Yield Response of Winter Squash to Irrigation Regime and Planting Density

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Abstract. Consumers are increasingly interested in buying local vegetables in the fall and winter. Winter squash is an important vegetable crop for local and regional fall and winter markets, and consumers are increasingly seeking high-culinary value *Cucurbita maxima* types such as kabocha and buttercup. Although consumer demand for kabocha and buttercup squash is increasing, Oregon farmers report they are marginally profitable. The goals of this project were 1) to identify productive kabocha and buttercup varieties for western Oregon when grown with or without overhead irrigation and 2) to describe the effects of planting density on yield, fruit weight, number of fruit per hectare, and fruit per plant. Seven varieties of *C. maxima* winter squash, including kabochas and buttercups, and one interspecific (*C. maxima* × *C. moschata*) hybrid ‘Tetsukabuto’ were grown in a split-split plot randomized complete block design experiment with irrigation as the main plot, planting density as the subplot, and variety as the sub-subplot. Four replications of four different planting densities for eight varieties were grown in 2016 and 2017. Irrigated planting densities ranged from 8611–32,292 plants/ha (0.86–3.2 plants/m²) and dryland planting densities ranged from 3827–14,352 plants/ha (0.38–1.4 plants/m²) in 2016 and 5741–21,528 plants/ha (0.57–2.2 plants/m²) in 2017. The seven *C. maxima* types had statistically comparable yield under both irrigated and dryland production, with an average yield of 33.9 t·ha⁻¹ with irrigation and 19.4 t·ha⁻¹ without irrigation. Dryland yields in 2016 and 2017 were 76% and 37% of irrigated yields, respectively. ‘Tetsukabuto’ had the greatest yield (mean, 51.4 t·ha⁻¹), the greatest number of fruit per hectare (mean, 12,080), and the greatest number of fruit per plant (mean, 1.94) when grown with irrigation, and yielded comparably with other varieties when grown in dryland production. Planting density impacted the fruit weight, number of fruit per hectare, and number of fruit per plant, although it did not impact yield statistically in both irrigated and dryland production. Average fruit weight decreased linearly from 1.89 to 1.30 kg for the irrigated trials, from 2.04 to 1.56 kg in the 2016 dryland trial, and from 1.42 to 0.93 kg in the 2017 dryland trial as planting density increased from 0.86 to 3.2, 0.38 to 1.4, and 0.57 to 2.2 plants/m², respectively. The number of fruit per hectare increased linearly from 6660 to 10,590 as the number of plants per hectare increased from 8611 to 32,292 plants/ha for the irrigated trials, because even at the lowest planting density, plants did not produce more than two fruit per plant on average across varieties when grown with irrigation. Farmers can manipulate squash fruit size to suit market preferences by changing planting density. The very low 2017 dryland yields were likely a result of unusually high summer temperatures in western Oregon. Increasingly hot summers may render dryland squash production unfeasible in this region.

There is increasing consumer demand for locally and regionally grown produce in the late fall and winter (King et al., 2015). Winter squash is a crop that can fill this market opportunity because it is harvested in the fall and can be stored for months before sale (Thompson, 2014). Consumers seek buttercups and kabochas (*C. maxima*) for their superior culinary qualities (Loy, 2004; Morgan and Midmore, 2003). Oregon farmers are interested in growing more of these squash

types; however, there are no Oregon data on the performance of diverse buttercup and kabocha types in this region.

The original buttercup (*C. maxima*), similar to the variety ‘Burgess Buttercup’, was bred by Albert Yeager at North Dakota State University (NDSU) (Yeager and Latzke, 1932). The NDSU breeders were trying to breed a sweeter hubbard, but instead developed the much sweeter and smaller buttercup. Buttercups were named for their blossom end scar and protruding ovary, giving the fruit a distinctive “cup.” Their flesh has a higher starch content and tastes drier when compared with acorn and butternut varieties, and are sometimes referred to as “turban squash.” American breeders have continued to improve on the older varieties, and their releases include ‘Bonbon’ (Johnny’s Selected Seeds) and ‘Thunder’, a buttercup ×

kabocha hybrid (Rupp Seeds). In America, “kabocha” refers to a type of *C. maxima* developed in Japan from crosses of open-pollinated *C. maxima* varieties that were selected for smaller size, sweeter flesh, nuttier flavor, longer storage life, more rounded shoulders, and lack of protruding ovary and blossom end scar. ‘Delica’ (‘Ebisu’ in Japan) was released by Takii Seed Co. in 1964 (Takii Seed Company, 2018) and ‘Sweet Mama’ (‘Tsurunashi Yakko’ in Japan) was released later (Morgan and Midmore, 2003). As a result of their common ancestry and similar appearance, the terms kabocha and buttercup are sometimes used interchangeably in marketing materials and in breeding work (Loy, 2012).

The interspecific hybrid ‘Tetsukabuto’ may also have fresh market potential in the United States and could fill a similar market niche, although it is distinctly different from kabochas and buttercups in some characteristics. ‘Tetsukabuto’ is round and ribbed with dark-green to green-and-orange-striped skin and is slightly smaller than most kabochas. ‘Crown’ is crown-shaped, with smooth gray to pink skin, and is larger than most kabochas. North American consumers are not familiar with either of these varieties. However, their sweet, nutty flavor and long storage potential may warrant expanded production for fresh market sales (Morgan and Midmore, 2003).

