THESIS

THE RELATIONSHIP BETWEEN GREENHOUSE AND FIELD PERFORMANCE OF DIVERSE CULTIVARS OF SUMMER SQUASH AND WATERMELON GROWN UNDER MOISTURE STRESSED CONDITIONS

Submitted by

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ABSTRACT

THE RELATIONSHIP BETWEEN GREENHOUSE AND FIELD PERFORMANCE OF DIVERSE CULTIVARS OF SUMMER SQUASH AND WATERMELON GROWN UNDER MOISTURE STRESSED CONDITIONS

Drought stress poses a major threat to the global food supply, and most domestic vegetable growers lack cultivar-specific information that would allow them to adopt best management practices to limit the impacts of these stressors. Summer squash (*Cucurbita pepo*) and watermelon (*Citrullus lanatus*) are two crops in the Cucurbitaceae family that are commonly grown and consumed in the U.S. Heirlooms and modern cultivars of these crops with reports of “drought resistance” are currently available on the market without concomitant recommended modifications to irrigation management. Many published greenhouse experiments have been used to screen cultivars and breeding lines for drought resistance, but often lack paired field trials to confirm results. We conducted a greenhouse dry-down study on nine summer squash and 10 watermelon cultivars, and sustained deficit irrigation (SDI) field trials on a selected 13. Our objective was to determine if crop characteristics identified in the greenhouse studies could be predictive of season-long field success under drought conditions. Colorado-bred conventional hybrids were used as control cultivars in both studies, and were hypothesized to have a more drought-sensitive response than cultivars with reports of drought resistance. Parameters evaluated in the greenhouse study included: days to death, percent soil moisture at death, root:shoot ratio, and root system characteristics. The cultivars that were then evaluated in the field study received one of three sustained deficit irrigation treatments:

control, deficit, or drought, using a drip irrigation system in a split-plot design with three replications. Control treatments were reduced to approximately half the average recommended number of acre-inches of water per season for each crop, averaging 5.9 and 4.8 inches for summer squash and watermelon, respectively. Deficit and drought irrigation treatments were reduced 50% beyond the control during the treatment interval, which began after flowering and extended over the course of 12 weeks for the squash, and six weeks for watermelon. The deficit treatment plots received irrigations of equal frequency to the control, in half the amount, and the drought treatment plots received irrigations at half the frequency of the control, with the same volume of water as the control applied at each irrigation event. Squash were grown under rain exclusion and watermelons were grown in an open field with rainfall amounts factored into total water application calculations. Soil moisture and environmental conditions were monitored, and yield and quality measures were taken in both crops. Photosynthetic activity was also evaluated twice each season in the summer squash plot using a MultispeQ. Our results revealed that greenhouse performance was often not indicative of field performance, and that almost all squash cultivars produced acceptable levels of marketable yield under severe water deficits in the field. Watermelon cultivars produced marketable fruits in both years, but performance was inconsistent from year to year, and yield was low across all cultivars and treatments. Modern cultivars and heirlooms with reports of drought resistance, such as ‘Desert King’ watermelon and ‘Desert F1’ zucchini, did not necessarily out-perform hybrids or open-pollinated cultivars without such reports, such as ‘Amiga’ watermelon, and ‘Jasper’ and ‘Dark Star’ summer squash. By imposing a sustained deficit of more than 50% below recommended season-long rates, we identified five bestperforming cultivars of summer squash that experience an approximate yield penalty of 30% under these conditions. The results of this study offer a prescriptive weekly method of irrigation management combined with recommendations for currently available cultivars that can be readily adopted by local, fresh-market growers to enable significant water savings without reductions in quality.

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1. INTRODUCTION

Water limitation is one of the single largest threats to agricultural production and the global food supply (Farooq et al., 2009). Therefore, the future of global food security depends partly on the identification and breeding of crop species and cultivars that can produce acceptable yields with reduced irrigation. The need for conserving the resources of the Colorado River, which supplies irrigation for seven of the 17 Western states has begun receiving public attention (Elliott, 2019). While extensive research has been conducted in the interest of reducing water use in agronomic crops and breeding drought-resistant grain crop cultivars, such experiments and breeding in annual horticultural food crops remains relatively limited in the United States (Jiang et al., 2019; Kuşçu et al., 2015; Mashilo et al., 2018; Yuan et al., 2006). Within the Cucurbitaceae family, cucumbers, melons, and watermelons have been more frequently studied than summer squash. In addition, the target environment of most available studies is outside of North America, even though watermelon is one of the top vegetable crops produced in the U.S. and summer squash continues to gain popularity (Agricultural Marketing Service, 2018; Kirnak and Demirtas, 2006; YuJue et al., 2011; Singh et al., 2019). The consumption of fruits and vegetables is considered essential for public health, so ensuring our ability to produce these crops into the foreseeable future is an important goal in the face of global climate change (Tuomisto et al., 2017).

Summer squash and watermelon are annual vegetable crops with an extensive distribution and natural history in North America (Blake, 1981; Paris, 2015; Smith, 2006). Irrigation recommendations for these two crops are variable, and though some cultivars are reported by seed companies to be drought-resistant, little specific information exists to assist growers in appropriately reducing irrigation inputs in these cultivars, and published studies in these crops are not always cultivar-specific (Daniello, n.d.; Molinar et al, n.d.; Kuşçu et al., 2015; Shrefler et al., 2017). It is important for this gap in research to be filled so that vegetable growers have access to information on cultivar-specific responses to reduced irrigation in conditions that vary across time, so that they may better understand crop yield and physiological consequences of these management decisions.

A large collection of terms is used to describe the way crop plants respond to sub-optimal moisture conditions in agricultural production systems. In order to understand the body of research on this subject, the terms surrounding it must be clearly defined and appropriately applied. Agricultural drought applies to any extended period of reduced soil moisture that negatively impacts crop yields and profitability (Vergni, 2004). While agricultural drought involves climatic and soil conditions, the term drought stress also involves the crop's response to such conditions. Drought stress refers to the moderate loss of water, which ultimately leads to a decrease in growth due to stomatal closure, a reduction in gas exchange and photosynthetic rate, and a loss of turgor. Desiccation involves a more extensive loss of water than drought stress and leads to the arrest of photosynthetic processes, and eventually plant death. Water stress is a general term which applies to any limitation of cell enlargement and reduction in growth caused by insufficient moisture conditions that negatively impact photosynthesis, respiration, and other metabolic processes (Jaleel et al., 2009). Therefore, water stress may occur before the onset of true drought stress, and may not significantly impact crop yields unless it progresses into drought stress. Drought stress, however, may lead to suboptimal yields without causing total desiccation. This reduction below optimal yield is referred to as a yield penalty, the degree of which may vary among cultivars grown under the same conditions (Costa et al., 2007). Overall water productivity applies to the harvestable crop production per unit of water used, which can vary by crop and cultivar as well (Fereres & Soriano, 2006). By contrast, water use efficiency is the ratio of total biomass produced per unit of water applied (Hatfield & Dold, 2019). In cases where drought stress severely reduces plant productivity, but does not inhibit reproduction altogether, the crop may produce a subsistence yield. Subsistence yield is the production of economically important plant parts as a result of drought resistance strategies that allow the plant to survive for a greater length of time under water limitation (Basu et al., 2016). Survivability is the length of time that a plant lives through stressful conditions, including drought, with or without the production of subsistence yield (Moradi et al., 2014). The presence of traits that contribute to crop survivability are not always indicative of a crop's ability to maintain yield potential under drought, however. The most directly observable and relevant trait contributing to success under drought is yield stability under drought, which should be observed in a field setting (Basu et al., 2016). Season-long success under drought will be used hereafter to refer to the production of economically important plant parts under reduced irrigation from flowering and through multiple harvests until the end of the growing season.

Another class of terminology refers to types of irrigation management that focus on reducing water use, which, at times, could lead to controlled moisture stress or drought stress. Fereres and Soriano (2006) concisely define deficit irrigation (DI) as "the application of water below full crop-water requirements", those water requirements often being determined by calculating evapotranspiration (ET) rates. Sustained deficit irrigation (SDI) is a specific pattern of deficit irrigation where a uniform application of water is given throughout the season so that the crop undergoes an increasing deficit as it reaches maturity, giving the plant time to adapt to more severe drought stress. This method is best used in areas with a high capacity for water storage (Fereres and Soriano, 2006). An example of SDI is provided by Mashilo et al. (2016) in a drought study conducted on breeding lines of bottle gourd. Rainfed conditions (26.2cm, 10.3 inches) were used as the drought stress treatment and the non-stressed treatment received fixed-schedule sprinkler irrigation totaling 35cm (13.8 inches) throughout the season in this field study. Under these conditions, they observed yield reductions that varied by genotype from 24-74%, thus allowing the authors to identify candidate breeding lines for drought resistance.

The adaptations which allow plants to respond to and overcome the negative impacts of drought stress fall into three categories: escape, avoidance, and tolerance, all of which can be referred to as drought resistance. Drought tolerance is mediated at the cellular and molecular levels and is sometimes referred to as “true” tolerance to drought because it allows plants to survive under periods of low cellular water potential. Adaptations that fall into the category of drought escape allow plants to respond to low soil moisture by expediting their life cycle in order to reproduce before the onset of more severe drought conditions. Drought-avoidance strategies, on the other hand, prevent the plant from undergoing drought stress through either water-saving or water-spending methods. Water-saving methods entail conservative water use and regulation of transpiration, which allows plants to maintain leaf water status under drought conditions. Water-spending methods involve the development of deep and extensive root systems which enable the plant to excavate soil moisture reserves (Basu et al., 2016). In contrast, drought sensitivity is the gravity of a plant's negative response to drought stress on a molecular, physiological, or morphological level, and typically has a negative impact on yield stability as well (Lobell, 2008). We will use the term drought response to characterize the degree of impact of drought on crop plants, which may have a positive or negative effect on yield stability.

Cucurbita pepo, which includes yellow crookneck, scallop, zucchini squash and others, has two centers of domestication in North America; one in what is now the Eastern United States, and one in Southern Mexico. These domestication events took place five and ten thousand years ago, respectively (Smith, 2006). Because of this vegetable crop's native status and extended history in North America, it was widely used by Native North Americans and has become adapted to a wide range of habitats, including the Southwest where water resources are naturally limited. Watermelon was first cultivated in semi-arid regions of Northern Africa over 3,500 years ago (Blake, 1981; Paris, 2015; Renner et al., 2019). While their center of origin is not in North America, watermelons were first brought to this continent by Spanish settlers in the 1600s and were quickly adopted by tribes throughout the U.S. and Mexico. Over the course of the past 400 plus years, this crop was grown in traditional farming systems throughout the semi-arid Southwestern U.S, allowing for region-specific selections to be made (Blake, 1981). The history and genetic diversity of these two crops makes them prime crops of interest in the study of drought adaptation and future breeding for improved response to water stress.

