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Agua Gorda Farm Cooperative

Jarl's Produce

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Chile Pepper Variety Evaluation at Four Sites across Minnesota and Wisconsin, 2020

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Latinx fresh market vegetable farmers in Minnesota face numerous barriers to market access. Many Latinx farmers live in rural communities where farmers market sales are low, and opportunities for wholesale are limited. The growers who make up Shared Ground Farmers' Cooperative have developed an innovative cooperative marketing system to aggregate produce and sell it in Twin Cities markets, but many of the individual farmers involved also wish to find ways to keep the produce they grow in their own communities. This project emerged through a series of discussions about finding niche markets for culturally relevant crops in small-town Mexican restaurants and grocery stores, and creating value-added products. The Shared Ground growers sought out a collaboration with the University of Minnesota to explore the viability of chile pepper production in Minnesota and Wisconsin. This paper reports on 24 chile pepper varieties, trialed at 4 sites across Minnesota and Wisconsin. In addition to yield, we report early-stage results from dehydration tests and Scoville heat unit testing.

Materials and Methods

The trial was conducted at four sites: the University of Minnesota Southern Research and Outreach Center (SROC) in Waseca, and at three partner farms. All transplants for the trial were started the first week of April at the West Central Research and Outreach Center in Morris Minnesota using Premier® PRO-MIX® MP Organik Mycorrhizae Multi-Purpose Grower Mix with 12 lbs. per cubic yard of 4-6-4 SUSTANE fertilizer and ¼ lb. per cubic yard of Nature's Source® Plant Biotik. Transplanting occurred on 20 May (Waseca), 27 May (Turtle Lake), and 28 May (Morris and Long Prairie).

At all four sites, the trial was set up as a randomized complete block design with four replications. At Agua Gorda Farm, habaneros and poblanos were grown in unheated high tunnels in their own randomized block designs, and the serranos and jalapeños were grown outdoors and combined in one randomized block design. Chile pepper entries were assigned to plots 5 (SROC) or 6 feet wide × 10–15 feet long, depending on the site. Plants were transplanted by hand into two rows per plot (1.5 ft spacing between rows) with ~16 inches between plants. Spacing details and site-specific soil and fertilizer information is included in Table 1. Growers made their own nutrient management decisions, and so fertilization rates vary considerably between sites. At all sites, drip irrigation was applied as needed. Weeds were managed manually at all sites, and no insecticides or fungicides were needed. Black plastic mulch was used at all sites. Plants were staked in Waseca, but not at the on-farm sites. All flowers were removed in Waseca until 20 June.

At the time of transplanting, three to five plants per plot were marked, either using string or spray paint on the plastic mulch. Three pepper harvests took place at each site, except 4 at Agua Gorda. There was a single harvest of red peppers at SROC, from plants that had no green fruits previously harvested. Harvest dates were set based on pepper maturity. At each of the harvest dates, all ripe fruit from the marked plants were harvested, counted, and weighed, and any unmarketable fruit was noted. This yield data was used to determine earliness, ripening uniformity, and marketable yield (number of fruit as well as fresh weight). At the first (Cala and Jarl's) or each harvest (Agua Gorda and SROC), 5 randomly-selected fruits were measured for width at the widest point and length to determine fruit shape.

Earliness was measured as the number of days from transplant to when at least 3 of the 4 replicates were harvested within a location (Agua Gorda, Cala, Jarl's, or SROC). Ripening uniformity was calculated by subtracting the yield from lowest-yielding day from the yield on the highest-yielding day, and dividing that difference by the total yield from each plot. For example, harvesting 3, 1.5, and 2 pounds on three separate days, for 6.5 pounds total, resulted in 46% uniformity [(3-1.5)/6.5 = 46%].

At the Waseca location, a ChilliPot device was used for rapid assessment of Scoville heat units in fruits from a subsample of plots. The device uses cyclic voltammetry and redox reactions involving capsaicin, the molecule most responsible for chile pepper heat. Typical HPLC solvents are avoided with this method, and the extraction and analysis is far more rapid. A ChilliPot, proprietary buffer, and disposable "chilli sensors" were purchased from Zimmer and Peacock Ltd (Royston, UK). We cut the caps off (and for poblanos, removed the large septum), weighed, and homogenized 80–200 g from at least 3 peppers or half-peppers with 10% v/w distilled water using a commercial bullet-style blender for 10 to 30 seconds. One part (v/w) ChilliPot buffer was added to ~2 g weighed homogenate in a small test tube. This was inverted multiple times to mix, and rested for 10 minutes. A subsample (100–300 μl) of this mixture was taken using a pipette with the tip cut off to avoid blockage from particulates, and diluted with 2 (poblano, guajillo) or 9 (other peppers) parts (v/v) ChilliPot buffer. This was vortexted briefly and measured directly (without regard for particulates in the mixture) on the ChilliPot using the FoodSense app on an iPod Touch™ according to manufacturer instructions. The resulting measurement was multiplied by (1.1×2) to account for the fruit and homogenate dilution, resulting in Scoville heat units (SHU) of the chiles themselves (the app accounts for the final dilution). To determine correspondence of the ChilliPot results with standard HPLC results, 11 samples of chiles were harvested on a single day; we used 5 red fruit and 6 green fruit samples from multiple plants of 7 different varieties. Samples were processed as described above. A sub-sample of the blended homogenate was frozen and sent to Southwest Bio-Labs (Las Cruces, NM) for HPLC analysis. The same homogenate was also diluted with ChilliPot buffer 3 separate times and analyzed using the ChilliPot as described.

Finally, chile pepper flavor was assessed for a subset of the varieties by two Mexican restaurant owners and their staff in Morris and Waseca, MN.

The number of fruits per plant and pounds of fruit per plant were analyzed using analysis of variance, with variety and replicate as fixed effects. This was done separately for each growing location. Within the SROC location, separate ANOVAs were performed for green and red fruits. Within Agua Gorda, jalapeños and serranos were analyzed together, and habaneros and poblanos were analyzed independently because these types were grown in different locations. Responses were transformed as needed to meet ANOVA assumptions. Per-plant yields are reported graphically as the back-transformed marginal means ± 95% confidence interval. Within each growing location, post-hoc contrasts were used to determine differences in yield within each pepper type. Contrast p-values were Holm-adjusted (n = 9, 6, and 3 contrasts at Agua Gorda, n = 13 at Cala, n = 2 at Jarls, n = 10 for green fruits at SROC, and n = 11 for red fruits at SROC). The only peppers to be grown in all locations were Early Jalapeño, PS11435807, and Serrano Chili. Per-plant and per-area yield comparisons of these varieties between paired locations (n = 6 tests between locations), and yield comparisons between paired varieties (n = 3 tests between varieties), were made using Holm-adjusted Mann-Whitney U tests.

Results and Discussion

At all sites except Agua Gorda in Long Prairie, MN, the season was warmer than usual for the duration of the study (Figure 1; Table 2). In Morris (Jarl's), growing degree day accumulation was as high as 250 GDD above the 30-year average in August. Precipitation was slightly above average at SROC (Waseca) and Cala (Turtle Lake), approximately average at Agua Gorda (Long Prairie), and slightly below average at Jarl's (Morris; Figure 2).

Of the three varieties grown across all locations (jalapeño PS11435807, Early Jalapeño, and Serrano Chili), PS11435807 had the most pounds per plant and per area, thanks in part to its larger fruit size (Figures 3 & 5). There was substantial variability between sites; SROC and Jarl's Produce (Waseca and Morris) consistently had significantly higher yields for all three varieties tested at each site, followed by Agua Gorda (Long Prairie). Cala had significantly lower yields than all other sites for all three varieties tested at all sites (Figure 4). The Cala farm trial had far less nitrogen than is recommended, and the plants experienced significant transplant shock. The higher yields at SROC and Jarl's could be partially attributed to more accumulated degree days at these sites compared to the others (Table 2).

Here, and in Figures 6–12, we report per-plant yield of each variety separately for each type of pepper. In addition, we have presented yield per 1000-ft row and yield per acre (Table 4). Per-ft and -acre mean separations are not reported directly in Table 4, but are the same as in Figures 6–12.

