper; Deere

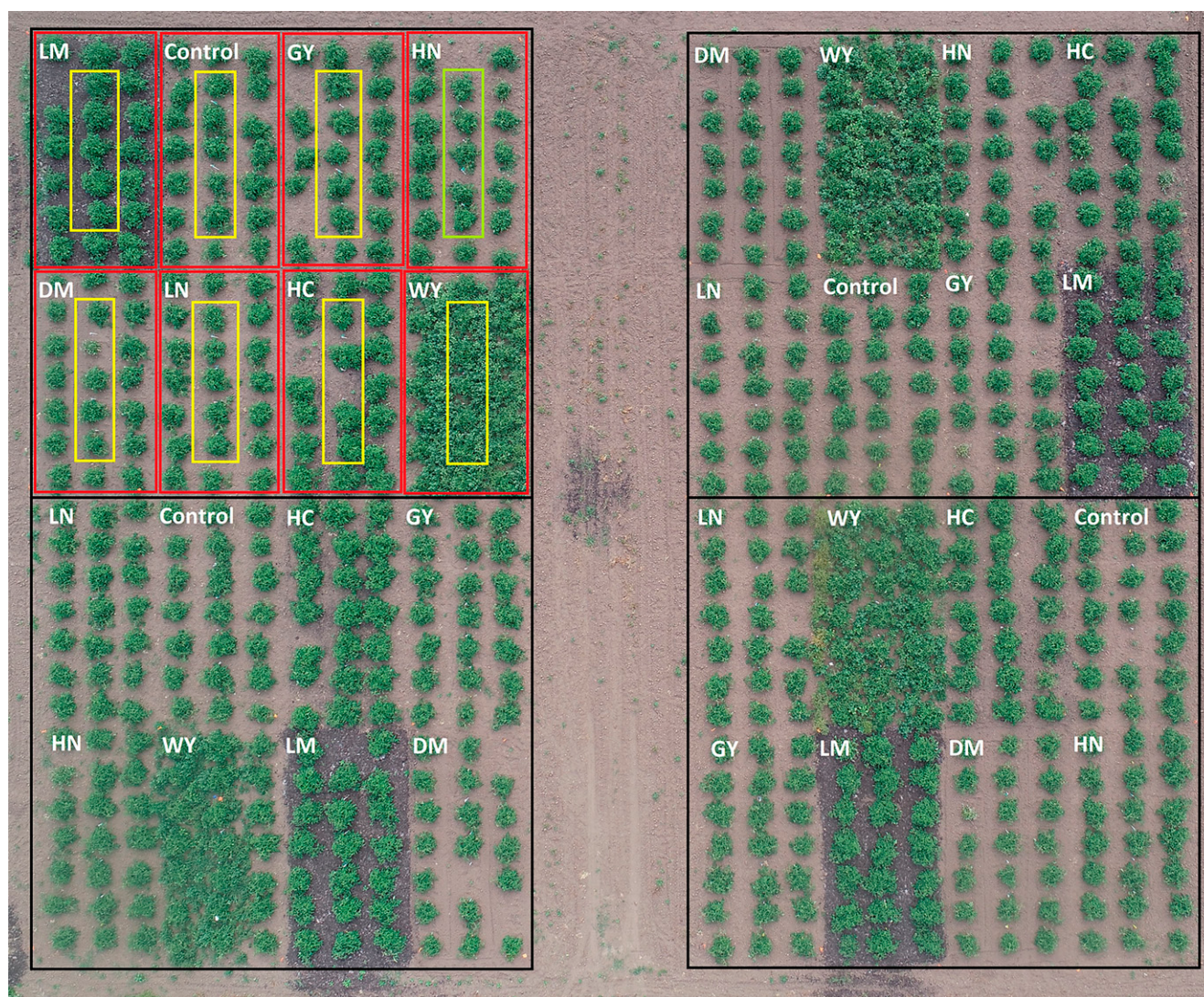


Fig. 1. Aerial photo of the experiment taken on 2 Jul 2020 (photo by Shinji Kawai). Blocks are indicated in black. (Top left) Block one. (Bottom left) Block two. (Top right) Block three. (Bottom right) Block four. Within block one, we indicated the locations of the plots (indicated in red) and data plants (indicated in yellow). The treatment applied to each plot can be found at the top left corner of the plot and includes high compost (HC), gypsum (GY), high nitrogen (HN), low nitrogen (LN), leaf mulch (LM), dust mulch (DM), and weedy (WY).

Table 2. Descriptions of the floor management and amendment treatments tested at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

Treatment	Compost (tons/acre, wet) ⁱ	Nutririch 4–1.3–1.7 (lb/acre) ⁱ	Feathermeal 12–0–0 (lb/acre) ⁱ	Gypsum (lb/acre) ⁱ	Floor management activity
Control	4.5	1500	800	0	Clean-cultivated (depth, 1 to 2 inches) ⁱ
Amendment treatments					
Gypsum	4.5	1500	800	2075	Clean-cultivated (depth, 1 to 2 inches) ⁱ
High compost	78.0	1500	800	0	Clean-cultivated (depth, 1 to 2 inches) ⁱ
High nitrogen	4.5	2400	1280	0	Clean-cultivated (depth, 1 to 2 inches) ⁱ
Low nitrogen	4.5	600	320	0	Clean-cultivated (depth, 1 to 2 inches) ⁱ
Floor management treatments					
Dust mulch	4.5	1500	800	0	Tilled with a rototiller to a depth of 6 to 8 inches after rain events [27 May (15 d after transplanting) and 19 Jun (38 d after transplanting)] ⁱ
Leaf mulch	4.5	1500	800	0	4 inches of semi-composted leaf mulch applied on 27 May (15 d after transplanting); plots were kept clean with hand weeding ⁱ
Weedy	4.5	1500	800	0	Not cultivated

ⁱ 1 ton/acre = 2.2417 t·ha⁻¹; 1 lb/acre = 1.1209 kg·ha⁻¹; 1 inch = 2.54 cm.