The demand for summer squash and watermelon among U.S. growers and consumers has increased in recent years. The Agricultural Marketing Resource Center (2018) cites an upward trend in watermelon consumption with an average of 7.3 kilograms (16.1 pounds) per person each year in the U.S. in 2017. 45,729 hectares (113,000 acres) of watermelon were grown in the U.S. in 2017, valued at $578.8 million. Total land area of all squash crops reached 15,135 hectares (37,400 acres) in 2016 and was valued at $149 million. Annual consumption of squash, including both summer and winter squashes, totaled 2.3 kilograms (5.1 pounds) per person in 2016 (Agricultural Marketing Resource Center, 2018). Summer squash are also regularly sold by diversified vegetable producers at Farmer's markets in Fort Collins and throughout Northern Colorado (Colorado State University Extension, n.d.). Rocky Ford, CO has been famed for its high quality watermelon and cantaloupe production since 1887 ("Our History | Rocky Ford Growers Association," 2019.) Consumers state that increased cultivar availability and the use of sustainable farming practices, including reduced water use, are two of the most important drivers for shopping at farmer's markets (Bond et al., 2006). Because of this, small-scale and fresh market growers are more likely to be receptive to unique cultivars and adopting alternative management strategies such as reduced irrigation.

The University of California Small Farms Program estimates typical summer squash yield at 37,659.8 kilograms per hectare (33,600 pounds per acre), with a planting density of 12,140 plants per hectare (4,915 plants per acre). This equates to about 3.1 kilograms (6.8 pounds) of squash per plant under optimal conditions in a growing season of about 150 days, starting in March and ending in August (Molinar et al., n.d.). A study on high tunnel summer squash production in Utah reported yields between 0.82 and 0.93 kilograms (1.86 and 2.04 pounds) per plant. These lower yields were assumed to be due to lack of pollinator activity within the high tunnel (Drost, 2011). Watermelon yield estimates are often reported in tons per hectare and vary widely depending on what region they are grown in, whether they are hybrid, open-pollinated, seeded or seedless, and size class (Schrefler et al., 2017). Nationwide average yield in 2014 was 35,643 kilograms per hectare (31,800 pounds per acre) (Agricultural Marketing Service, 2018). In the Arkansas Valley of Colorado, a typical 9.1 kilogram (20-pound) watermelon cultivar yields between two and four melons per plant, but harvesting only one watermelon per plant is still considered acceptable yield with a planting density of 4,942 watermelons per hectare (2,000 watermelons per acre). Because it is common for watermelons to not reach full weight, this averages out to a yield of 33,612-44,816 kg/ha (30-40,000 lbs/ac), slightly above the national average (Mike Bartolo, personal communication, 2019).

Supplemental irrigation is required to produce acceptable yields of fruit and vegetable crops in semi-arid regions, including on the Front Range where annual precipitation has ranged from 233-556 millimeters (9.2-21.9 inches) per year over the past 20 years (High Plains Regional Climate Center - CLIMOD, 1998-2018). The average effective precipitation for summer crops in Northern Colorado is just 165.1 millimeters (6.5 inches), less than half of estimated needs for many crops. Moisture that occurs during a crop's growing season and directly benefits the crop is considered effective precipitation. Therefore, since much of this moisture comes in the form of snowfall during the winter and spring, which recharges soil moisture reserves but has limited use in crop production later in the summer, supplemental irrigation is required for the production of a successful vegetable crop (Schneeckloth and Andales, 2017).

Irrigation recommendations for fruit and vegetable crops, including summer squash and watermelon, are often general and likely over-estimate the true water needs of the crop in an effort to avoid advising growers to reduce irrigation beyond what is necessary for optimal yields

(Singh et al., 2019). The high cosmetic and quality-related standards included in the USDA grading system in addition to those imposed by produce buyers makes any amount of crop stress potentially economically harmful (Agricultural Marketing Service, 2006; 2016). Oklahoma State extension recommends between 203 and 254 miliimeters (eight and ten acre-inches) of irrigation per hectare for watermelon crops, while TAMU AgriLife Extension recommends watermelon crops receive 254 to 381 millimeters (10 to 15 inches) per hectare per growing season (Shrefler et al., 2017; Daniello, n.d.). Texas A&M recommends summer squash be given 178 to 254 millimeters (7 to 10 inches) of irrigation at a uniform rate throughout its life cycle, and The University of California Small Farms Program recommends a minimum of 457 millimeters (18 inches) of irrigation for summer squash crops, adjusted based on ET (Masabni, n.d.; Molinar et al, n.d.). More generous estimations from The University of California Small Farms Program estimate summer squash water needs at 762 mm (30 inches) per season (Molinar et al, n.d.). The closest irrigation recommendation for a cucurbit crop in Fort Collins is an estimate for cantaloupe crops grown in Greeley, which require an estimated 437 millimeters (17.2 inches) of irrigation per growing season (Schneeckloth & Andales, 2017). The estimated mean ET rate for Fort Collins between 1971-2000 was 31-40 centimeters, while rates in California ranged from zero to 70 centimeters, depending on the county, making statewide irrigation recommendations of limited use (Sanford & Selnick, 2013).

Irrigating based on ET is a commonly recommended practice and results in irrigation management regimes that are adapted to each region and its precipitation rates. However, this is not a tool commonly employed by diversified vegetable crop producers. For example, field crop grower irrigation decisions in Utah were found to be made based on a variety of factors, from crop development stage, to evidence of plant stress, to following the behaviors of neighboring farms (Andriyas, 2012). It has also been shown that cultural management strategies, such as the use of plastic mulch, may be effective at reducing drought stress without increasing irrigation amounts, further reducing the accuracy of ET estimations in these contexts (Bartolo, 2019; Kirnak and Demirtas, 2006). While estimates made based on total millimeters or inches per season or volume of water per plant can be less precise, this prescriptive approach can more readily be adopted by growers with adjusted amounts each season based on cultural management practices and observed crop needs.

The USDA Economic Research Service (2013) reports that 225,420 (557,025) irrigated horticulture crop hectares (acres) exist across the Western U.S., to which over 148,018 hectare-meters (1.2 million acre-feet) of irrigation water is applied annually. Nearly half of this water comes from ground water sources, both in Colorado and throughout the 17 Western states. Reducing irrigation water inputs is most desirable in situations where the grower is obtaining ground water from aquifers that are in danger of overdraft, and in years when low snow-pack limits surface irrigation water availability from the Colorado River (Elliott, 2019; Barta et al., 2004). Well pumping costs, unpredictable water-delivery schedules, and saline irrigation water in the West further add to the complexity of vegetable crop irrigation management decisions. Farms with junior water rights and those facing aquifer overdraft will benefit from knowing what the consequences of reduced irrigation inputs are for their crops, and which cultivars are the most reliable under reduced irrigation regimes.

The search for drought resistance in the Cucurbitaceae family has revealed a series of typical drought-sensitive crop responses. A decrease in leaf chlorophyll content, biomass accumulation, stomatal conductance, water use efficiency, and photosynthetic rate were observed in squash seedlings studied under drought in a greenhouse setting (Ors et al., 2016). Similar results were observed in pumpkin seedlings grown in a greenhouse (Sure, 2011). Yield penalties were also observed in both grafted and non-grafted watermelons once irrigation was reduced to 50% ET. ET rates were calculated for watermelons grown in this study for the purpose of irrigation management, but the total volume of water applied was not reported (Proietti et al., 2008). YuJue et al. (2010) reported that drought stressed greenhouse-grown cucumber seedlings had reduced photosynthetic rates (Pn), activity of photosystem II (Phi2), and photochemical quenching (PhiNO). Non-photochemical quenching (PhiNPQ) increased under drought stress. Bottle gourd was observed to decrease gas exchange and water use efficiency under drought stress in both field and greenhouse conditions. However, Phi2, PhiNO, and PhiNPQ were not impacted by drought stress in these bottle gourd landraces (Mashilo et al., 2016; 2018). These drought effects, except for the resilience of photosynthetic processes in bottle gourd, are similar to those generally observed in other crop species (Anjum et al., 2011).

The depth and distribution of a plant's root system is well-known to impact drought response. Deep root systems with many fine roots, especially those that develop quickly during the seedling stage, are beneficial in allowing plants to extract moisture deep from the soil profile and thereby survive periods of low precipitation or lack of irrigation (Anjum et al., 2011). Having a finer average root diameter has also been identified as a root trait that contributes to success under drought conditions (Comas et al., 2013). Summer squash is a moderately deep-rooted crop, with an estimated rooting depth of between 91-122 centimeters (36-48 inches). Watermelons are deep-rooted, with a root system that extends 122 centimeters (48 inches) or deeper into the soil profile (Maynard et al., 2007). Rooting depth of some vegetable crops, such as tomatoes, can also be further impacted by cultural practices such as transplanting, field conditions, and irrigation management (Miller et al., 2013). It has been demonstrated in ornamental plants that transplanting may improve fine root development and plant stress response even after being moved to field conditions (Judd et al., 2015). Cultivar-specific differences in root system distribution under drought in a field setting has been documented in melons and in watermelons grafted to cucurbit rootstocks as well (Miller et al., 2013; Sharma et al., 2018). However, to date, cultivar-specific differences in root system development in summer squash and watermelon in relation to drought stress has not been investigated in a greenhouse setting.

Season-long success under drought in the field may provide the most practically useful results, but such studies are resource-intensive and are subject to fluctuations in rainfall and temperature from year to year, which does not always guarantee that the desired degree of stress is induced. Experiments on deficit irrigation in cucumber in an open field setting (Amer, Midan, & Hatfield, 2009) showed that any reduction in irrigation below 100% ET resulted in a yield penalty. A deficit of 50% ET in open field conditions resulted in a 31% yield penalty for one watermelon cultivar (not named) in a sub-humid environment in Turkey (Kuşçu et al., 2015). In a field-based root system evaluation of melon, rainfall fluctuations resulted in the induction of moderate stress in year two, but not year one, which resulted in differences in root system development between the two years (Sharma et al., 2018).

Rain out shelters are commonly used in agronomic studies evaluating season-long success under drought to exclude rainfall from crops grown in otherwise typical field conditions. Any structure used for the purpose of rain exclusion which help ensure that the desired degree of drought stress is induced is considered a rain out or rain exclusion structure (Blum, 2010). These structures provide more control over the moisture applied, but often restrict the experimental plot size due to infrastructure limitations (Blum, 2010). For this reason, rain exclusion is still a relatively uncommon method of studying irrigation management in horticultural crops (Yuan et al., 2006). Greenhouse drought studies allow more control, require less space, and can be completed at any time of year, but are typically conducted at the seedling stage and therefore results are not necessarily applicable to the behavior of mature plants in a field setting (Zhang et al., 2011; Hameed et al., 2009).

As small and large-scale growers alike face dwindling water resources, additional tools and information are needed to inform irrigation reduction decisions. Squash and watermelon are ideal crops for the exploration of drought resistance potential in currently available cultivars, both due to the wide variety of genetic resources available, and due to these crops' popularity among farmers and consumers in Colorado and the United States. Direct markets are increasingly important to both growers and consumers and provide opportunities to introduce unique cultivars and more sustainable management practices on a smaller scale. Sustained deficit irrigation practices can more readily be followed by small-scale local growers than irrigating based on ET in these crops and is more closely aligned with the methodology of irrigation decisions on some farms. Experimental results have informed us of what to expect from drought sensitive cucurbits but has not fully revealed the range of responses in the diverse cultivars that are currently on the market.

Based on available research, we know that currently available cultivars of summer squash and watermelon that are appropriate for Northern Colorado growing conditions may experience differing yield penalties under drought conditions that have not yet been fully elucidated. We hypothesize that traits that contribute to survivability in these cultivars, such as days to death and seedling root system development, can be measured in a greenhouse setting and further evaluated as potential indicators for season-long success under drought under field conditions. Furthermore, moisture reduction below 50% of recommended rates will impact cultivars described as drought resistant differently than those bred for conventionally irrigated systems. Defining these differences in terms of expected yield penalty can assist growers in managing both irrigation reductions and cultivar selection.