Jalapeños

Of the five tested jalapeño varieties, El Jefe, PS11435807, and Cinder yielded more pounds of fruit than the other tested varieties at all locations, though PS11435807 yield was not significantly greater at SROC (Figure 6). PS11435807 was slightly earlier than El Jefe, with yields spread fairly evenly across harvests (Table 3). At the SROC, Cinder ripened a few days earlier than PS11435807 (Table 3). El Jefe and Cinder produced more, smaller fruit, whereas PS11435807 produced fewer, larger fruit, resulting in similar yields in terms of fresh weight

(Figures 5 & 6). Farmers appreciated the larger size of PS11435807, saying that their customers preferred larger jalapeños for stuffing purposes. Spicy Slice (only grown at SROC) produced fruits similar in length to PS11435807, but narrower. Red jalapeños, only harvested at SROC, were longer and wider compared to their green counterparts (Figure 5), and were slightly more likely to experience blossom end rot (4.5% of all harvested red fruit). There was only a single harvest of red fruit at SROC. Cinder yielded more from the single harvest (Figure 10), but PS11435807 or Spicy Slice may have benefited more from multiple harvests; only 37% or 24% of marketable fruits from these varieties were red at harvest, compared to 44% of Cinder (Table 3). A restaurant in Waseca appreciated the unique sweetness of red-ripe jalapeños. At the on-farm locations, jalapeños that were allowed to mature to red were far more likely to experience blossom end rot, so the growers chose to harvest them all green.

Serranos

Serrano Altiplano and Hot Rod yielded more than Serrano Chili, though the difference was only significant in two of the three sites where these varieties were grown (Figure 7). Serrano Altiplano was preferred by all three grower co-ops for its size, color, and shape. Growers noted that this variety represented the archetypal altiplano that Mexican grocers, restaurants, and farmers market shoppers look for. Hot Rod was considered to be a suitable alternative worth planting again, and had similar yields and earliness. Serrano Chili was considered by the farmer-collaborators to be too small to be practical for harvest and use, and they noted that their customers lacked interest in this variety. The variability in fruit size for this open-pollinated variety (Figure 5) suggests that it may be possible to save seed from larger-fruited plants to increase average fruit size over time. Sureño yields were favorable at the only location they were grown (SROC; Figure 7), but they were smaller in size than Altiplano and Hot Rod from other locations (Figure 5). Serrano Chili also matured later than other varieties at 3 of the 4 locations, with more uniform maturity (Table 3).

Poblanos / Anchos

Poblanos were only trialed at Agua Gorda and SROC. In both locations, local restaurants had expressed interest in purchasing poblano peppers for stuffing. The poblanos were grown in a high tunnel at Agua Gorda. Among the peppers harvested green (the most common way to market poblanos), there was no difference in mass yield at Agua Gorda, and the larger-fruited Vencedor out-produced Ancho 101 at SROC (Figure 8). There was comparable earliness and ripening uniformity, though Ancho 101 was later to mature in Waseca (Table 3). All four varieties produced approximately the same number of fruit (Figure 8). The farmer-collaborator preferred Baron; it had the most standard color and form, and best fit the expectations of customers. The growers also noted that the Ancho Poblano variety was worth trialing again; while slightly lower yielding, it matched their expectations as well as their customers' expectations of how a Poblano pepper should look. Generally, the hybrids Baron, Sargento, and Vencedor were longer than the other poblanos, and might be more suited for stuffing than Ancho 101 (Figure 5). At SROC, some plants were allowed to ripen to red for harvest, as dried red poblanos (anchos) are a very common dried pepper. Due to fruit disease symptoms, 35% of red Ancho 101, 29% of red Sargento, and 47% of red Vencedor were unmarketable. Red Ancho 101 yield was slightly higher than red Sargento or Vencedor because of increased marketability. Yield of red anchos at SROC in 2020 were higher than reported in a 2018 Michigan State study (Phillips, 2018a)

Habaneros

Habaneros were only trialed at two farms. At Agua Gorda they were grown in a high tunnel, and at Cala Farm they were grown in the field. At both farms, Helios was earlier and had higher average yield than Magnum or 598G. Habanero Orange was only trialed at Cala, but was comparable to Helios in terms of both earliness and yield. By growing in a high tunnel environment, the yield nearly doubled at Agua Gorda, and the peppers matured up to 40 days earlier. The farmer-collaborators expressed interest in habaneros for use in value-added products such as chile flakes and salsas.

Guajillos

The farmer-collaborators were not interested in guajillo peppers; they considered guajillos to be similar enough to serranos and jalapeños, and preferred to grow the other varieties. However, a prospective collaborator near Waseca expressed a strong market for guajillos among friends and family, and so they were trialed at SROC. Guajillos are typically not eaten fresh, so all of the guajillos were harvested red for drying. Of the two varieties trialed, El Eden yielded higher than Durango (Figure 10), and matured at the same time (Table 3). Both varieties suffered from blossom end rot far more than any other chiles at SROC; of all fruits harvested on the single-day harvest, 48% of Durango fruits were red with blossom end rot, and 35% of El Eden fruits were red with blossom end rot. Results are similar to those reported for Durango in grown in Michigan (Phillips, 2018b). Only 6% of red Durango fruits were marketable, but 28% of El Eden red fruits were marketable. In addition, 49% of all Durango fruits and 52% of El Eden fruits were green. Due to blossom end rot, it seems unlikely that the green Durango fruits would ripen to become marketable red fruits, but perhaps there is potential with El Eden.

Cayenne and others

While cayenne peppers are not common in Mexican cuisine, the farmer-collaborators were interested in peppers with high capsaicin concentrations to add to salsas and chile flakes. Of the two cayennes trialed, the Red Ember variety was substantially larger (this was deemed beneficial by the growers for ease of picking; Figure 5), and yielded more at the farm where both were trialed (Cala Farm; Figure 11). Growers noted that while they appreciated the spiciness, both varieties lacked the complex flavor profile they were looking for.

The two additional varieties included: an open-pollinated Chile de Arbol selection from a local seed saver and Crackle, a hybrid recommended by a seed company representative. The Chile de Arbol variety was late to mature (Table 3), small (Figure 5; growers deemed it too small to be practical), and low-yielding (Figure 9). Crackle was early and high-yielding, but the grower who trialed it struggled to sell it; it had the flavor of a bell pepper but looked like a hot pepper. He commented that customers who wanted sweet peppers avoided it because of its appearance, and those who wanted hot peppers were disappointed by the lack of heat.

Dehydration

In Minnesota, farmers may dehydrate peppers without additional licensing as “products of the farm”. This classification also includes products like dried chile flakes as long as no off-farm ingredients are added, which would trigger a license requirement. The farmers involved in the project are interested in dehydrating chiles for multiple reasons: to create value-added products such as chile flakes, and to provide low-cost season extension via the sale of dried chiles. DIY solar dehydrators are attractive because they can be used in the field without an electrical supply, and can be easily transported for farmers without land tenure.

At SROC, passive and active systems for drying peppers were tested. First, three dryers were built based on a passive solar system from “Feeding Ourselves” by Larisa Walk and Bob Dahse (http://www.geopathfinder.com/Solar-Food-Drying.html). Briefly, the dryer consists of a lid with a polycarbonate panel on top and a thin metal bottom, separated by a 1.5-inch gap. Solar energy heats the metal on the bottom of the lid. Removable trays below the lid contain produce (peppers) on a stainless-steel screen, and the metal radiates accumulated heat to the produce. Passive airflow below the screens reduces humidity surrounding the fruit (Figure 13a & b). We found this system to be ineffective on intact peppers, regardless of type. The system performed poorly whether it was placed inside a high tunnel or outdoors. The high moisture content of fresh peppers (measured at 82–93% for most varieties) was not sufficiently reduced before most fruits rotted. Red fruits contained less initial moisture at harvest, but still did not dry sufficiently quickly. The material cost of three of these passive dehydrators (39 ft^2 total drying area) was $21 per ft^2.

One of the farmers built a second passive solar dehydrator based a design he was familiar with from Mexican farmers (Figure 13c). The dryer consisted of an elevated, hollow 3’ x 5’ x 1’ box made of 2x4’s and lined with black plastic. The front end included a small opening for airflow. A second 3’ x 1.5’ x 4.5’ box sat atop the back end of the bottom box and was lined with clear plastic. The top box had framed mesh screens every 8’’ or so vertically where the fruit were placed, and a back side that opened like a door. Warm air collected in the base, and flowed upwards through the vertical drying chamber. Similar to the results at SROC, the passive system was insufficient to dry intact peppers. However, the farmer tried the dryer with herbs, apple slices, and zucchini slices, and found it to be effective. The material cost of this passive dehydrator (up to 27 ft^2 total drying area) was unknown, as it was constructed with scrap materials.

A smoking system was also assembled at SROC, based on an “ugly drum smoker” (UDS). Briefly, a 55-gallon drum was fitted with three 21-inch diameter cooking grates for drying fruits, and another grate to support the drying racks on top of an expanded metal ring for holding charcoal and wood for smoking (Figure 13d). The design was modified from online plans (https://smokingmeatgeeks.com/ugly-drum-smoker-plans-uds-build/). The material cost of this smoker (7.2 ft^2 total smoking area) was $41 per ft^2. In our limited year 1 trial, we found that active smoking for ~3 hours, followed by resting overnight in the warm smoker, is promising for reducing initial moisture content of intact fruits to a level where further drying (passive or active), or processing smoked chiles into sauce, is feasible. A commercial smoker (Bradley 4-rack electric smoker) was found to perform similarly to the UDS, but a cost of $75 per ft^2 and higher wood costs make this electric option more expensive than the UDS. However, it requires less attention during smoking. The flavor of red jalapeños smoked using the electric smoker for 3 hours, then dried further in an electric dehydrator (not smoker), were favorable to a restaurant in Waseca.