& Company, Moline, IL, USA), disk-ing to 7 to 8 inches (Kello-Bilt Model 225; Kello-Bilt Inc, Red Deer County, Alberta, Canada), and power harrowing to 4 to 5 inches (Kuhn HR 3504 D; KUHN Group, Saverne, Bas-Rhin, France). Soil amendments [compost (Pacific Region Compost; Republic Services, Corvallis, OR, USA), granular chicken manure (Nutri-Rich 4–1.3–1.7 Granular Fertilizer; Stutzman Environmental Products, Inc., Canby, OR, USA), nonpelletized feather meal (Pro-Pell-It! Feather Meal 12–0–0; Marion AG Services, Inc., St. Paul, OR, USA), and pelletized gypsum (Pro-Pell-It! Pelletized Gypsum; Marion Ag Service, Inc.)] were applied to the plots on 7 and

8 May (4 to 5 d before transplanting). The HN treatment received fertilizers at a rate of 160 lb/acre nitrogen (N), and the LN treatment received them at a rate of 40 lb/acre N. All other treatments received organic fertilizers at a rate of 100 lb/acre N. The HC treatment received compost at a rate of 73.5 wet tons/acre (36 cubic ft for each plot measuring 420 square-ft), resulting in a total application of 78.0 wet tons/acre. The GY treatment received 2075 lb/acre of gypsum. On 8 May (4 d before transplanting), amendments were incorporated using a rototiller (Howard Rotavator; Howard Rotavator Company Limited, West Horndon, Essex, England) to a depth of 4 to 5 inches.

The implement was lifted between plots to minimize cross-contamination of soil amendments between plots.

On 11 May (1 d before planting), a soil sample was collected for each of the plots to a depth of 6 inches using a soil probe following the protocol of Fery et al. (2014). Soil samples were processed by A&L Western Agricultural Laboratories to determine the soil pH and soil nitrate, phosphorus (P) (weak Bray), potassium (K), calcium (Ca), sulfur (S), and boron (B) concentrations.

The tomato cultivar selected for the experiment was Early Girl (Johnny's Selected Seeds, Winslow, ME, USA) because this is the standard cultivar grown in coastal California (Leap et al.

Table 3. Nutrient and physical compositions of the cover crop, compost, and leaf mulch used in the floor management and amendment treatments at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

	% Nitrogen	% Phosphorus	% Phosphate	% Potassium	% Potash	% Sulfur	% Calcium	Bulk density (g·L ⁻¹) ^{i,ii}	% Moisture	Dry matter applied (ton/acre) ⁱ
Cover crop test ⁱⁱⁱ	3.65	0.38	–	2.47	–	– ^{iv}	– ^{iv}	–	85.7	1.56
Compost test ⁱⁱⁱ	1.69	0.32	0.73	0.94	1.13	0.19	1.95	391	38.8	Compost treatment: 47.72; all other treatments: 2.75
Leaf mulch test ⁱⁱⁱ	1.06	0.15	0.34	0.22	0.27	0.11	2.38	201	49.8	Leaf mulch treatment: 91.10; all other treatments: 0

ⁱ 1 g·L⁻¹ = 119.8264 lb/gallon; 1 ton/acre = 2.2417 t·ha⁻¹.

ⁱⁱ Bulk density reported for dry weight.

ⁱⁱⁱ Nutrient analyses were conducted by A&L Laboratory Western Agricultural Laboratories (Modesto, CA, USA). Nutrient concentrations are reported on a dry weight basis.

^{iv} Percent sulfur and calcium not tested for cover crop.

2017). Seeds were sown into 200-cell flats on 6 Apr (36 d before transplanting) at Eloisa Organic Farm LLC in Albany, OR, USA (lat. 44.6592°N, long. 123.1003°W) and up-potted into 60-cell trays at Avoca Seed Farm in Corvallis, OR, USA, on 23 Apr. The greenhouse at Eloisa Organic Farm LLC was a heated greenhouse with a semi-gabled style; it was 30 ft wide and 110 ft long (GK Machine Inc., Donald, OR, USA). The greenhouse at Avoca Seed Farm was an unheated gothic-style greenhouse (OBC Northwest, Canby, OR, USA). Seedlings were planted on 12 May using a planting tube (Planting Tube 63; Pottiputki, Savonlinna, Finland). Plants were not watered-in after planting and were never irrigated. Plants were not pruned or trellised.

Four inches of semi-composted leaf mulch (local municipal source, 1.5 years old) was applied to the soil surface of the LM plots on 27 May [15 d after transplanting (DAT)]. For the DM treatment, the dust mulch was tilled to a depth of 6 to 8 inches using a rototiller (Tractor Model 718; BCS America, Oregon City, OR, USA) with a rear-tine tiller attachment on 27 May (15 DAT) and 19 Jun (38 DAT), which were both soon after a period of rain. The WY treatment was never cultivated after the fertilizer was tilled-in. All other treatments were clean-cultivated using a wheel hoe (Valley Oak Wheel Hoe Garden Cultivator; Valley Oak Tool Company, Chico, CA, USA).

From planting until 24 Jul (73 DAT), 34 tomato plants (out of a total of 672) were rogued out of the field because they were infected with an unknown virus. This resulted in plots missing between zero and four plants (out of 21 plants) and zero or one data plant (out of 5 data plants). Yield and fruit count data were extrapolated based on the data plot area (100 ft²) instead of on the number of plants.

Soil moisture sensors (WATER-MARK 200SS; Irrometer Company, Inc., Riverside, CA, USA) were installed to a depth of 1 ft (4 Jun; 23 DAT), 2 ft (11 Jun; 30 DAT), 3 ft (19 Jun; 38 DAT), and 4 ft (22 to 23 Jun; 41 to 42 DAT). A single soil moisture sensor was installed between each of the data plants in each plot. These sensors measure electrical resistance in a granular matrix, which is an indirect measurement of soil water tension. The higher the soil water tension is, the less

water that is available (Shock and Wang 2011). Some have considered soil electrical resistivity as an indirect measure of deep root proliferation (Maeght et al. 2013). Starting on 6 Jul (55 DAT), data from these sensors were manually measured each week to determine the soil moisture status using a portable meter (WATERMARK Handheld Meter; Irrometer Company, Inc.). Although data were collected for all sensors each week, only two readings were used for the analysis. The weeks used in the analysis (for a given depth) were the 2 weeks before more than one of the sites reached the maximum reading of 199 cbars. These weeks were the only ones used because these measurements had the largest variance between plots before one of the plots reached the maximum possible reading. These readings were collected on 6 Jul and 13 Jul for the 1-ft sensors (55 and 62 DAT), 20 Jul and 27 Jul for the 2-ft sensors (69 and 76 DAT), 27 Jul and 3 Aug for the 3-ft sensors (76 and 83 DAT), and 3 Aug and 10 Aug for the 4-ft sensors (83 and 90 DAT).

On 20 Jul (69 DAT), all the data plants were measured to determine the height of the tallest shoot and diameter of the plant to the nearest cm. These measurements were used to determine the volume of the plant as a cylinder (m³). The average volume of the plants for each plot was calculated.