Takii Seed Co. released the popular interspecific hybrid ‘Tetsukabuto’ in 1951. ‘Tetsukabuto’ means steel helmet in Japanese. According to Bisognin (2002), this male-sterile variety comes from a cross between the female parent ‘Delicious’ (*C. maxima*) and the male parent ‘Kurokawa no. 2’ (*C. moschata*). However, other hybrid lines also use the name ‘Tetsukabuto’ (Amaro et al., 2017). ‘Tetsukabuto’ is grown and marketed as a popular fresh market winter squash in Japan (Pan, 1995) and Brazil (Amaro et al., 2017). Morgan and Midmore (2003) identified ‘Tetsukabuto’ as a fresh market winter squash similar to kabochas, with a “high yield and very sweet, nutty fruit,” and encouraged its adoption into the Australian market. It is commonly used in the United States as a rootstock that confers resistance to soilborne diseases in susceptible cucumber and melon varieties (Cañizares and Goto, 1998; Mohamed et al., 2014). ‘Crown’ was sourced from High Mowing Organic Seeds, which improved a variety from the Koanga Institute’s New Zealand Heritage Collection (High Mowing Organic Seeds, 2018).

In the United States, farmers grow kabochas and buttercups in response to local consumer demand. In western Oregon, farmers report they are marginally profitable (A. Stone, personal communication). *C. maxima* squash varieties grown in western Oregon have been shown to be susceptible to a soilborne disease complex with causal agents *Fusarium solani* and other fungal pathogens that reduce yield (Rivedal, 2019). In addition, there is a blossom end rot that rots squash

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early in storage (causal agent, *Fusarium culmorum*) (Rivedal et al., 2018). To support commercial production in western Oregon, varieties must be identified that are relatively high yielding and long storing when grown in this region.

Dryland farming is of increasing interest to farmers facing climate change in the Pacific Northwest. In western Oregon, almost all precipitation occurs from fall through spring, with very little during the summer (Western Regional Climate Center, 2019). Most annual crops are irrigated. Summers are becoming warmer and drier, and warmer winter and spring temperatures are reducing snowpack and summer groundwater supplies (Jaeger et al., 2017). Identifying crops and varieties suited to dryland production can increase overall farm water use efficiency and provide crop options to farmers with no access to water. Historically, the Oregon heirloom processing squash ‘Golden Delicious’ (*C. maxima*) was grown without irrigation in western Oregon. Winter squash are typically grown without irrigation in other regions such as Virginia (Bratsch, 2009) and New Zealand (Fandika et al., 2011).

Some farmers are interested in manipulating winter squash fruit size and number to meet consumer expectations better and improve profitability. Farmers selling through community-supported agriculture (CSA) may want higher numbers of smaller fruit to supply more CSA boxes per acre. Farmers selling at farmers markets or to retailers or wholesalers may also want a greater number of smaller fruit because urban customers do not want to carry or cook large fruit. In contrast, farmers selling to restaurants or processors may want smaller numbers of larger fruit to improve processing efficiency. Fruit size and number of fruit per plant and number of fruit per hectare are influenced by planting density.

Specific planting density recommendations from the United States cover a broad category of crops, including pumpkins and winter squash. For example, the National

Center for Appropriate Technology sustainable agriculture program recommends using 7413 to 9884 plants/ha (Bachmann, 2010). Other publications narrow the recommendations by categorizing squash according to vine length and/or fruit size (Kemble et al., 2000; National Integrated Pest Management Database, 2006). Oregon State University Extension Service has kabocha-specific recommendations at 0.30 to 0.45 m (1–1.5 ft) in-row and 1.8 m (6 ft) between rows (12,151–18,182 plants/ha) (Hemphill, 2010). Collectively, these recommendations vary from 1493 to 18,182 plants/ha (0.15–1.8 plants/m²). There is no information on planting density and its impact on overall yield as well as fruit size and number of fruit per plant for kabocha, buttercup, ‘Tetsukabuto’, and ‘Crown’ in this region when grown with or without irrigation.

The goals of this project were 1) to identify productive kabocha and buttercup varieties for western Oregon when grown with or without overhead irrigation, and 2) to describe the effects of planting density on yield, fruit weight, and number of fruit per plant and hectare.

Materials and Methods

Location. Experiments were conducted during 2016 and 2017. Field trials were located at the Oregon State University Vegetable Research Farm in Corvallis, OR, on a Chehalis silty clay loam at lat. 44.5646°N, long. 123.2620°W, and 71.6 m above sea level.

Experimental design. The experimental design was a split-split plot randomized complete block design with irrigation as the main plot, planting density as the subplot, and variety as the sub-subplot. There were four replications of each planting density for the irrigated trials in 2016 and 2017 and the dryland trial in 2017. There were three replications of each planting density for the dryland trial in 2016. Each block included a plot for each variety at all planting densities. The experimental field was surrounded by border

rows planted with bush-type acorn varieties (*C. pepo*). Row spacing in 2017 was 1.5 m for the irrigated trial and 2.3 m for the dryland trial. In-row spacing was 0.2, 0.3, 0.5, and 0.8 m. Plant populations for the irrigated trial were 0.8, 1.3, 2.2, and 3.3 plants/m². Plant populations for the dryland trial were 0.5, 0.9, 1.4, and 2.2 plants/m². Row spacing in 2016 was identical except for dryland in-row spacings, which were 0.3, 0.45, 0.8, and 1.1 m (0.6, 0.8, 1.5, and 2.2 plants/m²). Irrigated plots in 2016 and 2017 were one row wide × 3 m long. Dryland plots were one row wide × 4.6 m long (2016) or 3 m long (2017).