Low-temperature drying was generally unsuccessful in a 2018 Michigan study (Phillips, 2018a). We will continue to adapt and trial these systems in 2021, including drying chiles with tops removed to increase internal moisture loss rate.

Income from peppers

One Mexican restaurant owner in Waseca reported purchasing one 35-pound case of chiles per week, and paying $28 to $48 per case. This particular restaurant owner was not willing to pay more for local or organic chiles. Another Mexican restaurant owner did report a willingness to pay more for local chiles, but did not provide specifics about current purchasing practices.

Projected income from pepper sales are reported in Figure 14. For the highest yielding Jalapeños (El Jefe, PS11435807, and Cinder), growers produced 460–2576 pounds of green fruit per 1000 row-feet, depending on their practices (Table 4). The standard yield goal for peppers in Minnesota is 22,400 pounds per acre (Rosen & Eliason, 2005); this is for bell peppers and has not been adapted for hot peppers, but is fairly consistent with the yield data from SROC.

If a grower were able to find similar prices to those reported by the restaurant in enough outlets (restaurants, other wholesale accounts, plus farmers markets), an average yield of 22,400 pounds per acre could translate to $17,920 – $30,720 per acre with price of $28 per case on the low end, $48 per case on the high end (Figure 14). These numbers do not include production costs, and assume that growers will meet the yield goal; for emerging farmers in Minnesota, improved nutrient management would help growers achieve yields closer to this goal.

Scoville

The ChilliPot device was found to be simple and results were repeatable. Compared to HPLC, Scoville Heat Units (SHU) measured on the ChilliPot averaged ~4,600 higher than SHU reported by HPLC (Figure 15a). Red chile SHU were generally higher and green chile SHU were lower than what linear regression estimated, except for Chile de Arbol and green Spicy Slice. All 4 red pepper samples generally had higher SHU than green peppers from the same plants and same harvest day when measured by the ChilliPot, but only Spicy Slice showed the same trend when measured by HPLC. Red fruits measured reliably hotter than green fruits from all varieties (Figure 15b). On average, green jalapeños measured 6,463 ± 1,417 SHU (± standard deviation), green poblanos measured 1,742 ± 873, and green serranos averaged 4,319 ± 1,203. Red jalapenos measured 10,430 ± 1,776 and red poblanos measured 8,437 ± 1,382. Many of these are measurements were higher than expected, but relative to each other, they are reasonable. Updates to the algorithm used by the FoodSense app for reporting SHU may lead to results that more reliably match the standard HPLC assay.

Anecdotally, we found jalapeños to be at least as hot as serranos when tasting them fresh. A restaurant in Waseca rated red Spicy Slice, but not green, as ‘too spicy’ (5 on a 5-point scale), and these fruits were from the same harvest and plants as those measured in Figure 15a. Red Cinder was not rated by this restaurant, but green Cinder was rated as 4/5 on the ‘spicy’ scale. We will measure additional samples in 2021 to study the correspondence between HPLC, ChilliPot, and flavor results.

Consumables for each ChilliPot analysis were ~$13, but the measurement device itself costs >$4,000. Commercial HPLC analysis cost $58 per sample. At these prices, the per-sample cost of the ChilliPot becomes lower than HPLC per-sample cost after ~95 samples.

Conclusions

These data come from the first year of a two-year pepper trial. Our results reinforce the value of variety trials that include on-farm research sites, as growers provide valuable qualitative feedback that is not always reflected in yield or other quantitative data. Despite substantial variation between sites, we identified the following varieties as well-suited to the needs of Minnesota growers: El Jefe, PS11435807, and Cinder jalapeños; Altiplano and Hot Rod serranos; Helios and Orange habaneros; Baron, Sargento, and Vencedor poblanos; and Red Ember cayenne. Poblanos with the highest potential for both green *and* red production include Sargento and Ancho 101, and red Cinder and PS11435807 jalapeño show high potential as well. Based on our research, it is not feasible to dry intact chiles using passive drying systems in Minnesota. Smoking chiles is an interesting value-added option if a market can be identified. Rapid and relatively inexpensive quantitative assessment of SHU is possible with a ChilliPot device, but consumer and restaurant input remains crucial for determining marketability of specific chile varieties.

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Table 1. Soil properties and amendments used at the four sites in this study, with plant and row spacing details.

Site	Lat. & Long.	Soil Type	pH	Organic Matter (%)	Soil Test P (Bray-1, ppm)	Soil Test K (ppm)	Fertilizer Added (per acre)	Plant Spacing
Agua Gorda Farm Cooperative, Long Prairie, MN	45.9747° N 94.8656° W	Dulem loamy sand	7.4	4.1	23	54	1 ounce Sustane® 4-6-4 at the base of each plant at planting and again 3 weeks later (1360 pounds per acre total)	1500 plants per 1000-ft (double row) bed, 6 feet on-center between beds, 10,890 plants per acre
Cala Farm, Turtle Lake, WI	45.3944° N 92.1424° W	Anigon silt loam and Crystal Lake silt loam	6.4	2.3	188	227	150 lbs. Sustane® 4-6-4	
Jarl's Produce, Morris, MN	45.2803° N 95.5103° W	Tara silt loam	7.3	5.9	61	300+	None	
University of Minnesota **SROC**[1], Waseca, MN	44.0763° N 93.5235° W	Nicollet-Webster clay loam	7.1	4.8	27	148	83 lbs. organic N + 65 lbs. synthetic N + 75 lbs. P_2O_5 + 75 lbs. K_2O from Sustane® (8-2-4 and 4-6-4), ESN (44-0-0), KCl (0-0-60), and soluble starter fertilizer (12-45-10)	1454 plants per 1000-ft (double row) bed, 5 feet on-center between beds, 12,630 plants per acre

[1]Southern Research and Outreach Center

Table 2. Total growing degree days (GDD, base 50 °F) during the 2020 growing season at the 4 locations in the current study.

Site	June	July	August	1–18 Sept.
Agua Gorda	474	611	528	98
Cala	489	652	558	121
Jarl’s	629	708	615	134
SROC	665	720	630	150

Table 3. Varieties used, seed sources, time to harvest, and ripening uniformity of peppers used in this study. Fruits were harvested green unless noted. Red fruits at SROC were harvested from different plants than green fruits. Ripening uniformity is from 0–100%, where 100% indicates all fruits were ready on a single day and 0% indicates equal weight of fruit harvested on each harvest day. Red fruits were harvested on a single day per variety at SROC, so uniformity is presented as marketable red fresh weight as a percentage of total marketable fruits (green + red).

		Earliness / days to harvest						Ripening Uniformity (%)				
			Actual									
Pepper Type & Variety	Seed Source	Predicted	Agua Gorda	Cala	Jarl's	SROC (green)	SROC (red)	Agua Gorda	Cala	Jarl's	SROC (green)	SROC (red)
Jalapeño												
Cinder	SKT	midseason	--	--	--	54	118	--	--	--	48%	44%
Early Jalapeño	HMS	65	61	82	82	62	134	44%	78%	84%	35%	53%
El Jefe	JHN	67	61	82	--	--	--	49%	62%	--	--	--
PS11435807	SEM	65	61	61	61	57	98	25%	52%	38%	19%	37%
Spicy Slice	SKT	75	61	--	--	54	98	42%	--	--	38%	24%
Serrano												
Altiplano	JHN	57	61	61	--	--	--	27%	76%	--	--	--
Hot Rod	JHN	57	61	61	61	--	--	49%	67%	47%	--	--
Serrano Chili	JOR	75	61	102	82	83	119	56%	90%	74%	49%	62%
Sureño	SKT	mid-early	--	--	--	57	101	--	--	--	48%	41%
Poblano												
Ancho 101	JOR	78	61*	--	--	77	134	42%	--	--	41%	29%
Ancho Poblano	HMS	68	61*	--	--	--	--	41%	--	--	--	--
Baron	JHN	65	61*	--	--	--	--	42%	--	--	--	--
Sargento	SKT	midseason	--	--	--	62	134	--	--	--	39%	29%
Vencedor	SEM	unknown	61*	--	--	62	106	46%	--	--	32%	25%
Habanero (orange)												
598G	JHN	100	61*	102	--	--	--	40%	100%	--	--	--
Helios	JHN	87	61*	82	--	--	--	28%	91%	--	--	--
Magnum	HMS	100	61*	102	--	--	--	48%	91%	--	--	--
Orange	JOR	90	--	102	--	--	--	--	97%	--	--	--
Other												
Durango (red)	SKT	75	--	--	--	--	106	--	--	--	--	5%
El Eden (red)	JHN	85	--	--	--	--	106	--	--	--	--	27%
Red Ember (red)	HMS	70	--	61	--	--	--	--	74%	--	--	--
Slim (red)	JOR	70	--	82	82	--	--	--	66%	61%	--	--
Chile de Arbol (red)	GSF	unknown	--	--	102	--	113	--	--	99%	--	50%
Crackle	SKT	60	--	82	--	--	--	--	77%	--	--	--

GSF = Greenside Farm. HMS = High Mowing Seeds. JHN = Johnny's Seeds. JOR = Jordan Seeds. SEM = Seminis Seeds. SKT = Sakata Seeds.
*These varieties were grown in high tunnels at Agua Gorda.