Leaf samples were collected for the nutrient analysis on 27 Jul (76 DAT). The newest mature leaf on the tallest shoot was sampled from each data plant for analysis, and leaf samples were combined for each plot and submitted to the Oregon State University Soil Health Laboratory for plant tissue analysis [total N, P, K, Ca, S, and B concentrations (as the % of dry weight)]. The N and S concentrations were determined using dry combustion with an organic elemental analyzer (vario MACRO cube; Elementar Americas Inc., Ronkonkoma, NY, USA). Other leaf nutrients were extracted using hydrochloric acid following a dry ash procedure, and these extractions were analyzed using an optical emission spectrometer (5100 ICP-OES; Aligent, Santa Clara, CA, USA). All nutrients were reported as the percent of dry matter.

The PDLWP was measured using a pressure chamber (model 1505D

pressure chamber instrument; PMS Instrument Company, Albany, OR, USA). Measurements were obtained on 20 Jul (69 DAT), 3 Aug (83 DAT), 17 Aug (97 DAT), 31 Aug (111 DAT), and 14 Sep (125 DAT). Only one measurement was collected for each plot at each measurement date.

Tomatoes were harvested weekly from 27 Jul to 31 Aug (76 DAT–111 DAT). On 7 Sep (118 DAT), harvests were suspended because of wildfire smoke; then, a final harvest was conducted on 21 Sep (132 DAT). During harvests, all red ripe tomatoes were collected from each data plot and counted and weighed. Additionally, the number and weight of unblemished tomatoes and tomatoes with light BER (a gray, speckled blemish on the blossom end of the fruit), necrotic BER (a large, black or gray, sunken spot on the blossom end of the fruit), sunscald, or other issues (e.g., cracking) were recorded (Davis et al. 2024). If a tomato showed multiple blemishes (e.g., both BER and sunscald), then it was counted and weighed along with the other tomatoes for each issue. These data were used to determine total fruit yield (ton/acre), total fruit count (fruit/acre), average fruit weight (lb), unblemished fruit yield (ton/acre), proportion of fruit with BER (fruit with BER/total plot fruit), proportion of fruit with necrotic BER, and proportion of fruit with sunscald.

Three data plants were cut at the base from each plot [block 2 on 28 Sep (139 DAT) and blocks 1, 3, and 4 on 30 Sep (141 DAT)]. Green fruit were removed and plants were oven-dried until they reached a stable weight (106 h) and weighed.

Data analysis

The data analysis was performed using statistical software (R version 4.1.3) (R Core Team 2022; RStudio Team 2018). Floor management treatments and soil amendment treatments were analyzed separately. The analyzed data can be found in Supplemental Table 1.

The effects of treatments on the response variables soil pH and nutrient concentrations, soil water tension, average plant volume, plant dry weight, leaf nutrient concentrations, total yield, total fruit count, average fruit weight, and unblemished fruit yield were analyzed using mixed effects models (Pinheiro et al. 2022). Treatments

Table 4. Effects of amendment and floor management treatments on the estimated marginal means for soil nitrate concentration, soil phosphorus (P) concentration (weak Bray), soil potassium (K) concentration, soil sulfur (S) concentration, soil calcium (Ca) concentration, soil boron (B) concentration, and soil pH at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

Treatment	Soil nitrate (ppm) ⁱ	Soil P (ppm) ⁱ	Soil K (ppm) ⁱ	Soil S (ppm) ⁱ	Soil Ca (ppm) ⁱ	Soil B (ppm) ⁱ	Soil pH
Mean (SE) ⁱⁱ							
Amendment treatments							
Control	52.3 (9.1) BC ⁱⁱⁱ	103.7 (9.4) B	196 (20) B	8.8 (2.2) B	2496 (51) AB	0.20 (0.03) B	6.0 (0.1)
Gypsum	43.8 (9.1) C	95.5 (9.4) B	175 (18) B	90.7 (23.0) A	2663 (51) A	0.20 (0.03) B	6.0 (0.1)
High compost	80.1 (9.1) A	136.6 (9.4) A	385 (39) A	10.9 (2.8) B	2490 (51) AB	0.38 (0.03) A	6.0 (0.1)
High N	68.9 (9.1) AB	100.3 (9.4) B	196 (20) B	14.5 (3.7) B	2477 (51) B	0.20 (0.03) B	6.0 (0.1)
Low N	39.9 (49.1) C	87.2 (9.4) B	169 (17) B	6.3 (1.6) B	2532 (51) AB	0.20 (0.03) B	6.1 (0.1)
F-test ^{iv}	$F_{4,12} = 15.005$, $P < 0.001^{**}$	$F_{4,12} = 7.251$, $P = 0.003^{**}$	$F_{4,12} = 10.942$, $P < 0.001^{**}$	$F_{4,12} = 24.688$, $P < 0.001^{**}$	$F_{4,12} = 3.495$, $P = 0.041^{*}$	$F_{4,12} = 5.444$, $P = 0.010^{**}$	$F_{4,12} = 0.933$, $P = 0.477$
Floor management treatments							
Control	52.3 (9.7)	103.7 (8.6)	196 (10)	8.9 (1.2)	2496 (57)	0.2	6.0 (0.1)
Dust	43.0 (9.7)	86.9 (8.6)	165 (10)	6.7 (1.2)	2584 (57)	0.2	6.2 (0.1)
Leaf	52.2 (9.7)	105.8 (8.6)	195 (10)	9.8 (1.2)	2473 (57)	0.2	6.1 (0.1)
Weedy	48.7 (9.7)	88.6 (8.6)	178 (10)	8.9 (1.2)	2491 (57)	0.2	6.0 (0.1)
F-test ^{iv}	$F_{3,9} = 1.371$, $P = 0.313$	$F_{3,9} = 2.451$, $P = 0.130$	$F_{3,9} = 2.238$, $P = 0.153$	$F_{3,9} = 1.938$, $P = 0.194$	$F_{3,9} = 0.760$, $P = 0.544$	Perfect fit	$F_{3,9} = 1.895$, $P = 0.201$

ⁱ 1 ppm = 1 mg·kg⁻².

ⁱⁱ Values are estimated marginal means with the standard error (SE) in parentheses.

ⁱⁱⁱ Values for treatments not sharing a common letter within row are significantly different (Tukey's honestly significant difference test; $P < 0.05$).

^{iv} Statistical significance of the F-test is indicated in this column. -, *, ** significant at $P < 0.1$, 0.05, and 0.01, respectively.

were included in the models as fixed effects and blocks were included as random effects. Residual plots were examined to ensure that the analysis of variance assumptions were met. Soil K and S concentrations were log-transformed to deal with heterogeneous variations between amendment treatments. Fixed-effects terms were tested using F-tests. Estimated marginal means and standard errors (SEs) for the different treatments were reported, and mean separation was performed using Tukey's honest significant difference (Lenth 2020). Means and SEs were back-transformed for presentation.