Squash varieties. The varieties grown are listed in Table 1. They included seven *C. maxima* types and one *C. maxima* × *C. moschata* interspecies hybrid: ‘Tetsukabuto’. Within the *C. maxima* types, there were four kabocha types (‘Delica’, ‘Sunshine’, ‘Sweet Mama’, and ‘Winter Sweet’), two buttercup types (‘Bonbon’ and ‘Burgess’), and one other type (‘Crown’). In 2016, ‘Bagheera’, ‘Blue Kuri’, ‘Cha-Cha’, ‘Eastern Rise’, ‘Gold Nugget’, ‘Shokichi Shiro’, ‘Thunder’, and ‘Uncle David’s Dakota Dessert’ were grown. However, they were not grown in 2017 and are not included in this article because of their poor yields (likely a result of their susceptibility to the region’s unique soilborne disease complex), poor storability (in some cases resulting from their susceptibility to the region’s unique storage rot pathogen), size (‘Shokichi Shiro’), or because of field and storage space restrictions (A. Stone and J. Wetzel, unpublished data).

Nutrient management. Soil analyses indicated that phosphorus and potassium were at or above sufficiency. Nitrogen was applied to all fields at a rate of 67 kg·ha⁻¹ plant available nitrogen (60 lb/acre). Yard waste compost (nutrient analysis, Supplemental Table 1) was added at a rate of 19 m³·ha⁻¹ (10 yard/acre).

Crop planting and management. The dryland trial was direct-seeded on 11 May and 19 May in 2016 and 2017, respectively. One inch of water was applied via overhead

Table 1. Varieties grown during the 2016 and 2017 trials, including information on seed source and type.

Variety	Type	Hybrid status	Breeder	Seed source	Grown in 2016	Grown in 2017
Bagheera	Green kabocha	F ₁	Brent Loy, University of New Hampshire	High Mowing Organic Seeds	×	
Blue Kuri	Blue/gray kabocha	OP	Wim Brus, Bingenheimer Saatgut	Adaptive Seeds	×	
Bonbon	Green buttercup	F ₁	Rob Johnston, Johnny’s Selected Seeds	Johnny’s Selected Seed	×	×
Burgess Buttercup	Green buttercup	OP	North Dakota State University, Burgess Seed & Plant Co.	Fedco Seeds	×	×
Cha-Cha	Green kabocha	F ₁	Rob Johnston, Johnny’s Selected Seeds	Johnny’s Selected Seed	×	
Crown	Gray pumpkin	OP	Improved New Zealand heirloom, Koanga Institute New Zealand Heritage Collection	High Mowing Organic Seeds	×	×
Delica	Green kabocha	F ₁	Takii Seed Co.	Osborne Quality Seeds	×	×
Eastern Rise	Other	F ₁	Taiwanese origin, popular in China	Fedco Seeds	×	
Gold Nugget	Other	OP	North Dakota State University	Johnny’s Selected Seed	×	
Shokichi Shiro	Mini kabocha	F ₁	Takita Seed Co.	Johnny’s Selected Seed	×	
Sunshine	Red kabocha	F ₁	Rob Johnston, Johnny’s Selected Seeds	Johnny’s Selected Seed	×	×
Sweet Mama	Green kabocha	F ₁	Takii Seed Co.	Osborne Quality Seeds	×	×
Thunder	Buttercup × kabocha	F ₁	Brent Loy, University of New Hampshire	Fedco Seeds	×	
Uncle David’s Dakota Dessert	Green kabocha	OP	David Podoll	Fedco Seeds	×	
Winter Sweet	Gray kabocha	F ₁	Rob Johnston, Johnny’s Selected Seeds	Johnny’s Selected Seed	×	×
Tetsukabuto	Hybrid	F ₁	Seki Ogura, Takii Seed Co.	Nichols Garden Nursery	×	×

F₁ = filial 1 hybrid; OP = open pollinated.

irrigation. Plants were thinned to the desired density after emergence. The irrigated trial used transplants started on 4 May and 12 May, and were planted at the desired density in the field on 25 May and 31 May in 2016 and 2017, respectively. Overhead irrigation was applied weekly to field saturation. Weeds

were controlled using cultivation and hand weeding. Insect and disease pressure was monitored, and protective treatments were applied when necessary. The main concerns for winter squash production in the Willamette Valley are cucumber beetles, especially during establishment, and early

powdery mildew epidemics. There were no issues with other pests or diseases, including vine borers, squash bugs, aphids, Western flower thrips, angular leaf spot, curly top, or mosaic (Dicklow and McKeag, 2018; Pscheidt and Ocamb, 2018). In 2016 and 2017, cucumber beetles were controlled

Table 2. Yield and yield components of seven *C. maxima* varieties and one *C. maxima* × *C. moschata* interspecific hybrid under two irrigation regimes and four planting densities.