Table 4. Yield of peppers per row length and area, calculated from per-plant marginal mean yield at 4 growing locations. Mean separation within pepper type and farm are the same as in the per-plant yield charts.

Pepper Type & Variety	Pounds per 1,000 row-feet					Pounds per acre				
	Agua Gorda	Cala	Jarl's	SROC (green)	SROC (red)	Agua Gorda	Cala	Jarl's	SROC (green)	SROC (red)
Jalapeño										
Cinder	--	--	--	2,576	2,336	--	--	--	22,443	20,350
Early Jalapeño	378	88	1,158	1,642	1,219	2,745	636	8,409	14,305	10,623
El Jefe	1,658	460	--	--	--	12,038	3,342	--	--	--
PS11435807	1,434	464	2,663	2,338	1,563	10,414	3,370	19,334	20,372	13,619
Spicy Slice	824	--	--	1,688	804	5,985	--	--	14,706	7,000
Serrano										
Altiplano	914	320	--	--	--	6,634	2,325	--	--	--
Hot Rod	780	398	2,151	--	--	5,663	2,892	15,615	--	--
Serrano Chili	385	120	1,074	1,711	1,319	2,798	868	7,798	14,907	11,488
Sureño	--	--	--	1,731	1,160	--	--	--	15,080	10,106
Poblano										
Ancho 101	628	--	--	1,457	1,148	4,556	--	--	12,696	9,999
Ancho Poblano	603	--	--	--	--	4,379	--	--	--	--
Baron	731	--	--	--	--	5,309	--	--	--	--
Sargento	--	--	--	1,799	861	--	--	--	15,669	7,504
Vencedor	746	--	--	2,358	587	5,416	--	--	20,539	5,116
Habanero (orange)										
598G	30	25	--	--	--	2,683	181	--	--	--
Helios	712	133	--	--	--	5,116	967	--	--	--
Magnum	439	35	--	--	--	3,187	253	--	--	--
Orange	--	146	--	--	--	--	1,063	--	--	--
Other										
Durango (red)	--	--	--	--	43	--	--	--	--	371
El Eden (red)	--	--	--	--	485	--	--	--	--	4,225
Red Ember (red)	--	583	--	--	--	--	4,231	--	--	--
Slim (red)	--	164	923	--	--	--	1,193	6,699	--	--
Chile de Arbol (red)	--	--	146	--	699	--	--	1,060	--	6,088
Crackle	--	378	--	--	--	--	2,744	--	--	--

Figure 1. Cumulative divergence of daily GDD_{50} from 30-year normal GDD_{50} at the 4 locations in the study, starting at transplant. The harvest window at each location is highlighted. The lines terminate when 30°F was recorded at each location. Normal GDD_{50} were retrieved from NOAA (https://www.ncdc.noaa.gov/cdo-web/; NWS stations 214861, 477174, 215638, and 218692).

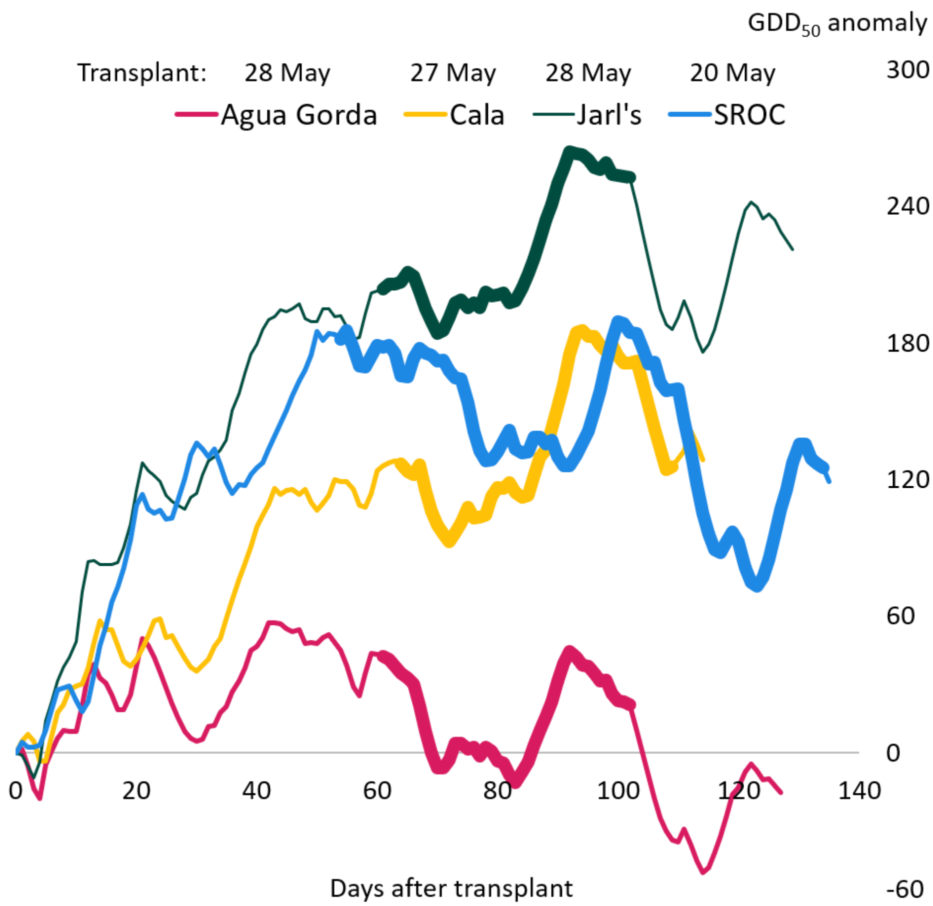

Figure 2. 2020 cumulative precipitation (colored lines) and 30-year normal at the 4 locations in the study, starting on May 1st. The harvest window at each location is highlighted, and planting date is indicated with a grey dot.