2. MATERIALS AND METHODS

2.1 Overview and Cultivar Descriptions

Greenhouse studies were conducted to evaluate morphological traits of squash and watermelon seedlings under induced moisture stress. These potential indicators of drought resistance were then compared to season-long field performance. Heirlooms and modern cultivars of squash and watermelon were selected based on seed companies' reports of drought resistance, a record of performance with reduced irrigation, and demonstrated success in dryland systems. Control cultivars were bred for conventional growing conditions in close proximity to the target environment of Northern Colorado. Our choice to evaluate both heirlooms and modern cultivars with unique physical characteristics was also based on farmer's market customers' interest in more sustainable and unique produce, and growers' desire to be able to choose from both open-pollinated and hybrid cultivars (Bond et al., 2006).

Nine squash cultivars with a range of traits and adaptations were chosen for inclusion in a greenhouse seedling dry-down study (Table 1). 'Jasper', 'Obsidian', HZS-03-849', and 'Daisy Mae' were all selected from a Colorado-based vegetable breeder and used as control cultivars. These cultivars were assumed to yield well under optimal moisture conditions, and were not reported to be drought resistant. These control cultivars were zucchini types, apart from 'Daisy Mae' (Daisy), a yellow crookneck summer squash (NE Seeds, 2019). 'Early Summer Crookneck' (Crook) was another yellow summer squash chosen for its earliness, which is a trait that can contribute to drought escape (Terroir Seeds, 2019; Basu et al., 2016). 'Rugosa Friulana' (Rugosa), a yellow summer squash with an irregular, bumpy rind, was selected based on its inclusion in dry-farming trials conducted by the Oregon State University (OSU) Dry Farming Collaborative (DFC) (Nebert and Garrett, 2019; Baker Creek Heirloom Seeds, 2019). ‘Genovese’ (Geno), a gray or light green Italian summer squash, was also selected on this basis (Adaptive Seeds, 2018; Seeds From Italy, 2019). ‘Dark Star’ (DkStar) is an organic, open pollinated zucchini reported to be “vigorous” by seed companies and successful in OSU DFC trials (Nebert and Garrett, 2019; Siskiyou Seeds, 2019). ‘Desert F1’ (Desert) was included in this study because it is the only currently available organic hybrid zucchini specifically reported to be drought tolerant (High Mowing Organic Seed, 2019) (Table 1). True “drought tolerance” involves a variety of complex cellular and molecular mechanisms that allow a crop to be successful under drought conditions. Unless specifically observed, drought resistance is a more appropriate and general term to describe any of a variety of adaptations that would lead to increased success under drought conditions. Drought resistance will be used to refer to cultivars with reported success in low-water conditions unless reports of “drought tolerance” are specifically made.

Ten cultivars of watermelon were evaluated in greenhouse studies, and six were carried forward and studied under field conditions. ‘Jemez’, ‘Rio Grande Red-seeded’ (RGRS), ‘Tohono O’odham Yellow-meated’ (TOY), and ‘Manzano Sandia’ (Manzano) were chosen from the Native Seeds/SEARCH collection of heirloom crop seeds from the Southwestern U.S. and Northern Mexico (Table 2) (Native Seeds/SEARCH, 2019). Another Southwestern heirloom, ‘Ancient’, was “cultivated in Arizona for generations before being made commercially available through Baker Creek Heirloom Seeds” (Baker Creek Heirloom Seeds, 2019). ‘Desert King’ (DesKing) is one of the most commonly known watermelon cultivars that is claimed to be drought-resistant and is grown on a commercial scale (Baker Creek Heirloom Seeds, 2019). This cultivar has also been successful in OSU DFC trials (Nebert and Garrett, 2019). ‘Chin Sun’ (ChinSun) is an heirloom cultivar made available through High Desert Seed+Gardens, a small-scale Colorado-based seed company focused on selecting seeds that are adapted to the semi-arid climate of Colorado (High Desert Seed+Gardens, 2019).

Table 1: Squash cultivar information for greenhouse and sustained deficit irrigation field studies in Northern Colorado, 2018-2019.

Cultivar	**Seed Source**	**Fruit Type**	**Days to Maturity**	**Seed Company Description**	**Additional Notes**	**Environment/ Year(s)**
‘Daisy Mae’	NE Seed	Yellow crookneck	40-45	High yielding	Colorado-bred, check cultivar	Greenhouse/ 2018-2019
‘Dark Star’	Siskiyou Seeds	Zucchini	50	“Remarkably vigorous”	Organic OP, OSU DFC	Greenhouse, Field/ 2018-2019
‘Desert F1’	High Mowing Organic Seed	Zucchini	50	“Drought-tolerant”	Organic hybrid	Greenhouse, Field/ 2018-2019
‘Early Summer Crookneck’	Terroir Seeds	Yellow crookneck	42-60	“Early squash”	Selected in AZ	Greenhouse/ 2018-2019, Field/ 2018
‘Genovese’	Adaptive Seeds, Seeds from Italy	Gray/light green	55	Seed produced in Oregon	OSU DFC	Greenhouse, Field/ 2018-2019
‘HZS-03-849’	NE Seed	Zucchini	40-45	High yielding	Colorado-bred, check cultivar	Greenhouse, Field/ 2018-2019
‘Jasper’	NE Seed	Zucchini	40-45	High yielding	Colorado-bred, check cultivar	Greenhouse/ 2018-2019, Field/ 2019
‘Obsidian’	NE Seed	Zucchini	45-50	High yielding	Colorado-bred, check cultivar	Greenhouse/ 2018-2019
‘Rugosa Friulana’	Baker Creek Heirloom Seeds	Yellow crookneck, irregular	60	Long-season	OSU DFC, long season comparison	Greenhouse, Field/ 2018-2019

Table 2: Watermelon cultivar information for greenhouse and sustained deficit irrigation field studies in Northern Colorado, 2018-2019.

Cultivar	Seed Source	Flesh Color	Days to Maturity	Seed Company Description	Additional Notes	Environment /Years
‘Amiga’	NE Seed	Red	95	High-yielding, disease tolerant	CO-bred check	Greenhouse, Field/ 2018-2019
‘Ancient’	Baker Creek Heirloom Seeds	Red	n/a	Dry-farmed in Arizona	Water management	Greenhouse, Field/ 2018-2019
‘Chin Sun’	High Desert Seed + Gardens	Red	n/a	Produces in CO at high elevations	OSU Dry Farming Collaborative	Greenhouse/ 2018
‘Cypriot’	Baker Creek Heirloom Seeds	Red	n/a	“Thrives with little irrigation”	Water management	Greenhouse/ 2019
‘Desert King’	Baker Creek Heirloom Seeds	Yellow/ Orange	85	“One of most drought resistant cultivars”	Grown commercially	Greenhouse, Field/ 2018-2019
‘Jemez’	Native Seeds/SEARCH	Red	n/a	High desert, “native watermelon”	Elevation, history in SW	Greenhouse, Field/ 2018-2019
‘Kaho’	Baker Creek Heirloom Seeds	Orange	75	“Short season”	Early-maturing	Greenhouse/ 2018-2019
‘Manzano Sandia’	Native Seeds/SEARCH	Red	n/a	“Dry-farmed in Manzano mountains”	Elevation, water management	Greenhouse/ 2018-2019
‘Tohono O’odham Yellow-meated’	Native Seeds/SEARCH	Yellow	n/a	“Grows with monsoon rains”, high desert	Elevation, water management	Greenhouse, Field/ 2018-2019
‘Rio Grande Red Seeded’	Native Seeds/SEARCH	White	n/a	High desert, “grows wild”	High elevation, vigor	Greenhouse, Field/ 2018-2019

2.2 Greenhouse Experiments

A lack of established methods for optimally studying drought response and root systems in annual fruit and vegetable crops led to our adoption of methods similar to those used in agronomic crop species (Becker et al., 2015). Greenhouse dry-down studies were conducted in order to study the root system development of squash and watermelon cultivars under increasingly drought stressed conditions. Seeds were first germinated on a misting bench

(2018) or in a growth chamber (2019) in rock wool plugs to ensure seedling uniformity. Once their first true leaves had developed, seedlings were transplanted into 10x10x30cm (4x4x12”) pots filled with Profile® Greens Grade™ (Profile Products, Buffalo Grove, Illinois) growing medium that had been fully saturated with a 6ml/L (1.5 tbsp/gal) fish emulsion (Alaska, 5-1-1, Pennington Seed Inc.) solution. The pots were drained to field capacity before planting. Seedlings, pots, dry medium, and dry medium with fish emulsion solution were all weighed so the gravimetric soil moisture content could be determined for each pot. Experimental units were defined as one plant of one cultivar in one pot. Pots were arranged in stands that fit 9 pots per stand (one of each cultivar) in a randomized complete block design. Six replications of each cultivar were planted, except in cases where germination rates limited the sample size; a minimum of three replications were included in these cases. Squash and watermelon cultivars were physically separated, but studies for both crops took place over the same time frame (22 May 2018-22 July 2019) in the same controlled environment greenhouse. In 2018, greenhouse conditions were set to a minimum temperature of 11°C (52°F), a maximum temperature of 22°C (72°F), and 72% humidity. In 2019, the minimum temperature of 19°C (67°F), the maximum temperature was 25°C (77°F), and 50% humidity was maintained. No additional irrigation or fertility was applied for the duration of the study, and the growing medium gradually dried down. Photos were taken weekly, and data was collected on each pot until total desiccation (plant death) was reached. Days to death, percent soil moisture at death, and dry weight of above-ground biomass were all recorded.

Once desiccation occurred, roots were washed and carefully collected for scanning. Roots were preserved in a 18% ethanol solution and stored in a 4°C cooler until they were scanned (Smit et al., 2013, p.200). An EPSON Expression 11000XL scanner was used to capture images of the root system of each plant in the dry-down study. Roots were suspended in deionized water for scanning and then re-collected for dry weight determination. Images of the roots were then analyzed using WinRHIZO (Regent, 2013) to determine total length of fine (0.0-0.5mm) roots and total root length. Above and below ground biomass was dried in an oven at 65°C for up to one week and weighed. Using the root and shoot dry weights, root:shoot ratio was determined for each cultivar by dividing root dry weight by shoot dry weight.

2.3 Field Studies

Field studies were conducted in Fort Collins, Colorado at Colorado State University's Agricultural Research, Development, and Education Center, South (ARDEC South) (40.610012, -104.993979, Altitude: 1523 m). Squash were grown in a retractable-roof A-frame Cravo (Cravo Equipment Ltd., Brantford, Ontario, Canada) structure and watermelon were grown in a certified organic open field. Both plots were managed using inputs approved for certified organic farms by the Organic Materials Review Institute (OMRI). Soil test results determined the soil type to be sandy clay loam, containing 2.4-3.0% organic matter. In year one, soil in the field and in the Cravo was amended with the addition of a one-inch layer of compost. Plots were rototilled prior to planting in both years.

Transplants for field studies were grown in greenhouse conditions with a minimum temperature of 18°C (65°F), a maximum temperature of 27°C (80°F), and an average humidity of 50% using Berger OM Series growing medium (Berger, Saint-Modeste QC) with three gallons of vermicompost, three cups of Down to Earth Fish Bone Meal (3-16-0) and three cups of Down to Earth Blood Meal (12-0-0) incorporated into each 3.8 cubic-foot bag of soilless potting mix. Seeds were planted at 1-2 cm depth in six-packs and watered daily as needed. Starts were transplanted to field conditions after hardening under shade cloth two to three weeks from seeding between 24-May and 6-July in both years. Plots were given fish emulsion (Alaska, 5-1-1, Pennington Seed Inc.) fertilizer by fertigation every three to four weeks following crop establishment in accordance with product label guidelines. Insect and disease pressures were monitored throughout the season. Following hail damage in the watermelon field in both years, damaged vines and damaged developing fruits were pruned off uniformly across the plot to encourage re-growth.