The BER, necrotic BER, and sunscald incidence data were proportional and tested using generalized linear mixed effects modeling with a binomial distribution (Bates et al. 2015). Treatments were included in the models as fixed effects and blocks were included as random effects. We detected overdispersion for all of these models; therefore, they were refit using a beta-binomial distribution (Brooks et al. 2017). Models were tested using type III Wald χ^2 tests (Fox and Weisberg 2018). Estimated marginal means and SEs for the different treatments were reported, and mean separation was performed using Tukey's honest significant difference (Lenth 2020). Means and SEs were back-transformed for presentation.

Results

SOIL pH AND NUTRIENT CONCENTRATIONS. Amendment treatments affected the soil nutrient concentrations (Table 4). The HC treatment increased the mean soil nitrate concentration by 53%, increased the mean soil P concentration by 32%, increased the mean soil K concentration by 96%, and increased the mean soil B concentration by 90% when compared with the control. The HN treatment increased the mean soil nitrate concentration by 73% when compared with that of the LN treatment. The GY treatment increased the mean soil S concentration by 931% when compared with that of the control.

SOIL WATER TENSION. Soil water tension is the force necessary for roots to extract water from the soil; the greater the soil water tension, the more force that is necessary (Shock and Wang 2011). Soil water tension can be used as an indirect measure of the rooting depth (Maeght et al. 2013). The HC treatment increased the mean soil water tension by 64% when compared with that of the LN treatment at the depth of 4 ft on 3 Aug (83 DAT), suggesting that the HC treatment was colonizing and depleting water at the depth of 4 ft more rapidly (Table 5). Floor management treatments also affected soil water tension. The LM

treatment decreased the mean soil water tension at the depth of 3 ft on 27 Jul (76 DAT) by 60%, at the depth of 4 ft on 3 Aug (83 DAT) by 73%, and at the depth of 4 ft on 10 Aug (90 DAT) by 47% when compared with that of the control.

PREDAWN LEAF WATER POTENTIAL. The PDLWP is considered to represent the soil water potential adjacent to the roots (Améglio et al. 1999). The more negative the PDLWP, the less water that is available to the roots. Significant differences were not detected in the mean PDLWP on any of the samplings between the different amendment treatments (Table 6). On 20 Jul (69 DAT), the LM treatment decreased the mean PDLWP by 33% when compared with that of the control. The WY treatment decreased the PDLWP by 27% on 20 Jul (69 DAT) and by 44% on 3 Aug (83 DAT) when compared with that of the control. The PDLWP decreased over the course of the experiment; however, it increased between 31 Aug (111 DAT) and 14 Sep (125 DAT), possibly because of decreased evapotranspiration attributable to wildfire smoke.

PLANT SIZE. Plant size was affected by amendment treatment (Table 7). On 20 Jul (69 DAT), the LN treatment had a mean average tomato plant aboveground volume that

Table 5. Effects of amendment and floor management treatments on the estimated marginal means for soil water tension for dry-farmed ‘Early Girl’ tomato at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

Treatment	Soil water tension at 1 ft (cbar) ⁱ		Soil water tension at 2 ft (cbar) ⁱ		Soil water tension at 3 ft (cbar) ⁱ		Soil water tension at 4 ft (cbar) ⁱ	
	6 Jul, 55 DAT ⁱⁱ	13 Jul, 62 DAT ⁱⁱ	20 Jul, 69 DAT ⁱⁱ	27 Jul, 76 DAT ⁱⁱ	27 Jul, 76 DAT ⁱⁱ	3 Aug, 83 DAT ⁱⁱ	3 Aug, 83 DAT ⁱⁱ	10 Aug, 90 DAT ⁱⁱ
Mean (SE) ⁱⁱⁱ								
Amendment treatments								
Control	77 (13)	116 (9)	114 (11)	157 (10)	129 (8)	160 (7)	85 (16) AB	130 (16)
Gypsum	74 (13)	110 (9)	109 (11)	152 (10)	130 (8)	161 (7)	97 (16) AB	135 (16)
High Compost	104 (13)	143 (9)	119 (11)	168 (10)	132 (8)	168 (7)	133 (16) A	170 (16)
High N	65 (13)	120 (9)	83 (11)	133 (10)	102 (8)	138 (7)	66 (16) AB	129 (16)
Low N	86 (13)	136 (9)	92 (11)	130 (10)	120 (8)	144 (7)	48 (16) B	104 (16)
F-test ^{iv}	$F_{4,12} = 1.292$, $P = 0.327$	$F_{4,12} = 2.325$, $P = 0.116$	$F_{4,12} = 2.069$, $P = 0.148$	$F_{4,12} = 3.509$, $P = 0.041^*$	$F_{4,12} = 2.741$, $P = 0.079$	$F_{4,12} = 2.973$, $P = 0.064$	$F_{4,12} = 4.147$, $P = 0.025^*$	$F_{4,12} = 2.380$, $P = 0.110$
Floor management treatments								
Control	77 (14) ab ^v	116 (13)	114 (19)	157 (18)	129 (16) a	160 (15)	85 (10) a	130 (11) a
Dust	80 (14) ab	121 (13)	107 (19)	127 (18)	100 (16) ab	135 (15)	53 (10) ab	113 (11) ab
Leaf	44 (14) b	126 (13)	64 (19)	110 (18)	52 (16) b	106 (15)	23 (10) b	69 (11) b
Weedy	124 (14) a	158 (13)	132 (19)	145 (18)	130 (16) a	165 (15)	84 (10) a	143 (11) a
F-test ^{iv}	$F_{3,9} = 5.906$, $P = 0.016^*$	$F_{3,9} = 2.076$, $P = 0.174$	$F_{3,9} = 2.404$, $P = 0.135$	$F_{3,9} = 1.377$, $P = 0.311$	$F_{3,9} = 9.277$, $P = 0.004^{**}$	$F_{3,9} = 3.905$, $P = 0.049^*$	$F_{3,9} = 8.425$, $P = 0.006^{**}$	$F_{3,9} = 8.997$, $P = 0.005^{**}$

ⁱ 1 cbar = 1 kPa; 1 inch = 2.54 cm.ⁱⁱ Days after transplanting (DAT).ⁱⁱⁱ Values are estimated marginal means with the standard error (SE) in parentheses.^{iv} Statistical significance of the F-test is indicated in this column. *, **, *** significant at $P < 0.1$, 0.05, or 0.01, respectively.^v Values for treatments not sharing a common letter within rows are significantly different (Tukey's honestly significant difference test; $P < 0.05$).

was 31% lower than that of the HC treatment and 28% lower than that of the GY treatment. The HC treatment increased the mean aboveground dry weight of three plants at the end of the season by 34% when compared with

that of the control. The WY treatment decreased the mean average tomato plant aboveground volume on 20 Jul (69 DAT) by 45% and decreased the mean aboveground dry weight of three plants at the end of the season

by 48% when compared with those of the control.