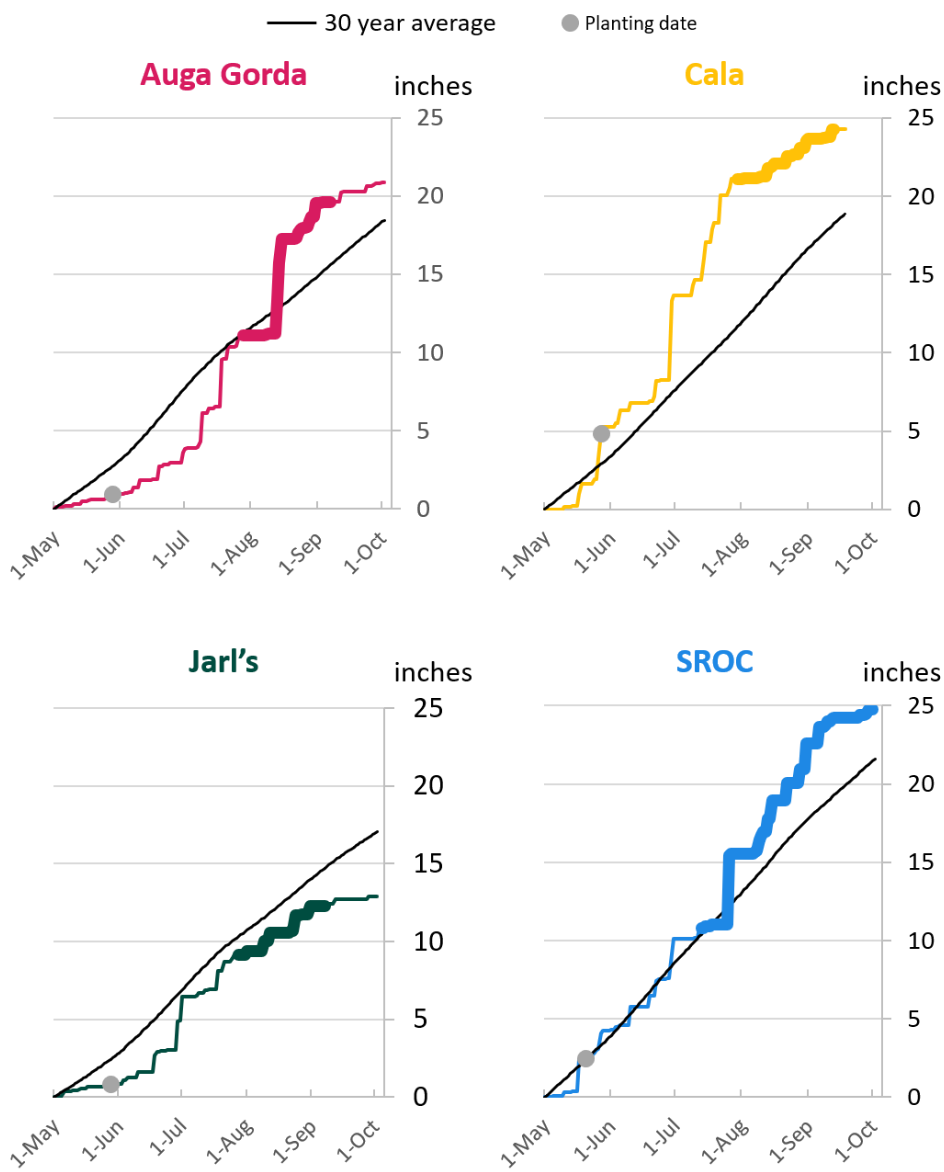

Figure 3. Yield of Early Jalapeño, jalapeño PS11435807, and Serrano Chili grown at 4 locations in 2020. Boxplots indicate median, interquartile range, and 1.5×IQR. Letters indicate significant differences at $\alpha = 0.05$, based on Holm-adjusted Mann-Whitney U tests (*n* = 3; no letter = not significantly different). These were the only three varieties grown at all four locations.

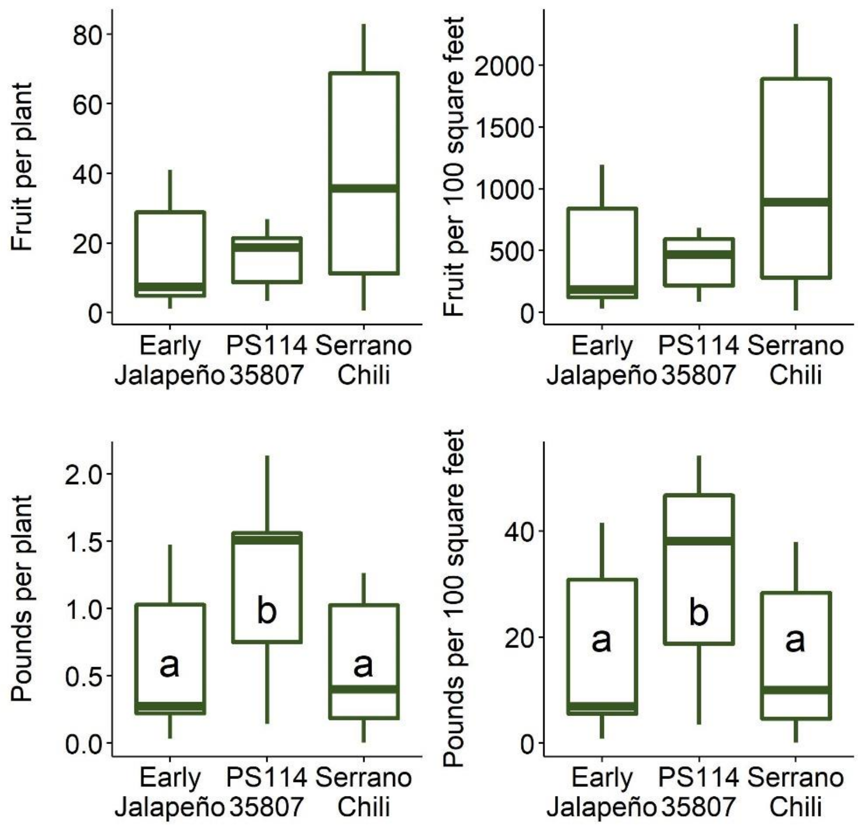

Figure 4. Average yield of Early Jalapeño, jalapeño PS11435807, and Serrano Chili at each of 4 locations in 2020. Boxplots indicate median, interquartile range, and 1.5×IQR. Letters indicate significant differences at $\alpha = 0.05$, based on Holm-adjusted Mann-Whitney U tests ($n = 6$).

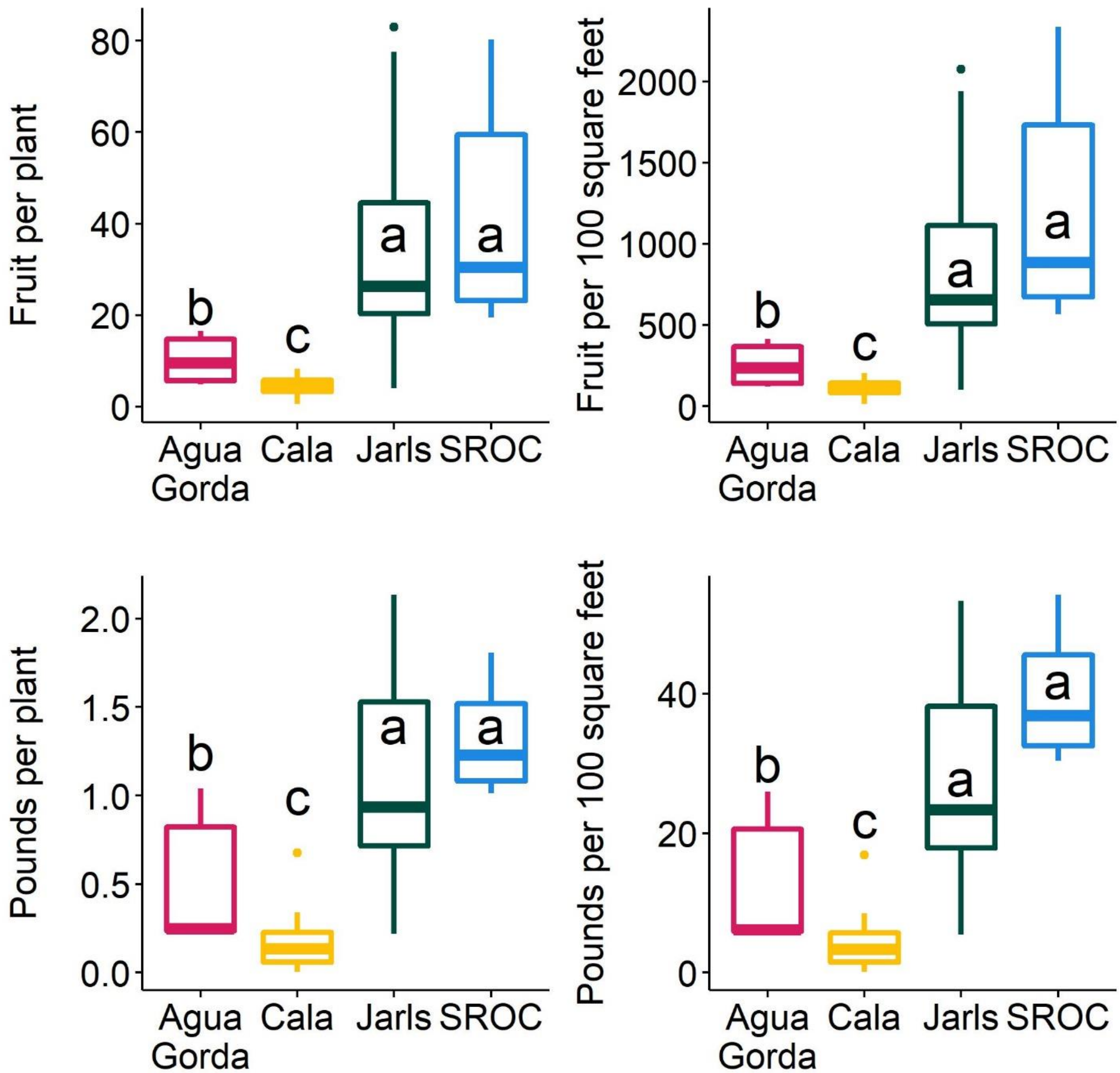

Figure 5. Length and width of marketable peppers from all farms. Up to 5 fruits per plot from each harvest at each location were measured. Plot color indicates fruit color at harvest (green, red, or orange). The violin plots show the distribution of the data, and the box indicates the interquartile range (the middle 50% of all data points fall within the range of the box). The vertical bar displays the median.