Treatment	Irrigated 2016 and 2017 trials			
	Yield (t/ha)	Fruit wt (kg)	No. fruit/ha	No. fruit/plant
Planting density (plants/ha)				
8,611	31.99	1.89 a	16,457 b	1.96 a
12,917	33.94	1.84 a	18,827 b	1.46 b
21,528	35.93	1.55 b	22,870 a	1.07 c
32,292	33.80	1.30 c	26,168 a	0.82 c
Significance ^z	NS	2.20E-16***	4.90E-09***	6.37E-06***
Variety				
Bonbon	31.43 b	1.45 c	21,389 bc	1.48 b
Burgess Buttercup	27.89 b	1.14 d	23,977 b	1.49 b
Crown	30.96 b	2.14 a	14,330 d	0.93 c
Delica	32.37 b	1.56 c	21,612 bc	1.29 bc
Sunshine	33.02 b	1.71 bc	20,317 bc	1.26 bc
Sweet Mama	31.11 b	1.90 ab	17,453 cd	1.01 bc
Tetsukabuto	51.42 a	1.64 c	29,850 a	1.94 a
Winter Sweet	33.11 b	1.63 c	20,557 bc	1.25 bc
Significance ^z	5.68E-09***	2.20E-16***	3.69E-13***	3.81E-14***
Interaction				
PD × V	NS	8.96E-05***	NS	2.42E-02
Dryland 2016 trial				
Treatment	Yield (t/ha)	Fruit weight (kg)	No. fruit/ha	No. fruit/plant
Planting density (plants/ha)				
3,827	26.92	2.04 a	13,435 b	3.51 a
5,741	25.29	1.99 ab	13,235 b	3.51 b
9,568	29.88	1.81 ab	17,502 a	1.83 b
14,352	26.34	1.56 b	16,944 ab	1.18 c
Significance ^z	NS	6.32E-03**	NS	1.83E-04***
Variety				
Bonbon	26.27 b	1.52 cd	17,460 ab	2.44a
Burgess Buttercup	23.61 b	1.24 d	18,180 a	2.48 a
Crown	37.50 a	3.09 a	12,439 bc	1.79 a
Delica	21.36 b	1.83 bc	11,881 c	1.68 a
Sunshine	28.87 ab	1.85 bc	15,548 abc	2.28 a
Sweet Mama	22.19 b	1.97 b	11,480 c	1.61 a
Tetsukabuto	27.82 b	1.64 c	19,455 a	2.91 a
Winter Sweet	29.32 ab	1.63 c	15,788 abc	2.46 a
Significance ^z	1.68E-05***	2.20E-16***	1.35E-06***	1.86E-05***
Interaction				
PD × V	NS	8.96E-05***	NS	4.95E-02*
Dryland 2017 trial				
Treatment	Yield (t·ha ⁻¹)	Fruit weight (kg)	No. fruit/ha	No. fruit/plant
Planting density (plants/ha)				
5,741	10.73	1.42 a	7,849 a	1.37 a
8,611	12.93	1.36 a	9,630 bc	1.12 b
14,352	11.90	1.13 b	10,898 ab	0.76
21,528	11.54	0.93 b	12,454 a	0.59 c
Significance ^z	NS	1.27E-04***	1.21E-09***	5.07E-06***
Variety				
Bonbon	13.90 a	1.09 bc	13,008 a	1.17 a
Burgess Buttercup	9.58 b	0.85 c	11,303 ab	1.14 a
Crown	13.87 a	1.80 a	7,893 c	0.71 b
Delica	10.77 ab	1.16 b	9,951 abc	0.90 ab
Sunshine	11.43 ab	1.13 bc	10,764 abc	0.97 ab
Sweet Mama	10.00 b	1.20 b	8,612 bc	0.79 ab
Tetsukabuto	13.01 ab	1.18 b	11,033 abc	1.07 ab
Winter Sweet	11.52 ab	1.25 b	9,8687 abc	0.91 ab
Significance ^z	2.05E-03**	2.20E-16***	1.45E-05***	2.24E-05***
Interactions				
PD × V	NS	0.0101	NS	NS

^zP value from mixed-model analysis.

Values are the means of three replicates (dryland 2016 trial), four replicates (dryland 2017 trial), or eight replicates (irrigated 2016 and 2017 trials). Values followed by the same letter within a column are not significantly different at the 0.05% level of probability according to Duncan's new multiple range test.

PD = planting density; V = variety.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

using carbaryl (Sevin; Bayer Crop Sciences, Kansas City, MO). Three applications were applied in 2016 and four applications were applied in 2017. In 2017, powdery mildew was controlled using two applications of fluxapyroxad with pyraclostrobin (Merivon, BASF, Beaumont, TX).

Harvest timing and measurements. Plots were harvested on or after 45 d after pollination from 29 Aug. to 9 Sept. 2016 and 5 Sept. to 14 Sept. 2017. All fruit were weighed individually. All fruit in each plot were photographed. Immature fruit were not included in the yield calculations.

Results

The effect of irrigation

The main split-plot treatment was full irrigation and no irrigation (dryland production). All varieties were higher yielding when irrigated, except for 'Crown' in 2016 (Table 2). The 2016 irrigated yield average was 35.7 t·ha⁻¹, and the 2017 irrigated yield average was 32.2 t·ha⁻¹. The 2016 dryland yield average was 27.1 t·ha⁻¹ (76% of 2016 irrigated yield) and the 2017 average was 11.8 t·ha⁻¹ (37% of 2017 irrigated yield). A combined analysis of the 2-year trial comparing fully irrigated squash to dryland-grown squash was not possible because most fruit from the 2017 dryland trial were small and yields were low across all planting densities. Moreover, the assumptions for conducting a mixed-model analysis across the dryland trials were not met because the fixed treatment (planting density) was not the same for both years and there was not homogeneity of variance between the dryland trials. A comparison between irrigated and dryland production was possible for 2016, and they were different at $P = 0.05782$.