Squash were sown in a 8x24 meter (25x80’) A-frame Cravo (Cravo Equipment, Ltd.) structure with a retractable roof and sides, similar to rainout structures described by Blum (2010) (Figure 1). Roof and sides were left open in order to maintain ambient environmental conditions except in cases of rain or hail. CRAVO was closed to exclude all precipitation during the treatment interval (5 July 2018-14 Sept. 2018; 28 June 2019-12 Sept. 2019). Drip irrigation was installed using Irritec P1 Ultra 5/8" drip tape with a flow rate of 1.2 liters per hour (0.33 gph) and plants were spaced on 61cm (24”) centers, aligned with 61cm (24”) spaced emitters. Beds were spaced one meter (three feet) apart within treatments and 1.3 meters (four feet) apart between irrigation treatments. Landscaping fabric was used for weed suppression and to limit soil moisture losses to evaporation. A total of six cultivars were used, and three irrigation treatments applied in a split-plot design with three blocks and 4-6 experimental units per block.

Figure 1- Summer squash planted in a Cravo structure with sides and roof partially closed.

Figure 2- Watermelon field layout with 3-meter spaced beds to separate irrigation treatments.

Watermelons were planted in open field conditions using Irritec P1 Ultra 5/8" drip tape with a flow rate of 0.33 GPH subsurface drip and plastic mulch on one meter (3’) wide raised beds. Watermelon seedlings were planted 91cm (36”) apart, aligned with 91cm (36”) spaced drip emitters. Three-meter (ten foot) aisles (Figure 3) were left between beds to prevent irrigation treatment carryover and to allow space for weed cultivation. A total of six cultivars were used and three irrigation treatments applied in a split-plot design where row corresponded to treatment in each of the three blocks. 8-10 experimental units (plants) were planted per plot.

Soil moisture sensors (Irrometer WaterMark Technology, Riverside, California) were installed at 30cm (12”) in 2018 and 20cm (8”) in 2019 and 91cm (36”) in both years to monitor soil matric potential in centibars. Watermark sensors were attached to 1.3cm (½”) schedule 200 PVC pipe with PVC glue and a drainage hole was drilled above the attachment site. Sensors were installed by removing soil cores with a 1.3cm (1/2”) soil corer and pouring a soil/water slurry into the hole to ensure good soil contact. A total of seventy-two sensors were installed in both fields, with one sensor per depth in each treatment/cultivar combination within block two. Twenty-one out of thirty-six sensors in the squash Cravo were connected to dataloggers (Irrometer WaterMark Monitor, Riverside, California) and calibrated using connected soil temperature sensors. The remaining fifteen sensors in squash Cravo and thirty-six sensors in watermelon field were hand checked three times weekly using a FieldScout Soil Sensor Reader (Spectrum Technologies, Aurora Illinois). HOBO 4-channel external data loggers (Model U12-008, Onset Computer Corporation, Bourne, MA) were installed to log canopy temperature inside and outside squash Cravo, in watermelon field, and soil temperature at 20cm depth (8”) in the watermelon field. A portable time domain reflectometry (TDR 150) meter (Spectrum Technologies Inc., Aurora, IL) was used to check volumetric soil moisture in the top 20cm (8”) of soil against the matric potential readings given by WaterMark sensors.

Irrigation treatments in squash and watermelon fields began after a well-watered establishment period that lasted from transplanting until flowering. Treatments began between 28-June and 5-July in the squash plot and between 3-Aug. and 16-Aug in the watermelon plot. Treatments were defined as control (Ctrl), deficit (Def), and drought (Drt). Irrigation applications were made on a recurring schedule, taking into account readings from WaterMark sensors and TDR, evidence of crop stress, and a target reduction of at least 50% from average recommended rates in the Western states for each crop, the average recommendation being 16 acre-inches for summer squash, and 11 acre-inches for watermelon (Masabni, n.d.; Molinar et al, n.d.; Shrefler et al., 2017; Daniello, n.d.). The control treatment received the “full” irrigation amount on a weekly schedule, with a season-long target reduction of 50% or more from average recommended rates in the Western states. Natural rainfall amounts were factored into irrigation decisions in the watermelon field, but not in the squash Cravo since rainfall was excluded during the treatment interval. Drought treatment plots received the same amount of water as the control at each irrigation event, but with two weeks between irrigations as opposed to the one week between irrigation events in the control treatment. Water was delivered through the system at 22-24 psi in accordance with drip line capacity in order to maintain a 1.2 liters per hour (0.33 gph) flow rate. Reduced irrigation treatments were applied, and yields compared to that of typical commercial crops in order to quantify yield penalties incurred. The deficit treatment received irrigations at the same time as the control treatment, but in half the control amount.

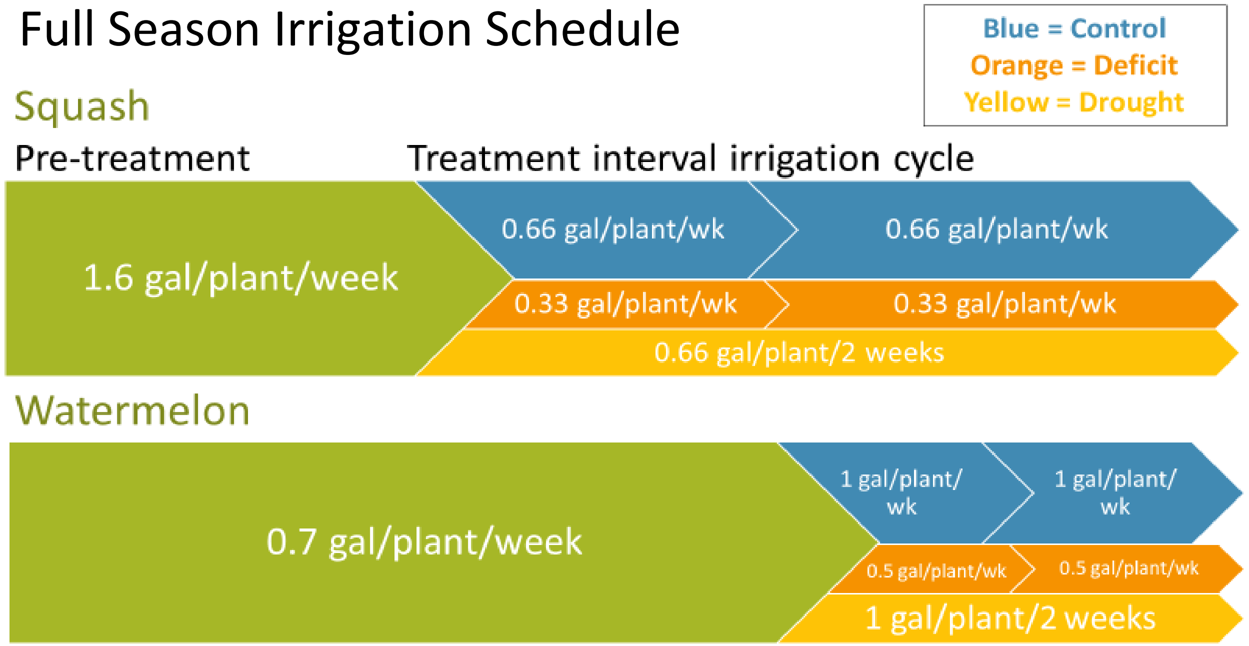


Figure 3- Average number of irrigation gallons of water applied per week to squash and watermelon crops during pre-treatment interval (four weeks for squash and 10 weeks for watermelon) and treatment interval (11 weeks for squash and six weeks for watermelon) in 2018-2019.

Table 3- Summer squash irrigation and rainfall amounts in Cravo rain-exclusion structure in 2018.

	Pre-treatment [z]		Treatment[y]		Season Total	
Treatment	Inches[x]	GPP[w]	Inches	GPP	Inches	GPP
Control	4	14.8	1.5	5.6	5.5	20.4
Deficit	4	14.8	0.7	2.6	4.7	17.4
Drought	4	14.8	0.8	3	4.8	17.8

[z] Pre-treatment interval lasted from transplanting to flowering and was a non-stressed period of crop establishment where rainfall was not excluded

[y] Treatment interval began at 50% flowering and continued through the end of the growing season. Rainfall was excluded during this interval by closing the roof and sides of the Cravo structure

[x] Inches of water include rainfall (pre-treatment) and irrigation (pre-treatment and treatment). Irrigation was converted from gallons per plant (GPP) to inches using a 6ft^2 effective crop area. All rainfall values taken from CoAgMet.

[w] GPP: gallons per plant of irrigation water (pre-treatment and treatment) and rainfall (pre-treatment). Rainfall values in inches were converted to gallons per plant using a 6ft^2 effective crop area.

Table 4- Summer squash irrigation and rainfall amounts in Cravo rain-exclusion structure in 2019.

	Pre-treatment [z]		Treatment[y]		Season Total	
Treatment	Inches[x]	GPP[w]	Inches	GPP	Inches	GPP
Control	4.6	17.1	1.6	6	6.2	23.1
Deficit	4.6	17.1	0.9	3.2	5.5	20.3
Drought	4.6	17.1	0.8	3	5.4	20.1

[z] Pre-treatment interval lasted from transplanting to flowering and was a non-stressed period of crop establishment where rainfall was not excluded.

[y] Treatment interval began at 50% flowering and continued through the end of the growing season. Rainfall was excluded during this interval by closing the roof and sides of the Cravo structure.

[x] Inches of water include rainfall (pre-treatment) and irrigation (pre-treatment and treatment). Irrigation was converted from gallons per plant (GPP) to inches using a 6ft^2 effective crop area. All rainfall values taken from CoAgMet.

[w] GPP: gallons per plant of irrigation water (pre-treatment and treatment) and rainfall (pre-treatment). Rainfall values in inches were converted to gallons per plant using a 6ft^2 effective crop area.

Table 5-Watermelon irrigation and rainfall amounts in 2018.

	Pre-treatment[z]		Treatment[y]		Season Total	
Treatment	Inches[x]	GPP[w]	Inches	GPP	Inches	GPP
Control	3.3	37	1.2	13.5	4.5	50.5
Deficit	3.3	37	0.9	10.1	4.2	47.1
Drought	3.3	37	0.9	10.1	4.1	46

[z] Pre-treatment interval lasted from transplanting to flowering and was a non-stressed period of crop establishment.

[y] Treatment interval began at 50% flowering and continued through the end of the growing season.

[x] Inches of water include rainfall and irrigation. Irrigation amounts were converted from gallons per plant (GPP) to inches using a 18ft^2 effective crop area. All rainfall values taken from CoAgMet.

[w] GPP: gallons per plant of irrigation water and rainfall. Rainfall values in inches were converted to gallons per plant using a 18ft^2 effective crop area.

Table 6- Watermelon irrigation and rainfall amounts in 2019.

	Pre-treatment [z]		Treatment[y]		Season Total	
Treatment	Inches[x]	GPP[w]	Inches	GPP	Inches	GPP
Control	4.3	48.2	0.9	9.6	5.2	57.8
Deficit	4.3	48.2	0.6	6.9	4.9	55.1
Drought	4.3	48.2	0.6	6.4	4.9	55.1

[z] Pre-treatment interval lasted from transplanting to flowering and was a non-stressed period of crop establishment.