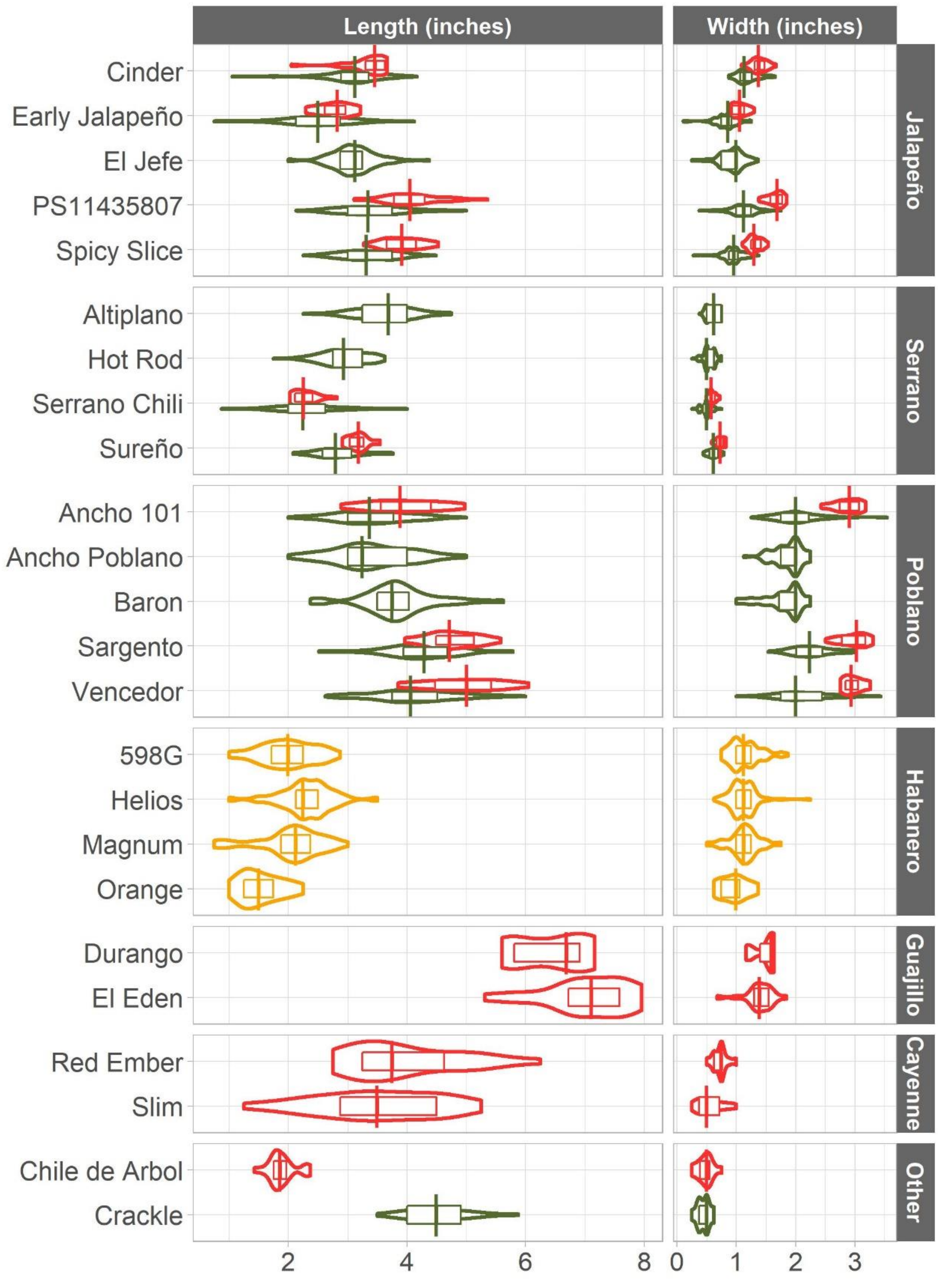

Figure 6. Per-plant yield of marketable green jalapeño fruits from 4 farms in 2020. Total yield is from 4 (Agua Gorda) or 3 (other locations) harvests. Bars indicate 95% confidence intervals of marginal means, and marginal mean is indicated. Within a growing location, significant differences (α=0.05) are indicated by letters, based on pairwise Holm-adjusted post-hoc contrasts (adjusted across all peppers within location; no letters = no significant difference).

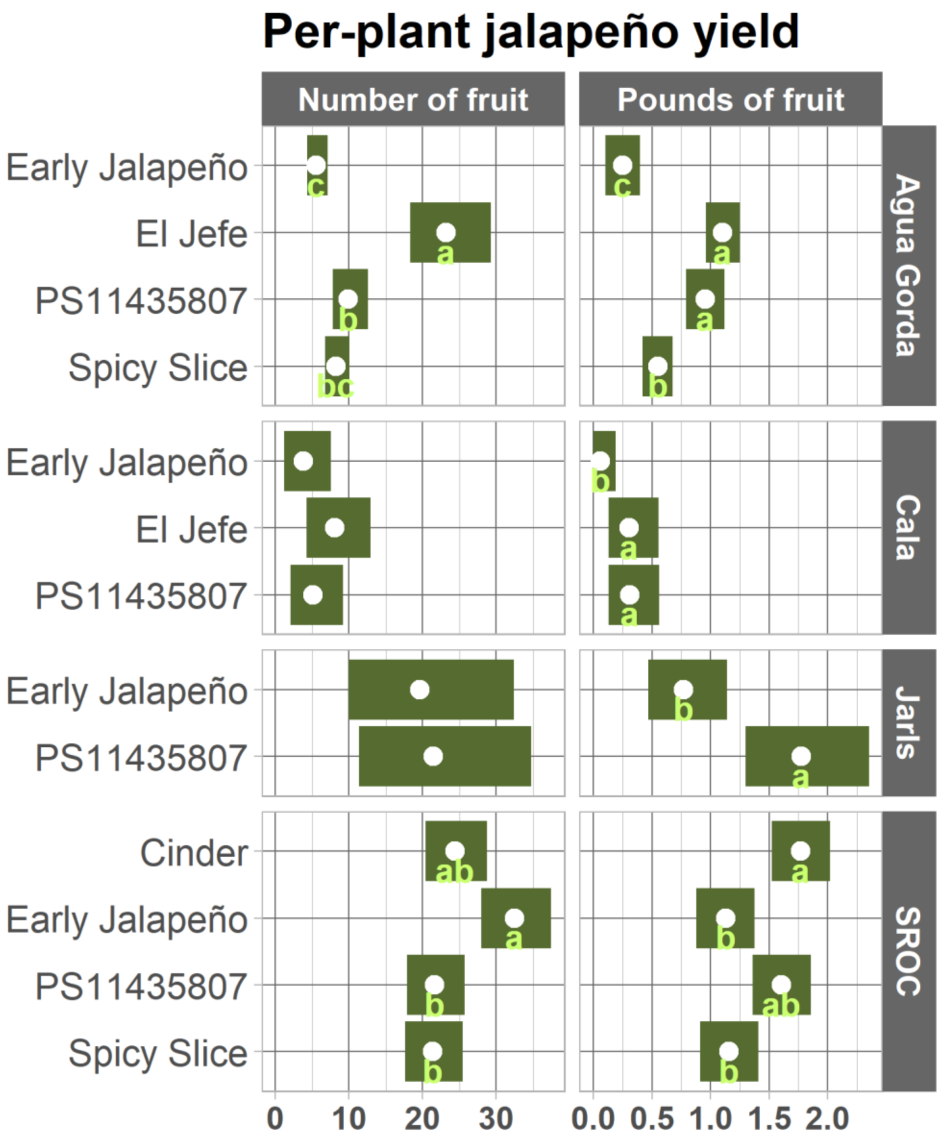

Figure 7. Per-plant yield of marketable green serrano fruits from 4 farms in 2020. Total yield is from 4 (Agua Gorda) or 3 (other locations) harvests. Bars indicate 95% confidence intervals of marginal means, and marginal mean is highlighted. Within a growing location, significant differences (α=0.05) are indicated by letters, based on pairwise Holm-adjusted post-hoc contrasts (no letters = no significant difference).