The effect of planting density

Planting density had no significant impact on yield across all varieties (Fig. 1A and E), but it had a significant impact on fruit size (Table 3, Figs. 1B and 1F, and 2), number of fruit per hectare (Table 4, Fig. 1C and G), and number of fruit per plant (Fig. 1D and H).

Yield. Planting density had no statistically significant impact on yield across all varieties (Fig. 1A and E). The number of fruit per hectare increased (153% more fruit at higher densities, averaged across all trials) at roughly the same rate that the size of the fruit decreased (143% larger fruit at lower densities, averaged across all trials) (Fig. 1B and F). Lower planting densities did not increase the number of fruit per plant produced to more than two in the irrigated trial (Fig. 1D), and so did not have a significantly greater average yield despite larger fruit size (Fig. 1B and F).

Fruit weight. A combined analysis of the irrigated trial showed that the average fruit weight decreased from 1.89 to 1.30 kg (a 31% decrease) as planting density increased from 8611 to 32,292 plants/ha (a 375% increase). In the dryland trials, fruit weight decreased from 2.04 to 1.56 kg (a 24% decrease) in 2016 and from 1.42 to 0.93 kg (a 35%

Irrigated

Fig. 1. Yield component response to planting density across 2 years of irrigated production (years averaged) including (A) tonnes per hectare, (B) fruit weight, (C) number of fruit per hectare, and (D) number of fruit per plant. Dryland production yield component response to planting density (2016 and 2017 shown separately) include (E) tonnes per hectare, (F) fruit weight, (G) number of fruit per hectare, and (H) number of fruit per plant.

Dryland

Fig. 1. (Continued)

Table 3. Fruit weight of seven *C. maxima* varieties and one interspecific hybrid grown at four planting densities for 2 years.

Variety	Irrigated 2016 and 2017 trials			
	Planting density			
	8,611 plants/ha	12,917 plants/ha	21,528 plants/ha	32,292 plants/ha
Bonbon	1.61 d	1.54 de	1.46 ab	1.25 b
Burgess Buttercup	1.23 e	1.23 e	1.06 a	1.05 b
Crown	2.61 a	2.36 a	1.87 a	1.77 a
Delica	1.89 cd	1.82 cd	1.44 ab	1.17 b
Sunshine	1.99 c	1.95 bc	1.78 a	1.15 b
Sweet Mama	2.29 b	2.25 ab	1.65 a	1.41 ab
Tetsukabuto	1.74 cd	1.70 cd	1.62 a	1.47 ab
Winter Sweet	1.80 cd	1.86 cd	1.61 a	1.28 b
Significance ^z	2E-16***	1.018E-11***	0.0003077***	0.0008368***
Variety	Dryland 2016 trial			
	Planting density			
	3,827 plants/ha	5,741 plants/ha	9,568 plants/ha	14,352 plants/ha
Bonbon	1.64 b	1.65 be	1.41 cd	1.39 b
Burgess Buttercup	1.63 b	1.42 c	1.16 d	1.17 b
Crown	3.28 a	3.50 a	3.07 a	2.49 a
Delica	1.85 b	2.12 b	1.90 b	1.48 b
Sunshine	2.13 b	2.10 b	1.72 be	1.45 b
Sweet Mama	2.34 b	1.98 bc	1.91 b	1.64 b
Tetsukabuto	1.51 b	1.41 c	1.33 d	1.38 b
Winter Sweet	2.12 b	1.77 bc	1.94 b	1.52 b
Significance ^z	0.0002809***	4.03E-07***	5.23E-09***	2.75E-08***
Variety	Dryland 2017 trial			
	Planting density			
	5,741 plants/ha	8,611 plants/ha	14,352 plants/ha	21,528 plants/ha
Bonbon	1.18 de	1.29 b	0.97 b	0.94 b
Burgess Buttercup	0.88 e	0.99 b	0.77 b	0.75 b
Crown	2.08 a	1.96 a	1.80 a	1.35 a
Delica	1.55 bc	1.40 b	1.02 b	0.74 b
Sunshine	1.42 bcd	1.35 b	0.97 b	0.78 b
Sweet Mama	1.47 bcd	1.41 b	1.00 b	0.92 b
Tetsukabuto	1.20 cde	1.13 b	1.37 ab	1.01 b
Winter Sweet	1.57 b	1.39 b	1.11 b	0.93 b
Significance ^z	1.96E-07***	5.44E-05***	0.0008192***	4.32E-05***

^zP value from mixed-model analysis.

Values are the means of three replicates (dryland 2016 trial), four replicates (dryland 2017 trial), or eight replicates (irrigated 2016 and 2017 trials). Values followed by the same letter within a column are not significantly different at the 0.05% level of probability according to Duncan's new multiple range test.

ns, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

decrease) in 2017 as planting density increased 375% in 2016 and 2017 (3827–14,352 plants/ha in 2016, 5741–21,528 plants/ha in 2017). There is a linear relationship between planting density and fruit weight. A simple linear regression was calculated to predict fruit weight based on planting density under irrigated production. A significant regression equation was found [$F(1, 238) = 77.0$, $P = 3.35E-16$], with an R^2 value of 0.24. Fruit predicted weight is equal to $2.12 - 0.025$ kg (thousands of plants per hectare). Average fruit weight decreased 0.025 kg for every 1000 plants/ha.