[y] Treatment interval began at 50% flowering and continued through the end of the growing season.

[x] Inches of water include rainfall and irrigation. Irrigation amounts were converted from gallons per plant (GPP) to inches using a 18ft^2 effective crop area. All rainfall values taken from CoAgMet.

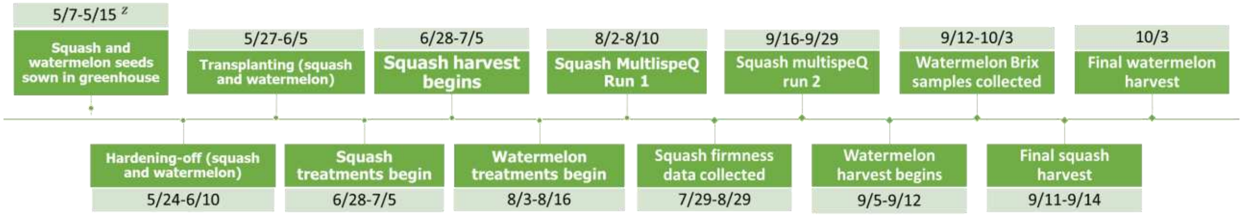
[w] GPP: gallons per plant of irrigation water and rainfall. Rainfall values in inches were converted to gallons per plant using a 18ft^2 effective crop area.

2.4 Field Study Data Collection

Season-long harvest data was collected in squash and watermelon crops. Squash were harvested three times per week from the first harvest (7 July 2018, 28 June 2019) through the end of the growing season (14 Sept. 2018, 11 Sept. 2019) for a total of 33 harvests in each year. Watermelons were harvested once fruit ripened (12 Sept. 2018, 5 Sept. 2019) and weekly until first frost/end of growing season (3 Oct. 2018, 3 Oct. 2019) for a total of four harvests in both years. Number of marketable and unmarketable fruits from each plot were counted at each harvest, and weights collected. Marketability in the squash crop was visually assessed based on the presence or absence of physical defects, fruit shape, uniformity of pollination, size, firmness, and dullness/luster. Fruits were considered ripe following pollination and once they reached the desired size based on cultivar, typically 13-18 centimeters (5-7 inches). Overripe fruits that were too large, firm, and/or dull were classified as unmarketable. Watermelons were considered unmarketable if they had two or more of the following characteristics: moderate to severe pock marks from hail or other mechanical damage, sunscald, damage from cucumber beetle feeding, misshapen, or too small for type. Marketable fruits were ripe, true to type and size, and had no or minor defects/damages.

Data was also collected on quality characteristics of squash and watermelons. Squash firmness was assessed using a penetrometer over the course of four consecutive mid-season harvests between 29 July and 29 Aug. in each year. Firmness of each cultivar and treatment was compared to the check cultivar in the control treatment. Data was collected over the course of a week in order to include multiple representatives of each plot. Watermelon quality was assessed by measuring total soluble solids (°Brix) using a digital refractometer (Milwaukee Instruments Inc. MA871 Digital Brix Refractometer, Rocky Mount, NC). Samples were collected by combining one uniform sample of flesh from the center of the melon, and one sample of flesh near the rind. Samples were refrigerated at 4°C until measurements were taken, and then homogenized so that watermelon juice could be filtered through cheese cloth and measured.

Photosynthetic parameters were measured in all squash plots both mid-season (8-10 Aug. 2018; 2 Aug. 2019) and late-season (24-29 Aug. 2018; 15-16 Aug. 2019) using a PhotosynQ MultispeQ v1.0. Main measures of interest were relative chlorophyll (SPAD), quantum yield of photosystem II (Phi2), light lost to non-photochemical quenching (PhiNPQ), and photochemical quenching (PhiNO). Phi2, PhiNPQ, and PhiNO are the three categories of uses of incoming light and are measured as a ratio of total incoming light. The youngest fully expanded leaf in full sun was selected from each sampled plant for measurements. Two plants were measured per plot at each time point. Two representative plants per plot were collected at the end of the growing season for dry-weight biomass measurements. Plants were oven-dried at 65°C for 10-14 days until fully dehydrated and then weighed.



[z]: All date ranges include dates from both the 2018 and 2019 growing season. The 2019 growing season began approximately one week earlier than the 2018 growing season, so management measures, treatments, and data collection events were adjusted accordingly.

Figure 4: Squash and watermelon SDI field trial general timeline 2018-2019.

2.5 Statistical Analysis

All data were analyzed using R version 3.6.1 in R Studio. Two-way ANOVA was used to identify the significance of main effects of cultivar and irrigation treatment. Interactions between treatment and cultivar were also evaluated and reported when present. The emmeans package was used to compare adjusted marginal means, and the ggplot2 packaged was used for data visualization. Standard errors were calculated, and error bars added to bar plots. Outliers were identified in each model using the outlierTest function. A Bonferroni adjusted p-value for the data points with the largest residuals was generated to determine outlier status. Once identified, outliers were removed from the model.

3. RESULTS

3.1 Greenhouse Results: Squash

Cultivar was the significant predictor of days to death for squash in 2018 and 2019 of the greenhouse studies. ‘Rugosa’ lived significantly longer than three other cultivars in 2018, (48 days vs. 37 days) and could be differentiated from all other cultivars in 2019 (93 days vs. an average of 62 days). All squash lived longer, on average, in 2019 due to an early start to the experiment in March 2019 vs. May 2018, and slightly different greenhouse set points (see p.17). Percent soil moisture values at death were comparable in both years (Figures 7 and 8). ‘Rugosa Friulana’ withstood the lowest soil moisture conditions on average in both years (23.4% in 2018, 17.5% in 2019), and ‘Genovese’, ‘Jasper’, ‘Obsidian’, and ‘HZS-03-849’ died at the highest soil moisture levels in both years (25.2-26.9% in 2018, 22.6-23.7% in 2019). No significant differences were found between root:shoot ratio in squash cultivars in 2018 or in 2019 (data not shown).

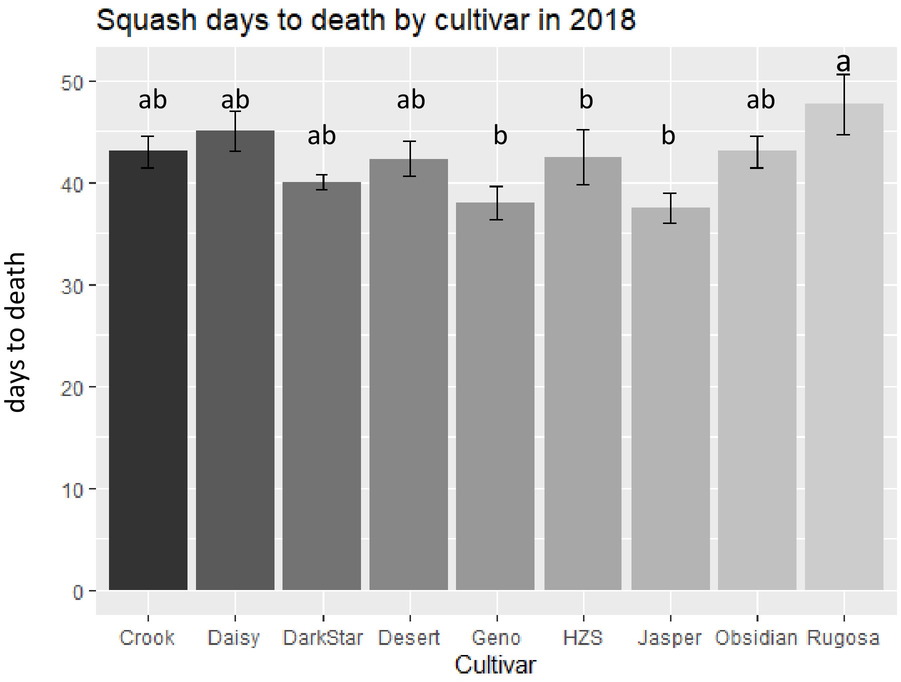


Figure 5: Days to death of nine summer squash cultivars in the 2018 greenhouse study.

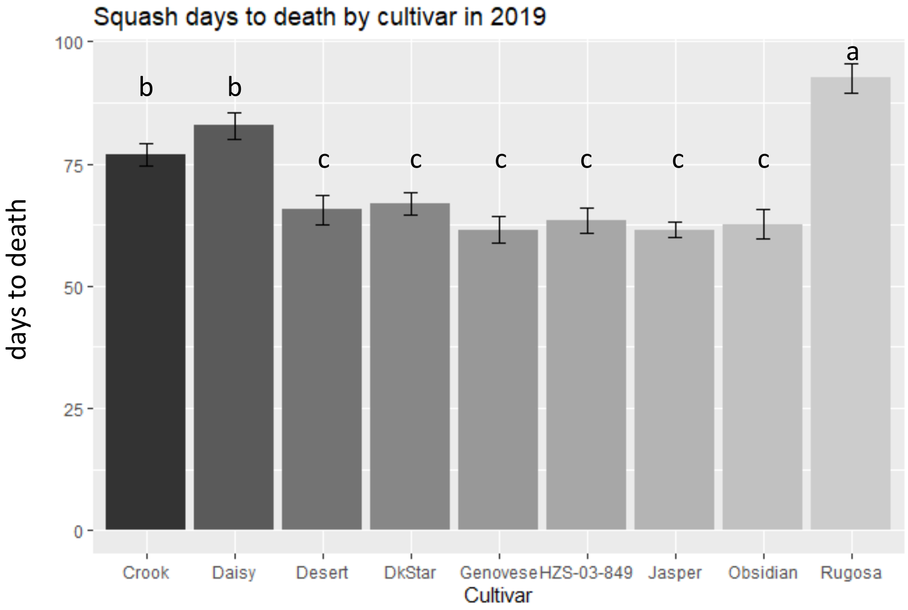


Figure 6- Days to death of nine summer squash cultivars in the 2019 greenhouse study.

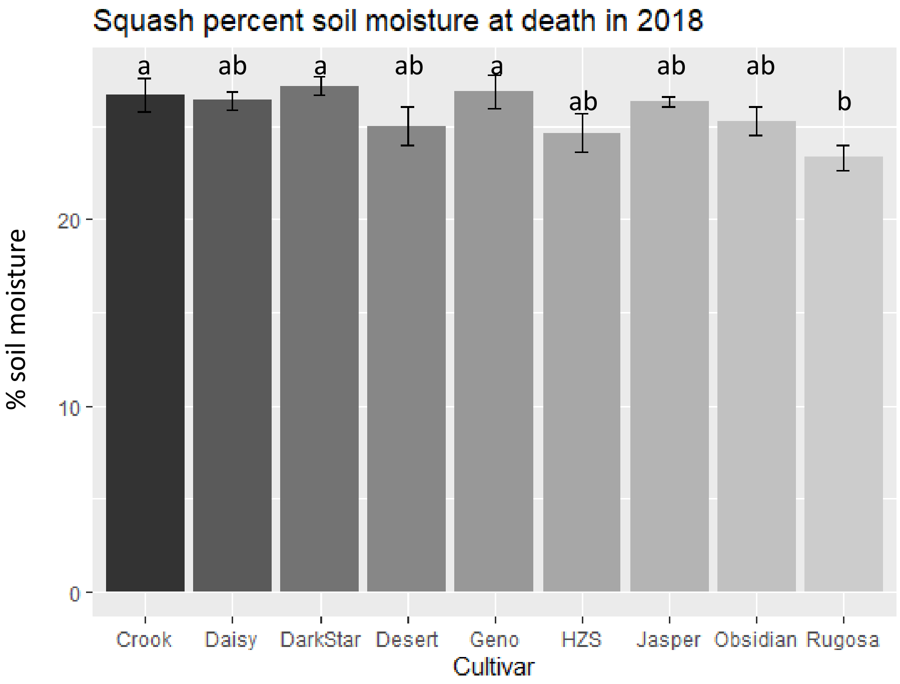


Figure 7- Percent soil moisture at death of nine summer squash cultivars in the 2018 greenhouse study.