LEAF NUTRIENT CONCENTRATIONS. Amendment and floor management treatments affected leaf nutrient concentrations at 76 DAT (Table 8). Amendment

Table 6. Effects of amendment treatments and floor management treatments on the estimated marginal means for predawn leaf water potential (PDLWP) for dry-farmed ‘Early Girl’ tomato at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

Treatment	PDLWP on 20 Jul (bar) ⁱ 69 DAT ⁱⁱ	PDLWP on 3 Aug (bar) ⁱ 83 DAT ⁱⁱ	PDLWP on 17 Aug (bar) ⁱ 97 DAT ⁱⁱ	PDLWP on 31 Aug (bar) ⁱ 111 DAT ⁱⁱ	PDLWP on 14 Sep (bar) ⁱ 125 DAT ⁱⁱ
Mean (SE) ⁱⁱⁱ					
Amendment treatments					
Control	−2.82 (0.20)	−4.14 (0.30)	−5.29 (0.21)	−5.66 (0.47)	−4.34 (21)
Gypsum	−2.73 (0.20)	−4.06 (0.30)	−4.94 (0.21)	−5.71 (0.47)	−4.07 (21)
High compost	−3.35 (0.20)	−4.98 (0.30)	−5.16 (0.21)	−5.58 (0.47)	−4.14 (21)
High N	−2.91 (0.20)	−4.92 (0.30)	−5.32 (0.21)	−5.23 (0.47)	−4.03 (21)
Low N	−2.86 (0.20)	−4.97 (0.30)	−5.25 (0.21)	−5.15 (0.47)	−3.92 (21)
F-test ^{iv}	$F_{4,12} = 1.594$, $P = 0.239$	$F_{4,12} = 3.461$, $P = 0.042^*$	$F_{4,12} = 0.593$, $P = 0.674$	$F_{4,12} = 0.318$, $P = 0.861$	$F_{4,12} = 0.585$, $P = 0.679$
Floor management treatments					
Control	−2.82 (0.17) a ^v	−4.14 (0.25) a	−5.29 (0.27)	−5.66 (0.42) ab	−4.34 (0.42)
Dust	−2.93 (0.17) ab	−4.43 (0.25) a	−5.11 (0.27)	−4.64 (0.42) a	−3.38 (0.42)
Leaf	−3.76 (0.17) c	−4.64 (0.25) a	−5.14 (0.27)	−5.33 (0.42) ab	−3.50 (0.42)
Weedy	−3.58 (0.17) bc	−5.96 (0.25) b	−5.98 (0.27)	−6.66 (0.42) b	−5.20 (0.42)
F-test ^{iv}	$F_{3,9} = 7.548$, $P = 0.008^{**}$	$F_{3,9} = 10.725$, $P = 0.003^{**}$	$F_{3,9} = 2.268$, $P = 0.150$	$F_{3,9} = 4.015$, $P = 0.046^*$	$F_{3,9} = 3.993$, $P = 0.046^*$

ⁱ 1 bar = 100 kPa.ⁱⁱ Days after transplanting (DAT).ⁱⁱⁱ Values are estimated marginal means with standard error (SE) in parentheses.^{iv} Statistical significance of the F-test is indicated in this column. *, **, *** significant at $P < 0.1$, 0.05, or 0.01, respectively.^v Values for treatments not sharing a common letter within row are significantly different (Tukey's honestly significant difference; $P < 0.05$).

Table 7. Effects of amendment treatments and floor management treatments on the estimated marginal means for average tomato plant aboveground volume and aboveground dry weight of three plants for dry-farmed ‘Early Girl’ tomato at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

Treatment	Avg tomato plant aboveground volume on 20 Jul 2020 (m ³ /plant) ^{i,ii} 69 DAT ⁱⁱⁱ	Aboveground dry wt of three plants at end of season (lb) ⁱ 139 to 141 DAT ⁱⁱⁱ
Mean (SE) ^{iv}		
Amendment treatments		
Control	1.24 (0.08) AB ^v	5.87 (0.42) B
Gypsum	1.37 (0.08) A	6.08 (0.42) AB
High compost	1.42 (0.08) A	7.84 (0.42) A
High N	1.23 (0.08) AB	5.79 (0.42) B
Low N	0.98 (0.08) B	5.89 (0.42) B
F-test ^{vi}	$F_{4,12} = 5.231, P = 0.011^*$	$F_{4,12} = 4.861, P = 0.015^*$
Floor management treatments		
Control	1.24 (0.07) ab	5.87 (0.39) a
Dust mulch	1.08 (0.07) b	5.93 (0.39) a
Leaf mulch	1.44 (0.07) a	7.08 (0.39) a
Weedy	0.68 (0.07) c	3.05 (0.39) b
F-test ^{vi}	$F_{3,9} = 20.448, P < 0.001^{**}$	$F_{3,9} = 36.521, P < 0.001^{**}$

ⁱ 1 m³ = 35.3147 ft³; 1 lb = 0.4536 kg.

ⁱⁱ All of the data plants were measured for height of the tallest shoot and diameter of the plant to the nearest cm. These measurements were used to determine the volume of the plant as a cylinder, and the average volume of the plants for each plot was calculated.

ⁱⁱⁱ Days after transplanting (DAT).

^{iv} Values are estimated marginal means with standard error (SE) in parentheses.

^v Values for treatments not sharing a common letter within row are significantly different (Tukey’s honestly significant difference; $P < 0.05$).

^{vi} Statistical significance of the F-test is indicated in this column. *, **, significant at $P < 0.1, 0.05$, or 0.01 , respectively.

treatments differed in their leaf K concentrations, with HC having a higher mean leaf K concentration than LN (44%). Floor management treatments also influenced leaf nutrient concentrations. The DM treatment increased the mean

leaf B concentration by 26% when compared with that of the control.

HARVEST DATA. There were no significant differences in mean total yield, mean unblemished yield, or mean total fruit count between the different

amendment treatments (Table 9). The HC treatment decreased the mean average fruit weight by 15%, increased the mean BER incidence by 39%, and increased the mean necrotic BER incidence by 67% when compared with those of the control. The LN treatment resulted in a lower mean BER incidence when compared with that of the HN treatment (23% lower). The mean sunscald incidence was unaffected by the amendment treatment.

The WY treatment decreased the mean total yield by 65%, decreased the mean unblemished yield by 88%, decreased the mean total fruit count by 53%, decreased the mean average fruit weight by 25%, increased the mean BER incidence by 53%, and increased the mean necrotic BER incidence by 82% when compared with those of the control. The LM treatment decreased the mean average fruit weight by 30%, increased the mean BER incidence by 34%, and increased the mean necrotic BER incidence by 88% when compared with those of the control. There was no effect of floor management treatment on mean sunscald incidence.