Figure 2 illustrates fruit size distribution at different planting densities for the top three numerically largest varieties: 'Crown', 'Sunshine', and 'Sweet Mama'. The fruit size distribution at four different planting densities had SDs ranging from 0.14 to 0.45 kg with mean fruit weights of 2.61 ± 0.20 kg, 2.36 ± 0.34 kg, 1.87 ± 0.34 kg, and 1.77 ± 0.45 kg for 'Crown'; 1.99 ± 0.14 kg, 1.95 ± 0.20 kg, 1.78 ± 0.25 kg, and 1.15 ± 0.28 kg for 'Sunshine'; and 2.29 ± 0.23 kg, 2.25 ± 0.21 kg, 1.65 ± 0.36 kg, and 1.41 ± 0.28 kg for 'Sweet Mama' at 8611, 12,917, 21,528, and 32,292 plants/ha respectively (Table 3, Fig. 2). As planting density increased, average fruit size decreased,

whereas the variance in fruit size stayed at or below an SD 0.45 kg. The SD increased as planting density increased for 'Crown' and 'Sunshine', but not 'Sweet Mama'.

Fruit per hectare. A combined analysis of the irrigated trial showed that the number of fruit per hectare increased from 6660 to 10,590 (a 159% increase) as planting density increased from 8611 to 32,292 plants/ha (a 375% increase). In the 2016 and 2017 dryland trials, the number of fruit per hectare increased from 5437 to 6857 (a 126% increase) in 2016 and from 3176 to 5040 (a 158% increase) in 2017 as planting density increased from 3827 to 14,352 plants/ha in 2016 (a 375% increase) and 5741 to 21,528 plants/ha in 2017 (a 375% increase). A simple linear regression was calculated to predict the number of fruit per hectare based on planting density under irrigated production. A significant regression equation was found [$F(1, 238) = 31.6$, $P = 5.34E-8$], with an R^2 value of 0.113. The fruit per hectare predicted number is equal to $14,631 + 362$ fruit/ha (thousands of plants per hectare). The average number of fruit per hectare increased by 362 for every 1000-plants/ha increase in planting density.

Fruit per plant. In the combined analysis of the irrigated trial, the number of fruit per

plant decreased from 1.96 to 0.82 (a 58% decrease) from the lowest density (8611 plants/ha) to the highest density (32,292 plants/ha)—a 375% increase. In the irrigated trials, even at the lowest planting density, plants did not produce more than two fruit per plant on average across varieties. In the 2016 and 2017 dryland trials, the number of fruit per plant decreased from 3.51 to 1.18 (a 66% decrease) in 2016 and from 1.37 to 0.59 (a 57% decrease) in 2017 as planting density increased 375% in both trials.

The effect of variety

The effect of variety was significant for all measured components of yield in a combined analysis of the irrigated trials ($P \leq 0.0001$), in the 2016 dryland trial ($P \leq 0.0001$), and in the 2017 dryland trial ($P \leq 0.01$) according to a mixed-model analysis (Table 2, Fig. 3). In the combined analysis of the irrigated trials, 'Tetsukabuto' had the statistically highest yield (mean, 51.4 t·ha⁻¹), the highest number of fruit per hectare (mean, 12,080), and the highest number of fruit per plant (mean, 1.94). Fruit size for 'Tetsukabuto' averaged 1.64 kg. 'Crown', 'Sweet Mama', and 'Sunshine' averaged numerically heavier fruit (2.14, 1.90, and

Fig. 2. Histogram of fruit weight distribution at each planting density for the three varieties with the top three numerically largest fruit weights, including Crown, Sunshine, and Sweet Mama, under irrigated production. Fruit weight classes are (A) ≤ 0.59 kg, (B) 0.6 to 0.99 kg, (C) 1.0 to 1.39 kg, (D) 1.4 to 1.79 kg, (E) 1.8 to 2.19 kg, (F) 2.2 to 2.59 kg, and (G) ≥ 2.6 kg.

1.71 kg, respectively), although these differences were not statistically different. ‘Crown’ had the largest average fruit size (2.14 kg) and the lowest number of fruit per plant (0.93), although other varieties had statistically similar outcomes for both of these components of yield.

‘Tetsukabuto’ had comparable yield performance to the other varieties in the dryland trials. In 2016, the three highest yielding varieties were not statistically different from each other: ‘Crown’, at 37.5 t·ha⁻¹; ‘Sunshine’, at 28.9 t·ha⁻¹ and ‘Winter Sweet’, at 29.3 t·ha⁻¹. Yields of ‘Sunshine’ and ‘Winter Sweet’ were not statistically different from all the other varieties. In 2017, there were no standout varieties for yield, number of fruit per plant, or number of fruit per hectare. In 2016 and 2017, there were no standout varieties for number of

fruit per plant and number of fruit per hectare.

Discussion

The goals of this project were 1) to identify productive kabocha and buttercup varieties for western Oregon when grown with and without irrigation, and 2) to describe the effects of planting density on yield, fruit weight, number of fruit per hectare, and number of fruit per plant.