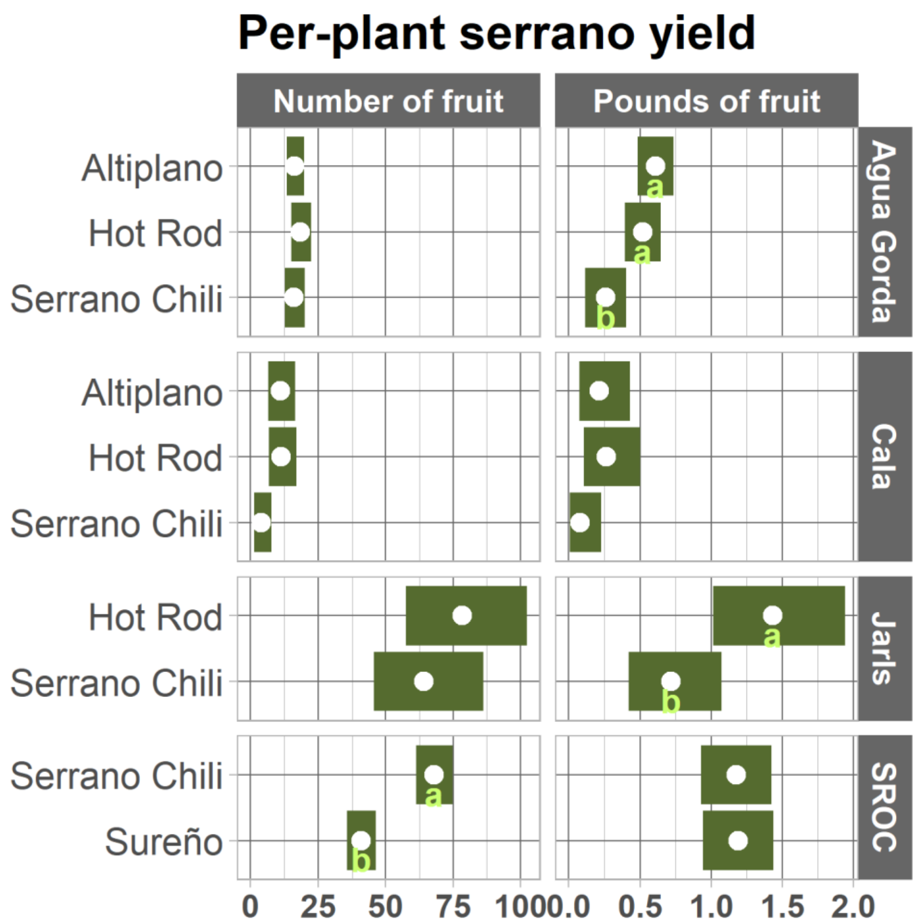

Figure 8. Per-plant yield of marketable green poblano fruits from 2 farms in 2020. Total yield is from 4 (Agua Gorda high tunnel) or 3 (SROC) harvests. Bars indicate 95% confidence intervals of marginal means, and marginal mean is highlighted. Within a growing location, significant differences (α=0.05) are indicated by letters, based on pairwise Holm-adjusted post-hoc contrasts (no letters = no significant difference).

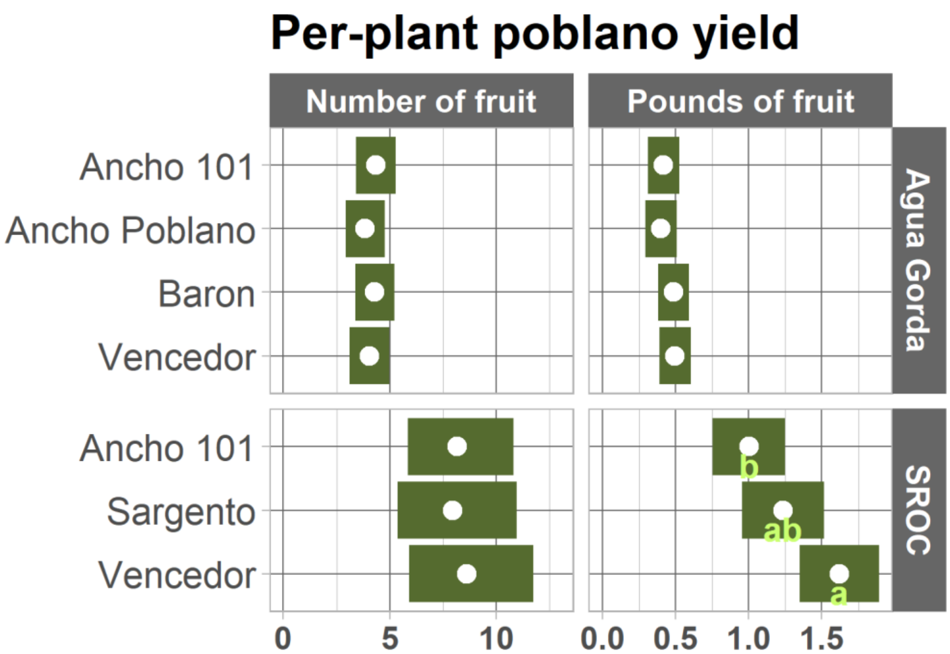

Figure 9. Per-plant yield of marketable orange habanero fruits from 2 farms in 2020. Total yield is from 4 (Agua Gorda high tunnel) or 3 (Cala) harvests. Bars indicate 95% confidence intervals of marginal means, and marginal mean is highlighted. Within a growing location, significant differences (α=0.05) are indicated by letters, based on pairwise Holm-adjusted post-hoc contrasts (no letters = no significant difference).

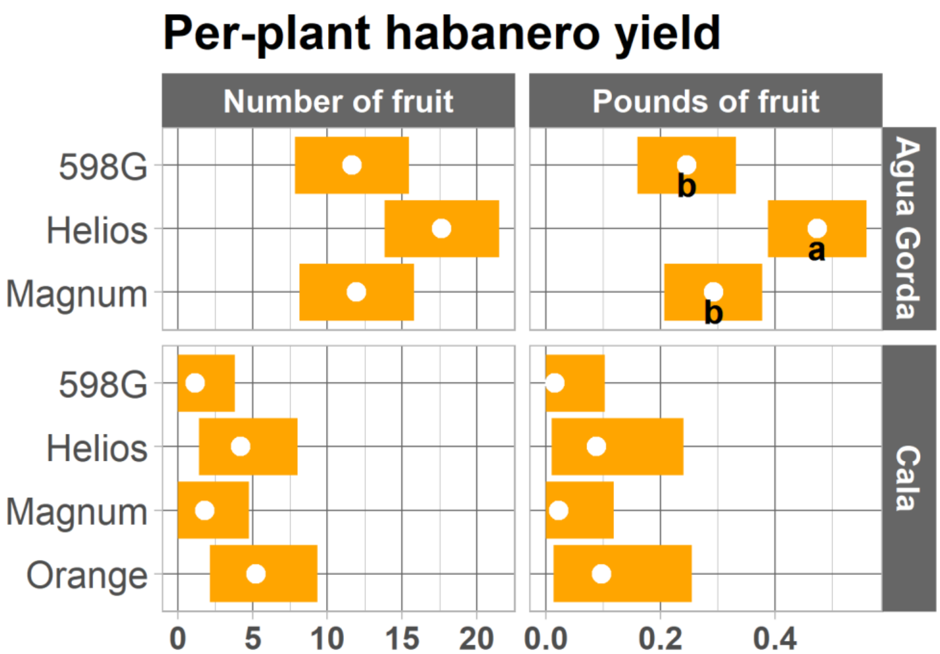

Figure 10. Yield of marketable ripe red fruits from SROC (Waseca, MN). Red fruits were harvested on a single day per variety from different plants than green fruits. Bars indicate ±95% confidence interval of marginal mean. Letters indicate significant differences based on pairwise Holm-adjusted post-hoc contrasts (α = 0.05, n = 11 contrasts; no letters = no significant difference).

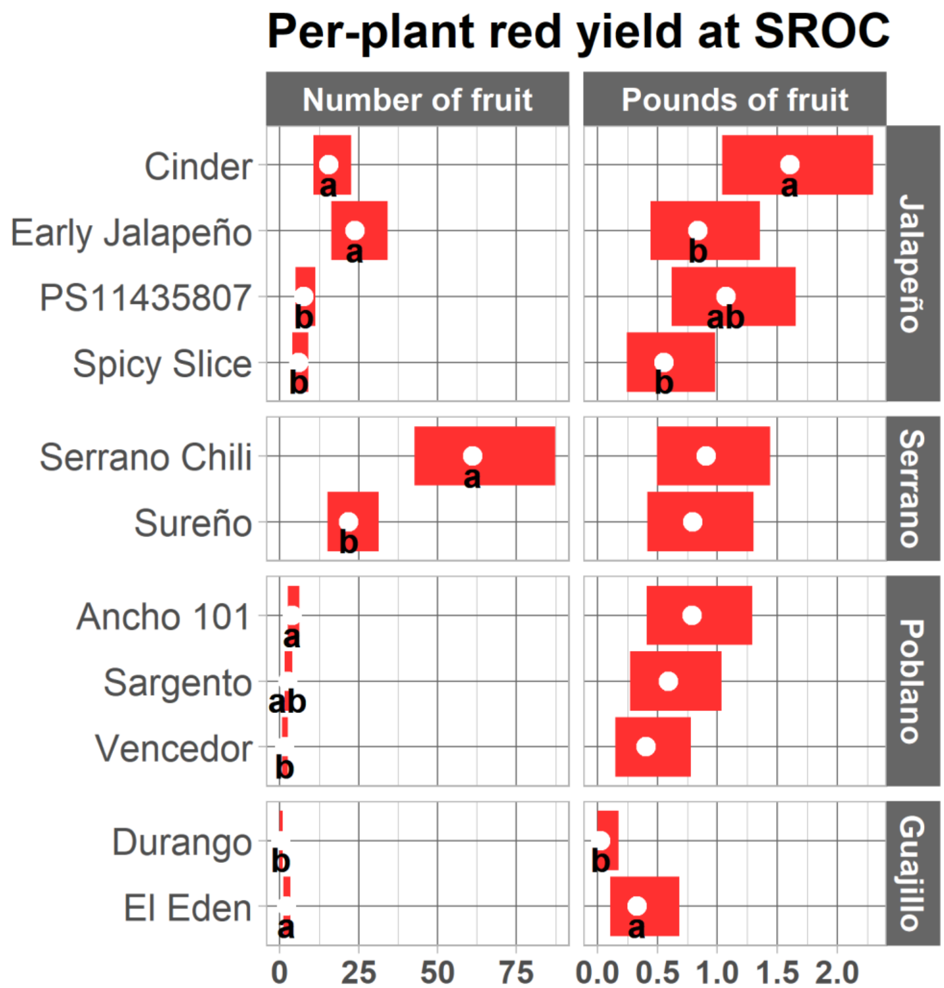

Figure 11. Yield of marketable cayenne peppers grown at Cala and Jarl's. Bars indicate ±95% confidence interval of marginal mean. Letters indicate significant differences based on Holm-adjusted post-hoc contrasts within each location (α = 0.05; no letters = no significant difference).