Discussion

EFFECTS OF FLOOR MANAGEMENT TREATMENTS. These results indicate that floor management affects dry-farmed tomato production. No treatment

Table 8. Effects of amendment treatments and floor management treatments on the estimated marginal means for leaf nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and boron (B) concentrations on 27 Jul 2020 (76 d after transplant) for dry-farmed ‘Early Girl’ tomato at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA).

Treatment	Leaf N (%DW)	Leaf P (%DW)	Leaf K (%DW)	Leaf S (%DW)	Leaf Ca (%DW)	Leaf B (ppm) ⁱ
Mean (SE) ⁱⁱ						
Amendment treatments						
Control	2.7 (0.3)	0.28 (0.03)	2.4 (0.3) AB ⁱⁱⁱ	0.26 (0.03)	2.7 (0.2)	26.7 (2.8)
Gypsum	2.9 (0.3)	0.25 (0.03)	2.1 (0.3) AB	0.27 (0.03)	3.0 (0.2)	29.9 (2.8)
High compost	3.4 (0.3)	0.28 (0.03)	2.6 (0.3) A	0.27 (0.03)	2.8 (0.2)	24.6 (2.8)
High N	2.9 (0.3)	0.26 (0.03)	2.1 (0.3) AB	0.28 (0.03)	3.3 (0.2)	29.9 (2.8)
Low N	2.9 (0.3)	0.30 (0.03)	1.8 (0.3) B	0.31 (0.03)	3.3 (0.2)	34.8 (2.8)
F-test ^{iv}	$F_{4,12} = 1.477,$ $P = 0.270$	$F_{4,12} = 2.400,$ $P = 0.108$	$F_{4,12} = 3.492,$ $P = 0.041^*$	$F_{4,12} = 0.702,$ $P = 0.606$	$F_{4,12} = 2.887,$ $P = 0.069$	$F_{4,12} = 2.628,$ $P = 0.087$
Floor management treatments						
Control	2.7 (0.2) ab	0.28 (0.03) ab	2.4 (0.3) ab	0.26 (0.02)	2.7 (0.2)	26.7 (2.8) b
Dust	3.2 (0.2) a	0.29 (0.03) a	2.3 (0.3) ab	0.24 (0.02)	2.9 (0.2)	33.6 (2.8) a
Leaf	3.3 (0.2) a	0.25 (0.03) ab	2.7 (0.3) a	0.23 (0.02)	3.0 (0.2)	23.6 (2.8) b
Weedy	1.9 (0.2) b	0.22 (0.03) b	1.7 (0.3) b	0.25 (0.02)	3.4 (0.2)	25.5 (2.8) b
F-test ^{iv}	$F_{3,9} = 10.060,$ $P = 0.003^{**}$	$F_{3,9} = 4.782,$ $P = 0.029^*$	$F_{3,9} = 5.759,$ $P = 0.018^*$	$F_{3,9} = 0.750,$ $P = 0.549$	$F_{3,9} = 3.084,$ $P = 0.083$	$F_{3,9} = 9.244,$ $P = 0.004^{**}$

ⁱ 1 ppm = 1 mg·kg⁻¹.

ⁱⁱ Values are estimated marginal means with standard error (SE) in parentheses.

ⁱⁱⁱ Values for treatments not sharing a common letter within row are significantly different (Tukey’s honestly significant difference; $P < 0.05$).

^{iv} Statistical significance of the F-test is indicated in this column. *, **, significant at $P < 0.1, 0.05$, or 0.01 , respectively.

DW = dry weight.

Table 9. Effects of amendment treatments and floor management treatments on the estimated marginal means for yield, fruit count, fruit weight, blossom-end rot (BER) incidence, and sunscald incidence for dry-farmed ‘Early Girl’ tomato at the Oregon State University Vegetable Research Farm (Corvallis, OR, USA) in 2020.

Treatment	Total yield (ton/acre) ^{i,ii}	Unblemished yield (ton/acre) ^{i,ii}	Total fruit count (fruit/acre) ^{i,ii}	Avg fruit wt (lb/fruit) ⁱ	BER incidence (proportion)	Necrotic BER incidence (proportion)	Sunscald incidence (proportion)
Mean (SE) ⁱⁱ							
Amendment treatments							
Control	25.5 (2.1)	11.7 (1.7)	253,000 (24,000)	0.20 (0.01) A ^{iv}	0.533 (0.043) BC	0.172 (0.024) B	0.054 (0.011)
Gypsum	29.0 (2.1)	10.9 (1.7)	311,000 (24,000)	0.19 (0.01) AB	0.596 (0.042) B	0.185 (0.024) B	0.059 (0.011)
High compost	26.6 (2.1)	6.9 (1.7)	310,000 (24,000)	0.17 (0.01) B	0.741 (0.035) A	0.287 (0.031) A	0.061 (0.011)
High N	25.7 (2.1)	8.6 (1.7)	284,000 (24,000)	0.18 (0.01) AB	0.621 (0.041) B	0.221 (0.027) AB	0.064 (0.012)
Low N	27.9 (2.1)	12.9 (1.7)	280,000 (24,000)	0.20 (0.01) A	0.475 (0.043) C	0.161 (0.023) B	0.064 (0.012)
Statistical test ^v	$F_{4,12} = 0.505$, $P = 0.733$	$F_{4,12} = 3.253$, $P = 0.050$	$F_{4,12} = 1.004$, $P = 0.443$	$F_{4,12} = 4.980$, $P = 0.013^*$	$\chi^2_{df=4} = 42.99$, $P < 0.001^{**}$	$\chi^2_{df=4} = 30.37$, $P < 0.001^{**}$	$\chi^2_{df=4} = 1.29$, $P = 0.863$
Floor management treatments							
Control	25.5 (1.8) a	11.7 (1.8) a	253,000 (18,000) a	0.20 (0.01) a	0.533 (0.057) b	0.173 (0.026) b	0.057 (0.010)
Dust	26.7 (1.8) a	11.2 (1.8) a	278,000 (18,000) a	0.19 (0.1) a	0.562 (0.056) b	0.201 (0.028) b	0.063 (0.010)
Leaf	23.5 (1.8) a	6.5 (1.8) ab	326,000 (18,000) a	0.14 (0.1) b	0.715 (0.048) a	0.325 (0.034) a	0.054 (0.009)
Weedy	9.0 (1.8) b	1.4 (1.8) b	120,000 (18,000) b	0.15 (0.1) b	0.813 (0.039) a	0.314 (0.036) a	0.040 (0.009)
Statistical test ^v	$F_{3,9} = 21.155$, $P < 0.001^{**}$	$F_{3,9} = 11.297$, $P = 0.002^{**}$	$F_{3,9} = 24.390$, $P < 0.001^{**}$	$F_{3,9} = 23.207$, $P < 0.001^{**}$	$\chi^2_{df=3} = 51.19$, $P < 0.001^{**}$	$\chi^2_{df=3} = 24.93$, $P < 0.001^{**}$	$\chi^2_{df=3} = 3.76$, $P = 0.288$

ⁱ 1 ton/acre = 2.2417 Mg·ha⁻¹; 1 fruit/acre = 2.4711 fruit/ha; 1 lb = 0.4536 kg.