Productive kabocha and buttercup varieties with and without irrigation

All varieties included in the analysis performed well in western Oregon, and this is strongly dependent on the prevalence of the regionally unique soilborne disease complex

(Rivedal, 2019). The kabocha/buttercup varieties grown in the trial had statistically similar yields, ranging from 27.9–33.1 t·ha⁻¹ when grown with irrigation. These yields fall within the range of the previously reported maximum yields of 21 to 38 t·ha⁻¹ for kabochas and buttercups (Botwright et al., 1998; Chung et al., 1992; Douglas et al., 1990; Morgan and Midmore, 2003; Sánchez et al., 2012). Yields for kabochas and buttercups decrease when a proportion of fruit are rejected because of size and quality standards. ‘Tetsukabuto’ yields were significantly greater than all other varieties when grown with irrigation ($P = 5.68E-9$). This interspecific hybrid is used as a rootstock in melon production (Karaağaç and Balkaya, 2013; King et al., 2010) and has rarely been grown for fresh market in the United States, although it is sold as a fresh market squash in Japan (Pan, 1995) and Brazil

(Amaro et al., 2017). Additional research is warranted to determine whether U.S. consumers will find the appearance and culinary quality of ‘Tetsukabuto’ acceptable.

All these winter squash varieties yielded well when grown in dryland conditions in 2016, but dryland yields, fruit per plant, and fruit size were very low in 2017. It is most

likely that the 2017 low yield was the result of the extremely high summer temperatures and dry conditions in western Oregon, as up until that date, 2017 had the driest July, the 33rd driest June, the hottest August, the 16th hottest June, and the 12th hottest July in 126 years (National Weather Service, 2017). Sufficient water is needed during the critical growth stages of pollination, fruit set, and particularly fruit expansion and fill, which occurs in late July and early August (Loy, 2004). High air temperatures increase transpiration and wilting, likely suppressing fruit pollination and set (which determines fruit per plant) and fruit expansion (which determines fruit size). Temperatures in western Oregon are predicted to increase by 4.5 °F for the mean low and 6.5 °F for the mean high by 2050. In addition, extreme heat events are predicted to increase in intensity, frequency, and duration (Dalton et al., 2017). More research is required to determine the impact of high summer temperatures on dryland winter squash performance.

Farmers with and without access to irrigation are considering dryland production because of the many benefits to this production system, including fewer weeds (as there is no water applied to stimulate weed seed germination) and reduced costs

Fig. 3. Mean yield for irrigated and dryland production in 2016 and 2017 across all planting densities.

Table 4. Number of fruit per hectare of seven *C. maxima* varieties and one interspecific hybrid grown at four planting densities for 2 years.

Variety	Irrigated 2016 and 2017 trials			
	Planting density			
	8,611 plants/ha	12,917 plants/ha	21,528 plants/ha	32,292 plants/ha
Bonbon	16,685 abc	20,720 b	22,066 b	26,761 ab
Burgess Buttercup	26,094 ab	18,760 b	25,575 ab	30,443 a
Crown	11,033 c	15,877 b	15,068 b	15,338 b
Delica	17,582 abc	16,504 b	22,758 b	28,294 ab
Sunshine	16,146 abc	15,877 b	21,797 b	27,453 ab
Sweet Mama	11,070 c	13,531 b	18,451 b	26,761 ab
Tetsukabuto	29,331 a	29,060 a	34,743 a	30,765 a
Winter Sweet	14,532 bc	19,067 b	23,411 b	25,032 ab
Significance ^z	0.001959**	7.88E-06***	0.0007218***	0.02424*
Variety	Dryland 2016 trial			
	Planting density			
	3,827 plants/ha	5,741 plants/ha	9,568 plants/ha	14,352 plants/ha
Bonbon	12,758 ab	16,264 a	21,688 a	19,136 a
Burgess Buttercup	12,758 ab	15,308 a	22,645 a	22,007 a
Crown	12,121 ab	8,930 a	13,077 a	15,627 a
Delica	10,205 b	9,568 a	13,077 a	14,671 a
Sunshine	13,396 ab	15,627 a	16,904 a	16,264 a
Sweet Mama	8,612 b	11,162 a	12,439 a	13,714 a
Tetsukabuto	21,048 a	13,077 a	22,963 a	20,730 a
Winter Sweet	16,583 ab	15,946 a	17,223 a	13,396 a
Significance ^z	0.02231*	1.93E-01 NS	4.23E-02*	9.98E-03**
Variety	Dryland 2017 trial			
	Planting density			
	5,741 plants/ha	8,611 plants/ha	14,352 plants/ha	21,528 plants/ha
Bonbon	8,612 ab	16,624 a	15,068 a	16,504 a
Burgess Buttercup	10,047 ab	15,308 a	10,406 ab	11,481 a
Crown	5,024 b	8,930 a	7,534 b	10,764 a
Delica	7,534 ab	9,568 a	10,764 ab	12,916 a
Sunshine	7,534 ab	15,627 a	11,122 ab	15,068 a
Sweet Mama	5,740 ab	11,162 a	10,047 b	10,047 a
Tetsukabuto	10,406 a	13,077 a	12,200 ab	12,916 a
Winter Sweet	7,893 ab	15,946 a	10,047 b	12,200 a
Significance ^z	2.65E-02*	9.47E-02 NS	0.009021**	2.76E-01 NS

^zP value from mixed-model analysis.