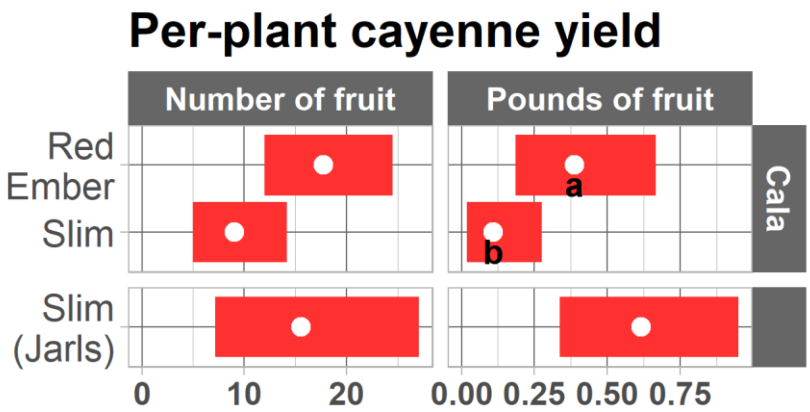

Figure 12. Yield of marketable green Crackle peppers grown at Cala and red Chile de Arbol (CdA) peppers grown at SROC and Jarl's. Bars indicate ±95% confidence interval of marginal mean.

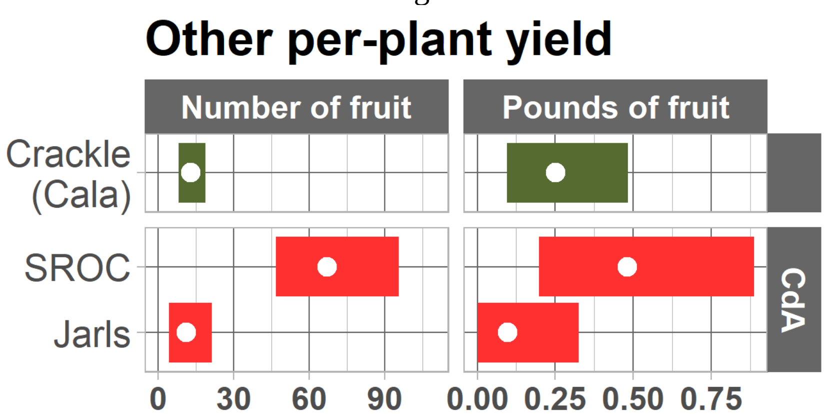

Figure 13. A passive solar dryer was constructed and tested on intact peppers at SROC in Waseca (a, b) and at a farmer-collaborator site (c). A smoker (d) was also constructed and tested for pepper drying at SROC. The SROC passive system was tested both outside and inside a high tunnel.

Figure 14. Gross profit based on chile pepper yield at $28, $38, or $48 per 35-pound case. The lowest and highest yield for jalapeño peppers grown at Jarls and SROC, and revenue at those yields with $38 per case, is illustrated by the dotted lines. Yields and revenues are shown per 1,000 row-ft (a) or acre (b).

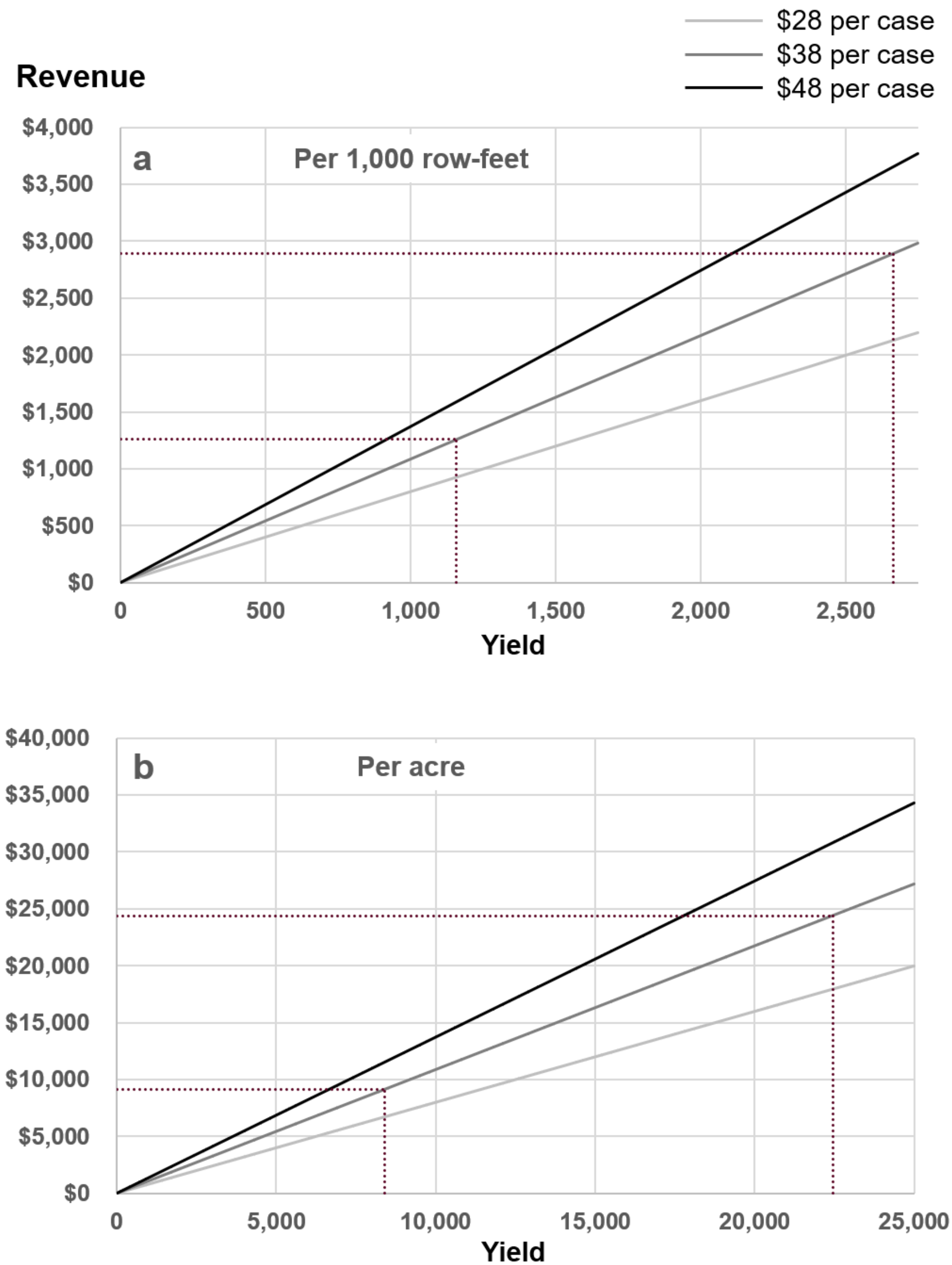

Figure 15. Scoville heat units of peppers measured by a ChilliPot Scoville Meter. In (a), the average (closed circles) of triplicate technical replicates on the ChilliPot (open circles) are regressed against Scoville results from a commercial lab using a standard HPLC analysis. The same fruit homogenate was used for both HPLC and ChilliPot analysis. Yellow lines connect red and green fruits from the same varieties (harvested from the same plants on the same day at SROC). The regression line is shown, ±95% confidence interval (p = 0.019). CdA = Chile de Arbol, and PS114 = PS11435807. In (b), ChilliPot-measured Scoville heat units are shown from green (g) and red (r) fruits of the 12 varieties grown at SROC, harvested throughout the season.