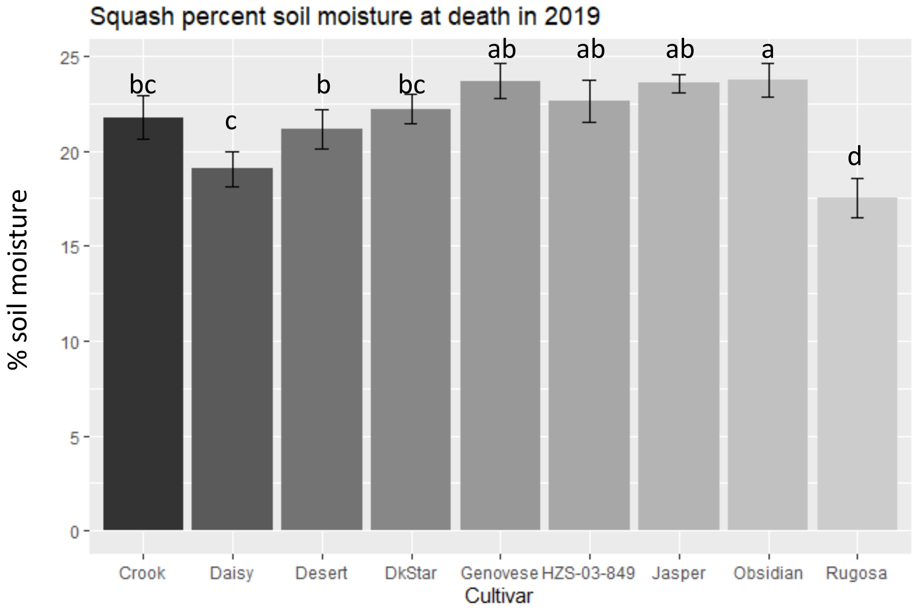


Figure 8- Percent soil moisture at death of nine summer squash cultivars in the 2019 greenhouse study.

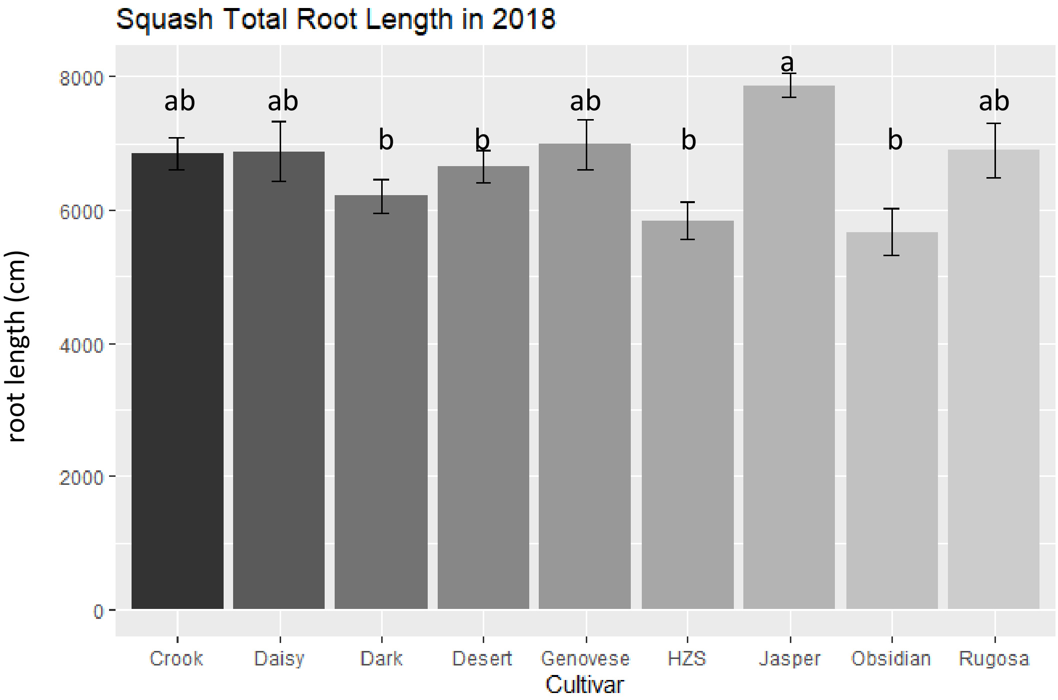


Figure 9- Total root length in cm of nine cultivars of summer squash in the 2018 greenhouse study.

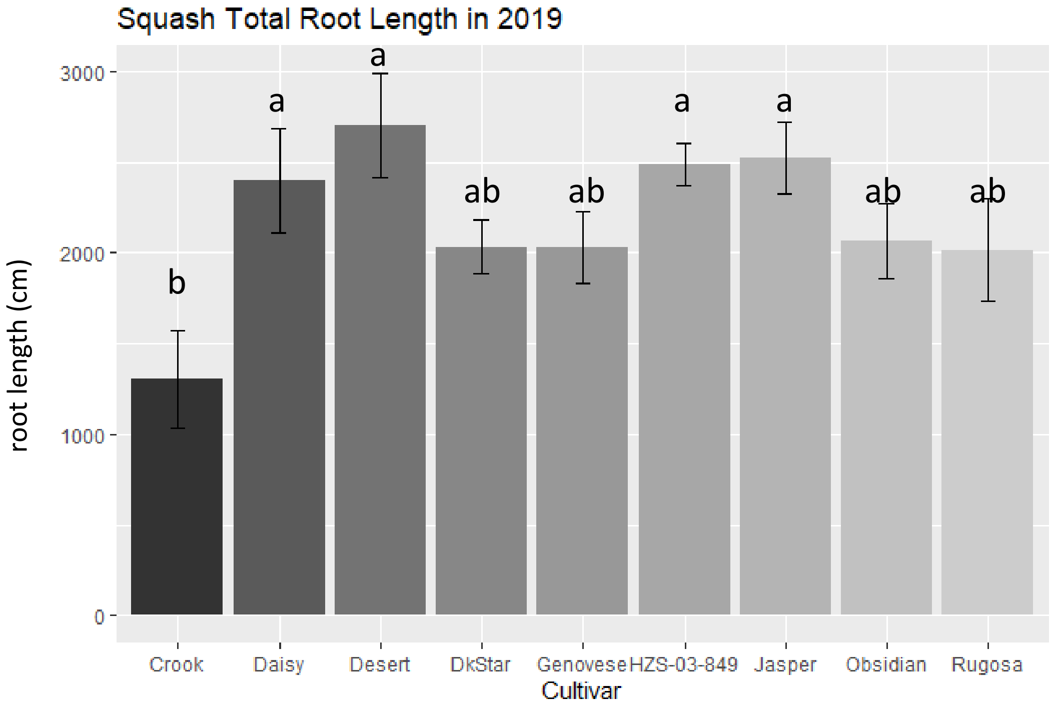


Figure 10- Total root length in cm of nine cultivars of summer squash in the 2019 greenhouse study.

Fine root length was significantly different between cultivars in 2018, following the same trend as total root length. Only total root length results are presented (Figures 9 and 10). In 2018, ‘Jasper’ had significantly longer total root length than ‘Dark Star’, ‘Desert F1’, ‘HZS-03-849’, and ‘Obsidian’ (Figure 9). In 2019, ‘Jasper’ still had relatively high root growth, but this cultivar along with ‘HZS-03-849’, ‘Desert F1’, and ‘Daisy Mae’ could only be significantly differentiated from ‘Early Summer Crookneck’ (Figure 10).

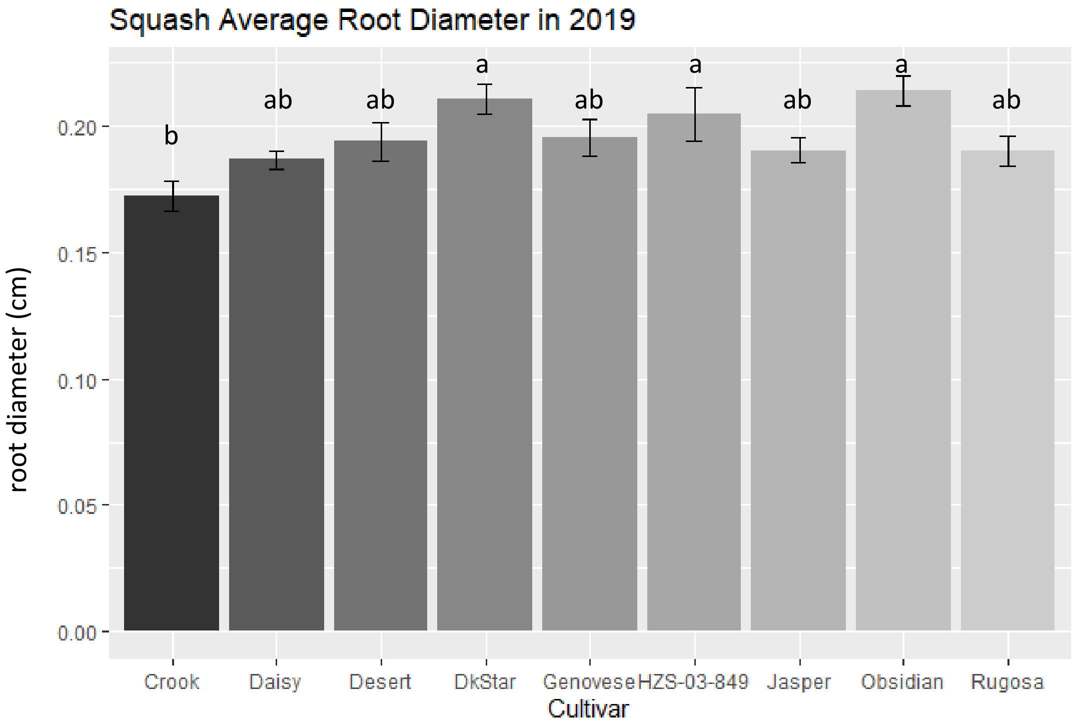


Figure 11- Average root diameter in cm of nine cultivars of summer squash in the 2019 greenhouse study.

Cultivar was a significant predictor of average root diameter in 2018 and 2019, but pairwise comparisons in 2018 were not significant. The cultivar with the lowest average root diameter, 'Early Summer Crookneck' was not more successful than other cultivars based on other response variables evaluated in the greenhouse study. In 2019 'Early Summer Crookneck' had a significantly finer average root diameter than 'Dark Star', 'HZS-03-849', and 'Obsidian' (Figure 11).