ⁱⁱ Per-acre yields were extrapolated from the data of a 100 ft² plot (not shown).

ⁱⁱⁱ Values are estimated marginal means with the standard error (SE) in parentheses.

^{iv} Values for treatments not sharing a common letter within row are significantly different (Tukey’s honestly significant difference; $P < 0.05$).

^v Statistical significance of the F-test and χ^2 test is indicated in this column. *, **, ** significant at $P < 0.1$, 0.05, or 0.01, respectively.

improved the clean-cultivated control, but two treatments (LM and WY) performed much worse than the control, with low yields and high incidences of BER (Table 9).

This experiment showed that producing a dust mulch to a depth of 6 to 8 inches using a rototiller did not affect total productivity, BER incidence, soil water tension, or PDLWP for dry-farmed ‘Early Girl’ tomato when compared with a control cultivated to a depth of 1 to 2 inches using wheel hoes (Tables 5, 6, and 9). Historically, dust mulching has been used as a floor management strategy for preserving soil moisture in dry-farmed vegetable production (Garrett 2019) and has been recommended by recent publications (Leap et al. 2017). For dry-farmed tomato, it is recommended that the dust mulch should be established before planting and then every 2 to 3 weeks using shallow mechanical tillage until the crop is too large to cultivate effectively (Leap et al. 2017). Although dryland farmers historically used dust mulching, it has been largely abandoned because of its environmental impacts, including wind erosion and reduced soil organic matter (Stewart and Thapa 2016). Additionally, dust mulching results in greater losses of soil moisture when compared with no-till management systems, with evaporation of soil moisture occurring to the depth of tillage (Greb et al. 1979;

Stewart and Thapa 2016). Although we expected that dust mulching would result in a poorer performance for this reason, our results did not show a difference in the loss of soil moisture between the DM and control treatments (Table 5). This may have been the result of the depth of the sensors, with the shallowest sensor planted at a depth of 1 ft, which was below the depth of tillage. Alternatively, shallow cultivation in the control may have been sufficient to disrupt soil capillaries or insulate the vaporization plane (Rao and Rekapalli 2020). Further research is needed. Soil texture and climate are two factors that may determine the effectiveness of dust mulching for dry-farmed tomato production.

Dust mulching did influence leaf B concentrations (Table 8). It is possible that the additional tillage aerated the soil and damaged tomato roots at the soil surface, and that this changed the nutrient availability and plant growth. The LN treatment also had higher leaf B concentrations and was similar to the DM treatment in terms of the average tomato plant aboveground volume (Table 7). Therefore, the B in the DM treatment may have a higher concentration in the leaves because the plants were smaller and other nutrients were less available. Alternatively, B availability is related to the breakdown of organic matter in the soil, and additional tillage may have

assisted in making B more available to the crop (Marzadori et al. 1991).

Although dust mulching may not be necessary for dry-farmed tomato production, the results clearly indicate that controlling weeds is one of the most consequential floor management decisions that a dry farmer can make to improve yields and fruit quality and reduce drought stress for tomato. We found that controlling weeds, whether through clean cultivation with a wheel hoe or by dust mulching with a rototiller improved several outcomes for dry-farmed tomato, including increased yield, improved fruit quality, lower soil water tension, higher PDLWP, higher leaf nutrient concentrations, and larger plant size (Tables 5–9). Weeds compete with the crop for moisture and nutrients, and dry-farmed tomato trials in southern Italy have shown that the relative effect of weeds on yield losses is greater under unirrigated conditions when compared with full irrigation (Valerio et al. 2013). Alternative cultivation tools that are also recommended include sweeps, side knives, and shallow furrow chisels (Leap et al. 2017).

The leaf mulch reduced water use and increased early season plant growth, but it also resulted in the increased BER incidence and decreased average fruit weight (Table 9). The leaf mulch potentially increased the BER incidence by promoting luxurious growth, making the fruit more susceptible to BER

(Saure 2014). Saure (2014) hypothesized that an excessive N supply (and other factors) can result in vigorous growth and high levels of bioactive gibberellins, and that these bioactive gibberellins can make the fruit more susceptible to BER. The increase in growth observed in the LM treatment may have been caused by an increase in soil moisture or soil nutrient availability caused by the leaf mulch (Schonbeck and Evanylo 1998; Youssef et al. 2021). Roots were observed growing in the leaf mulch (personal observation) and may have absorbed additional nutrients (Table 3) and moisture from the leaf mulch. Additionally, by reducing evaporation at the soil surface, soil nutrients held there would be available for longer than those in other treatments. Mulches with lower nutrient concentrations, like wood chips and plastic mulch, may be more appropriate for dry-farmed tomato production. In addition, leaf mulches may be appropriate for other crops that are less susceptible to physiological disorders such as BER or in regions more suited to dry-farmed tomato production, like coastal California.

The LM treatment reduced soil water tension at depths of 3 ft and 4 ft (Table 5). Slower rooting to 3 ft and 4 ft may have resulted from increased rooting at the surface, including within the leaf mulch itself. However, this reduction in soil water tension did not result in an increase in PDLWP; instead, the LM treatment had a lower PDLWP on 20 Jul (69 DAT) than that of the control and DM treatments and did not differ from them in terms of the other measurements (Table 6). It is possible that increased aboveground biomass made LM more susceptible to drought stress because large plants have a greater water requirement (Hagiwara et al. 2012).

EFFECTS OF AMENDMENT TREATMENTS. Although none of the amendment management treatments improved the control, HC performed significantly worse than the control, with the lowest unblemished yield, smallest fruit, and highest BER incidence of any of the amendment treatments (Table 9). Additionally, increasing applications of organic fertilizers resulted in increased BER incidence.