Values are the means of three replicates (dryland 2016 trial), four replicates (dryland 2017 trial), or eight replicates (irrigated 2016 and 2017 trials). Values followed by the same letter within a column are not significantly different at the 0.05% level of probability according to Duncan's new multiple range test.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

associated with irrigation (including equipment, energy, and labor). However, not all soils are equally suited to dryland production. In both years, this research was conducted on a Chehalis silty clay loam. This soil series, with a dryland productivity rating of 80 (the highest possible dryland rating), is better suited to dryland production than other soils in the Willamette Valley (Huddleston, 1982). More work is needed to assess soils for winter squash dryland production capacity.

The effect of planting density

Yield. Across all varieties, an increase in planting density did not increase yield significantly in this study. This is in contrast to other studies (Botwright et al., 1998; Chung et al., 1992) in which increased planting density did increase yield. Douglas et al. (1990) reported a small decline in yield at the greatest planting density. The same parabolic trend is evident in yield response to planting density across all varieties under irrigated production in this study, however it is not statistically significant. The lack of significant difference in this study may be the result of a different climate or growing conditions, or because of the relatively small number of density treatments ($n = 4$) or small range of planting densities (0.86–3.2 plants/m²) used compared with the number of density treatments ($n = 6$ –16) and wider range of planting densities (0.23–6 plants/m²) used in other studies (Botwright et al., 1998; Douglas et al., 1990).

Fruit weight. Across all varieties, an increase in planting density decreased fruit size. This trend is evident and important for the three numerically largest varieties in the irrigated trial: ‘Crown’, ‘Sunshine’, and ‘Sweet Mama’. Average fruit size decreased from 2.61 to 1.77 kg, 1.99 to 1.15 kg, and 2.29 to 1.41 kg from the lowest to highest planting density, respectively. This is a decrease of 32%, 42%, and 38%, respectively. Fruit size distribution as measured by the SD of the mean ranged from 0.14 to 0.45 kg when measured at each planting density for these three varieties. Fruit size for ‘Crown’ increased by 14% when grown in dryland conditions, whereas fruit size for ‘Sweet Mama’ and ‘Sunshine’ decreased by 17% and 13%, respectively. The 2016 irrigated trial suffered from early-onset and severe powdery mildew, and if ‘Crown’ is particularly susceptible, this may explain why the average fruit size was larger under dryland production.

There is not one agreed-on marketable fruit size range for kabochas, and as discussed previously, different markets may require different sizes. ‘Crown’ and ‘Sweet Mama’ average fruit size was within the range set by Botwright et al. (1998) of 1.2 to 2.0 kg when planted between 21,528 to 32,292 plants/ha (2.2–3.2 plants/m²) under irrigated production. ‘Sunshine’ average fruit size was within the range when planted between 8611 and 21,528 plants/ha (0.9–2.2 plants/m²). These are greater planting densities for ‘Crown’ and ‘Sweet Mama’ than the previously recommended 0.6 to 2.2 plants/m²

for New Zealand and Tasmania (Botwright et al., 1998; Douglas et al., 1990), and greater than the 0.15 to 1.8 plants/m² mentioned in U.S. Extension publications (Bachmann, 2010; Hemphill, 2010; Kemble et al., 2000; National Integrated Pest Management Database, 2006). Farmers can manipulate planting density to produce fruit of the size preferred by their customers.

Number of fruit per hectare. Across all varieties, an increase in planting density increased the number of fruit per hectare (and decreased fruit size). If American consumers (excluding processors and restaurants) are amenable to smaller fruit, a greater planting density could be more profitable for some farms, such as CSAs wanting to fill more shares per hectare with greater numbers of smaller fruit.

Fruit per plant. ‘Tetsukabuto’ is high yielding resulting in part from its high number of fruit per plant. The kabocha and buttercup types averaged 1.35 fruit/plant across all densities and 2.03 fruit/plant at the lowest density in the irrigated trials, whereas ‘Tetsukabuto’ averaged 1.94 fruit/plant across all densities and 3.4 fruit/plant at the lowest planting density (8611 plants/ha) (Table 2). This concurs with Australian research in which ‘Tetsukabuto’ had, on average, a greater number of fruit per plant compared with kabochas, with an average of 4.5 fruit/plant across three trials (Morgan and Midmore, 2003). In our work, ‘Tetsukabuto’ also yielded well when grown under dryland conditions; its dryland yield was comparable to seven varieties in 2016 at 27.8 t·ha⁻¹ and comparable to all other varieties in 2017 at 13.0 t·ha⁻¹ (Table 2).

Conclusions

All of the varieties for which yield data are reported performed well when grown with overhead irrigation in this region. Overall, ‘Tetsukabuto’ was the highest yielding, on average, when grown with irrigation. Consumer preference for this squash is unknown, but its agronomic performance in this study and anecdotal information about its texture and flavor warrant further investigation into its potential for fresh market sales. Farmers can manipulate planting density to generate the average fruit size preferred by buyers. Winter squash can be grown in dryland conditions on soils of high dryland potential (Huddleston, 1982) but yields may be low in years with extreme heat events that occur during critical growth phases of the crop.

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Supplemental Table 1. Compost nutrient analysis for 2016 and 2017.

Compost Parameters	Reported as (units of measure)	2016	2017
Plant nutrients	%, dry weight basis		
Nitrogen	Total N	1.3	1.4
Phosphorus	P ₂ O ₅	0.6	0.6
Potassium	K ₂ O	1.1	0.7
Calcium	Ca	1.6	2.1
Magnesium	Mg	0.3	0.3
Moisture content	%, wet weight basis	66.2	61.0
Organic matter (as received)	%, dry weight basis	59.6	70.0
pH	pH units	7.6	7.7