3.2 Greenhouse Results: Watermelon

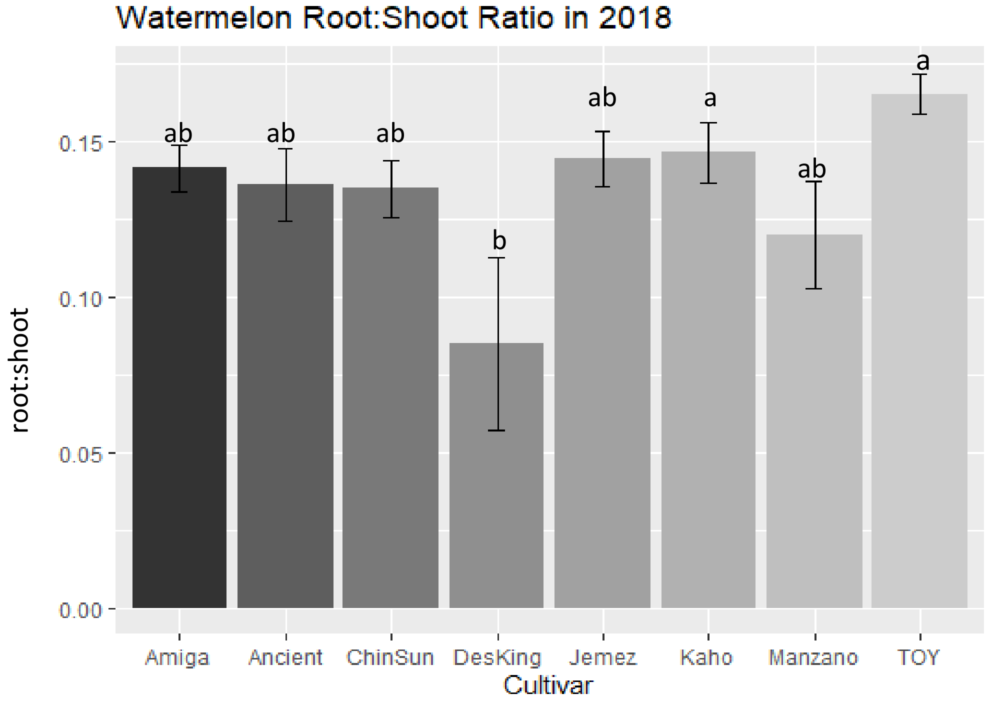


Figure 12- Root:shoot ratio of nine cultivars of watermelon in the 2018 greenhouse study.

There were no significant differences between root:shoot ratios of different watermelon cultivars in 2019. In 2018, ‘Kaho’ and ‘TOY’ had a root:shoot ratio significantly higher than ‘DesKing’. None of the other cultivars could be differentiated from these two groups. There were no significant differences between days to death or percent soil moisture at death of watermelon cultivars in the greenhouse in 2018 or in 2019.

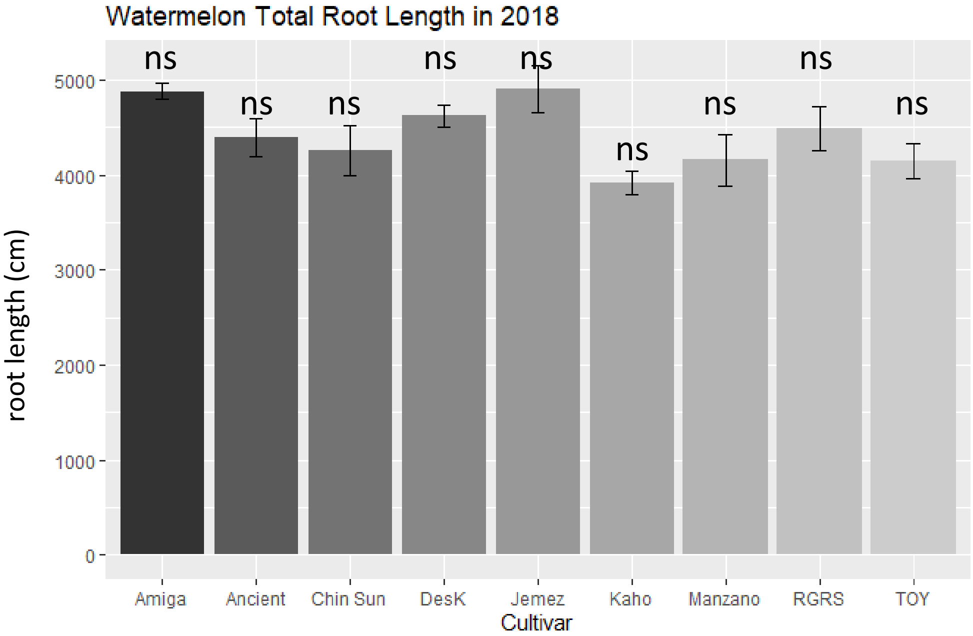


Figure 13- Total root length in centimeters of nine cultivars of watermelon in the 2018 greenhouse study. There were no significant differences detected.

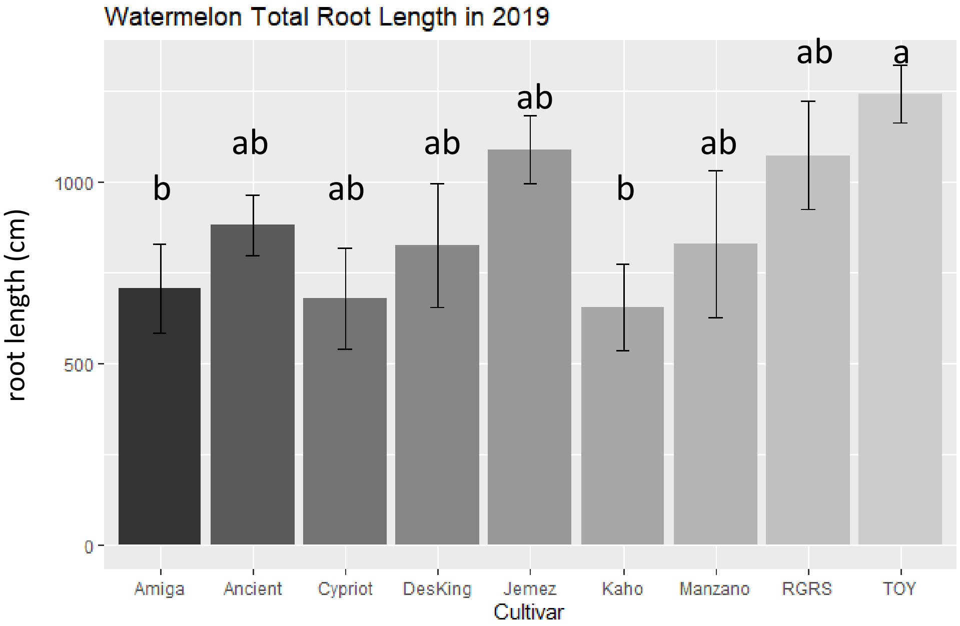
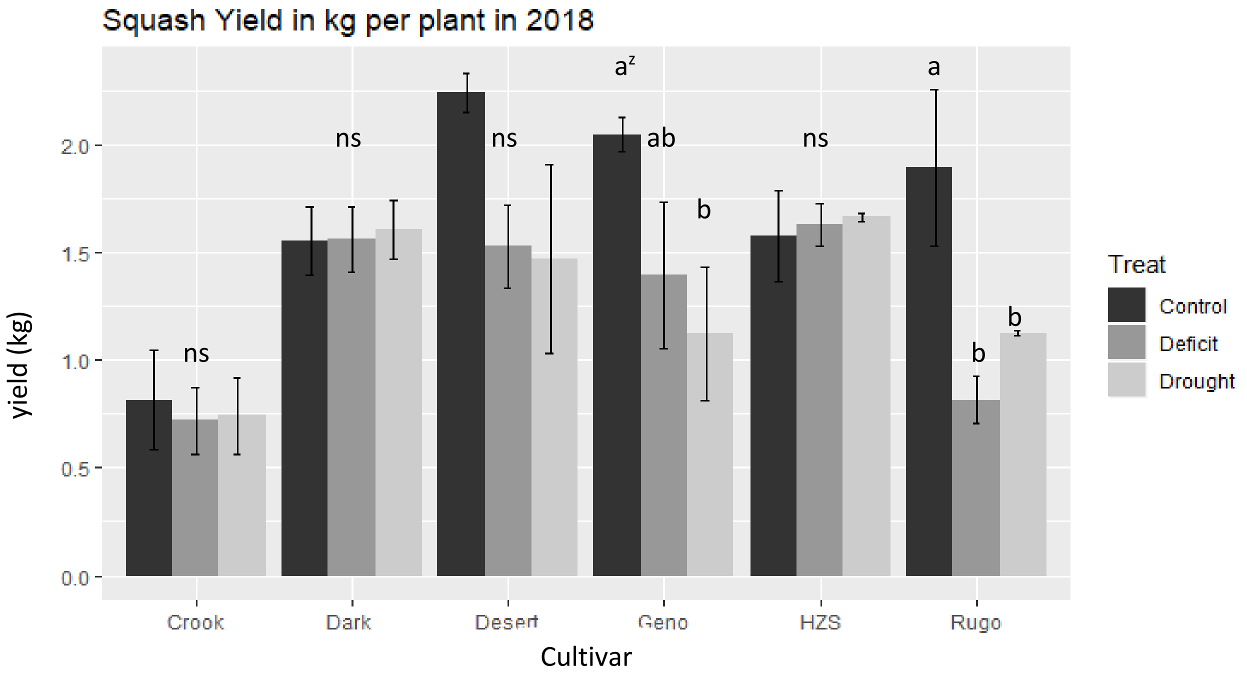


Figure 14- Total root length in centimeters of nine cultivars of watermelon in the 2019 greenhouse study.

Cultivar-level differences in total root length were significant in both years. However, in 2018 (p=0.0423) no pairwise comparisons were significant. In 2019, 'Tohono O'odham Yellow-Meated' (TOY) had significantly longer total root length than 'Kaho' and 'Amiga'. Fine root length results were very similar to total root length results, but with only a borderline significant (p=0.05825) main effect of cultivar in 2018. In 2019 there was a significant cultivar main effect (p=0.01227) with the same cultivar ranking as with total root length. Overall root length of all cultivars was greater in 2018 than 2019 due to slight changes in environmental conditions in the greenhouse from year one to year two (p.17). There were no significant differences in average root diameter between cultivars in 2018 or in 2019.

3.3 Field Results: Squash



[z] Pairwise comparisons made between treatments within each cultivar, not between cultivars. Different letters indicate statistically significant differences. Error bars on bar plots indicate standard errors.

Figure 15- Yield per plant in kg of six summer squash cultivars in the field trial, 2018.