Although some authors have shown that compost increases soil water holding capacity (Brown and Cotton 2011; Hernando et al. 1989), we clearly

showed that a large compost application can have deleterious effects on dry-farmed tomato production in the Willamette Valley of Oregon, USA. During this experiment, HC resulted in large plants that set many fruit; however, these fruit were small and had a high incidence of BER. This result was similar to that of LM and can also be explained by luxurious growth, as hypothesized by Saure (2014). Additionally, there was evidence that HC used water more quickly than LN (Table 5). Leap et al. (2017) recommended compost for dry-farmed tomato production, although they did not provide a recommended compost application rate; however, they also recommended that compost should be applied in the fall. This may allow some nutrients to leach into the subsoil over the winter. Additionally, larger applications of soil amendments may be more appropriate in coastal California because the cooler, more humid climate in coastal California may result in lower rates of BER (Davis et al. 2023).

We hypothesized that an application of gypsum would control BER in dry-farmed tomato by increasing soil calcium concentrations. However, GY had no effect on dry-farmed tomato production compared with the control. This may be, in part, an effect of the timing of application. We applied the amendments at the start of the growing season; therefore, these nutrients may have remained near the soil surface, whereas dry conditions at the soil surface early in the season made them less available for the crop. Perhaps applying the fertilizer in the fall, before the growing season, will allow some soil nutrients to leach deeper into the soil profile, thus making them available throughout the growing season, as predicted by Leap et al. (2017). However, another study found that gypsum did not affect BER in irrigated tomato, further supporting our results (Taylor et al. 2004).

Increasing organic fertilizer applications resulted in an increased BER incidence (Table 9). The fertilizers used included composted chicken manure and feather meal. Although these treatments are referred to as HN and LN, N was not the only nutrient that increased with increasing fertilizer applications. Increases in fertilizer applications have been shown to increase the BER incidence, especially under

conditions of water deficit (Hagassou et al. 2019; Taylor and Locascio 2004). Future research should seek to determine an optimal soil fertility program for dry-farmed tomato production, although this will probably be site-dependent. Testing multiple fertilizer rates at multiple sites will be required. Additionally, sufficient soil K may be crucial for controlling yellow shoulders (Hartz et al. 1999), which is another physiological disorder associated with dry-farmed tomato (Stone et al. in press). Yellow shoulder is a ripening disorder that can blemish fruit, thus making them unmarketable. Yellow shoulder data were not collected during this study; however, it should be included in future studies of amendments in dry-farmed tomato.

YIELD AND AVERAGE FRUIT WEIGHT. The total yields for the highest-performing treatments in this study were relatively high, ranging from 9.0 tons/acre for WY to 29.0 tons/acre for GY (Table 9). In contrast, Davis et al. (2023) found a mean total tomato yield of 14.1 tons/acre across 13 sites in 2019. The high yields at the Oregon State Vegetable Research Farm may be the result of the high available water holding capacity of the soil. A schematic of the relationship between total available water (available water holding capacity and in-season rainfall) and dry-farmed tomato yield for the Willamette Valley in Oregon has been developed, and our data are within the estimated water-limited yield potential presented there (Davis et al. 2023).

Average fruit weights in this study were lower than the range of 1/4 to 3/8 lb reported by the seed company (Johnny's Selected Seeds). Consumers and farmers may prefer smaller tomatoes produced by dry farming because the total soluble solids is inversely proportional to the fruit weight (Beckles 2012). However, we found that treatments that resulted in smaller, potentially sweeter fruits also resulted in an increased incidence of BER (Table 9).

BER INCIDENCE IN DRY-FARMED TOMATO. The mean BER incidence in the experiment ranged from 48% (LN) to 81% (WY), which is high compared with the 10% to 20% recorded by Leap et al. (2017) and the mean of 38% recorded in 2019 by Davis et al. (2023). An increased BER incidence is likely the result of differences in climate. An

increased vapor pressure deficit increases BER for tomato (Bertin et al. 2000; Leonardi et al. 2000). Coastal California has a lower average maximum daily vapor pressure deficit during the summer than that of the Willamette Valley (Davis et al. 2023). Additionally, the trial site was exposed to wind, which results in increased evapotranspiration and potentially increased drought stress and BER incidence. It is possible that treatment effects would differ under different climatic, weather, and microclimatic conditions, with the increase in BER under HC, HN, LM, and WY being diminished.

In tomato crops, BER is a physiological disorder that results in major losses, especially when tomato is dry-farmed (Bouquet 1922; Davis et al. 2023; Leap et al. 2017). Therefore, controlling BER is a key interest of dry farmers. In the case of this experiment, two factors seemed to relate to BER. The first factor was increased plant growth, which occurred in HC and LM. In addition, increasing soil fertilizer application from 40 lb/acre to 160 lb/acre increased BER. The other factor that may have induced BER was drought stress, as measured by PDLWP, and PDLWP was lowest in WY. If BER is caused by rapid growth followed by abiotic stress, then it would be expected that factors that result in either rapid early season growth (e.g., compost, organic fertilizer, or leaf mulch) or drought stress (e.g., weeds) would increase BER (Saure 2001, 2014). Alternatively, if calcium deficiency in the fruit results in BER, then increasing soil cation concentrations could result in reduced calcium uptake (e.g., compost, organic fertilizer, and leaf mulch), whereas weeds in WY competed with the crop for moisture required to transport calcium (Ho and White 2005; Taylor and Locascio 2004). However, increasing soil calcium through the application of gypsum did not decrease BER. In addition, WY had both the highest leaf calcium concentration at 69 DAT (although not statistically different from the control) (Table 8) and the highest BER incidence of the experiment (Table 9). Although this study did not intend to definitively prove the direct causes of BER in dry-farmed tomato, skepticism of the significance of calcium is warranted.

Conclusions

Our results highlight practices that support dry farming in the Willamette Valley of Oregon. Increasing compost and organic fertilizer application rates and leaf mulching can result in an increased BER incidence for dry-farmed tomato. Although soil amendments may increase the BER incidence for dry-farmed tomato, additional research is needed to determine the optimum amount of fertilizer to apply to maximize marketable yields. The optimal amount of fertilizer is likely dependent on site factors like soil fertility, available water holding capacity, climate, and microclimate. In addition, fertilizer applications could affect other physiological disorders of tomato, like yellow shoulders. Producing a dust mulch by cultivating with a rototiller does not appear to improve dry-farmed tomato production when compared with a clean-cultivated control. However, controlling weeds is critical to improving yield and fruit quality. Although leaf mulching may be inappropriate for dry-farmed tomato production, other mulches with lower nutrient concentrations, including plastic mulch, straw, and wood chips, may improve outcomes. Crops that are not as susceptible to physiological disorders may perform well with leaf mulch, and leaf mulches may be more appropriate in regions with lower vapor pressure deficit or on sites with lower soil available water holding capacity. Dry farmers can use floor management and amendment treatments to affect the growth, water use, yield, and fruit quality of their dry-farmed tomato crop.

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