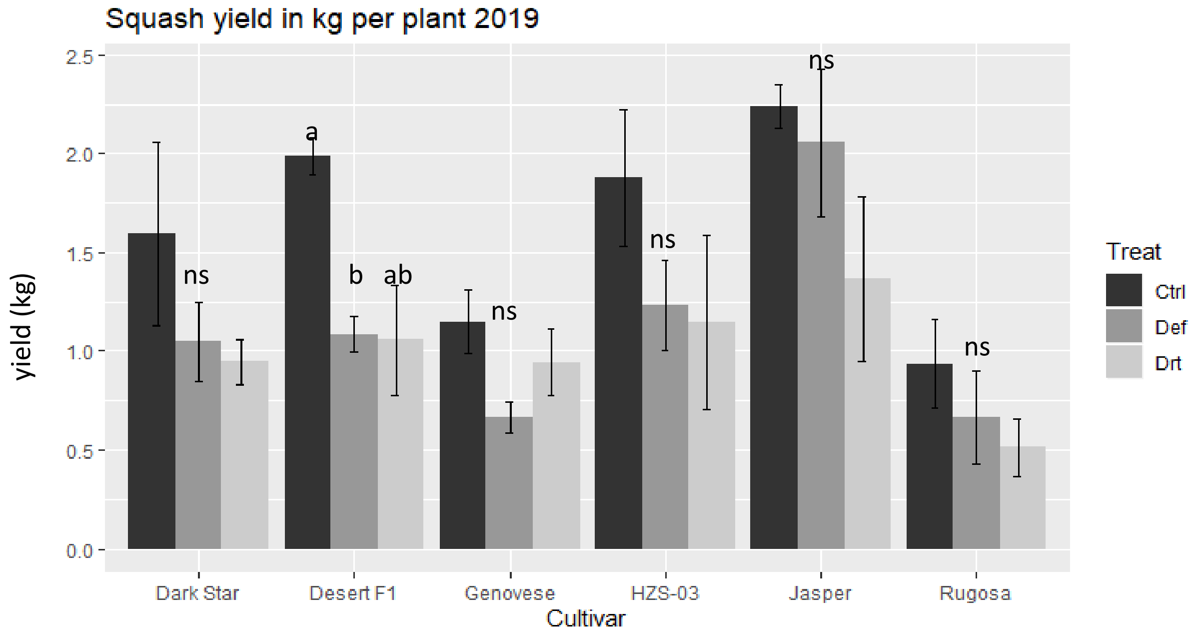


Figure 16- Yield per plant in kg of six summer squash cultivars in the field trial, 2019.

The main effects of cultivar and treatment were significant for yield per plant in 2018 and 2019. Therefore, pairwise comparisons were made between treatments within each cultivar. In 2018, the drought plot in block three was flooded due to rain seepage into the Cravo. This was prevented in 2019, and yield data from this plot was excluded in 2018. The conventional hybrid check cultivar, ‘HZS-03-849’, had no significant yield differences between irrigation treatments in either year. ‘Desert F1’, the “drought tolerant” organic hybrid, did similarly well in all treatments in 2018, but in 2019, plots in the deficit treatment yielded significantly less. In 2018, ‘Rugosa Friulana’ did significantly better in the control treatment than in deficit or drought, but in 2019, ‘Rugosa Friulana’ performed poorly overall and there were no differences between yields across treatments. When comparing cultivars to one another, averaging over treatment, ‘Dark Star’, ‘Desert F1’, ‘Genovese’, and ‘HZS-03-849’ yielded significantly higher than ‘Early Summer Crookneck’ in 2018. ‘Rugosa Friulana’, however, could not be differentiated from any of the other cultivars. Yields for the more successful cultivars ranged from 1.5-1.7 kilograms (3.3-3.7 pounds) per plant in 2018. In 2019, yields were generally higher, and ‘Jasper’ yielded significantly more than ‘Rugosa Friulana’, ‘Dark Star’, ‘HZS-03-849’, and ‘Genovese’, with a mean yield of 1.9 kilograms (4.2 pounds) per plant, which is less than the average yield of 3.1 kilograms (6.8 pounds) per plant cited by the University of California Small Farms Program (Molinar, 2005). ‘HZS-03-849’ also yielded significantly more than ‘Rugosa Friulana’, with an average yield of 1.4 kilograms per plant. In the OSU Dry Farming Collaborative trials, ‘Dark Star’ also yielded much higher than ‘Rugosa Friulana’ (Nebert and Garrett, 2019). There were no significant differences between unmarketable yields in any treatments or between any cultivars in 2018 or 2019.

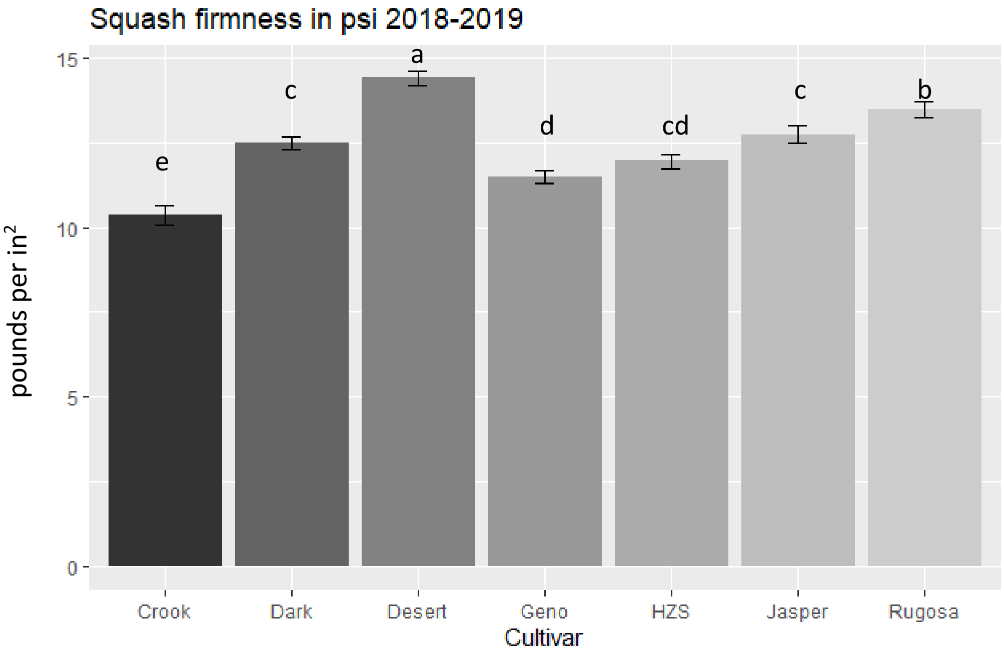


Figure 17- Firmness in pounds per square inch (psi) of six summer squash cultivars in the field trials 2018-2019.

A similar trend was apparent between the firmness of squash cultivars in both years. Cultivar differences were highly significant at ($P<2.2x10^{-16}$). The check cultivar, 'HZS-03-849' had an average firmness of 11.9 pounds per square inch (psi). 'Genovese', 'Dark Star', and 'Jasper' had a similar mean firmness, and 'Early Summer Crookneck' was punctured at a lower psi and so was significantly less firm than the other cultivars, but still firm enough to be considered "fairly firm". 'Desert F1', and 'Rugosa Friulana' were significantly firmer than the control cultivar (Figure 17). According to the USDA Agricultural Marketing Service (2019), a lack of firmness is considered a defect in squash, but having increased firmness is not formally considered a negative characteristic.

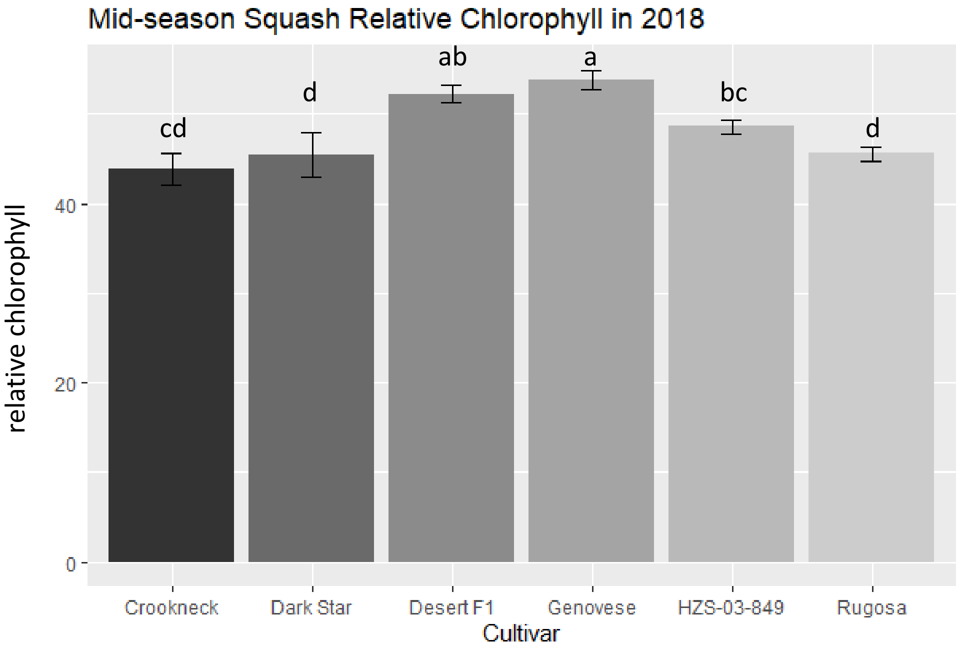
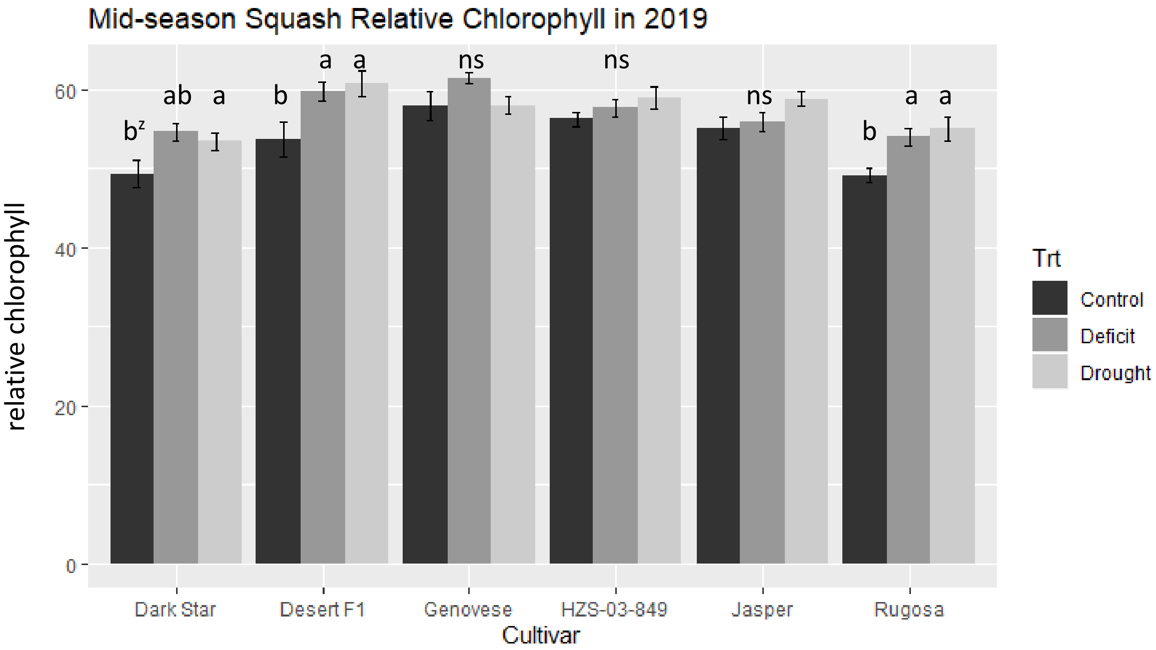


Figure 18- Mid-season relative chlorophyll values (SPAD) of six summer squash cultivars in the 2018 field trials measured with a handheld photosynthetic measurement system (MultispeQ).



^{z}: Means compared across treatments within a cultivar. Different letters denote statistical significance at α=0.05

Figure 19- Mid-season relative chlorophyll values (SPAD) of six summer squash across treatments within cultivars in the 2019 field trials measured with a handheld photosynthetic measurement system (MultispeQ).

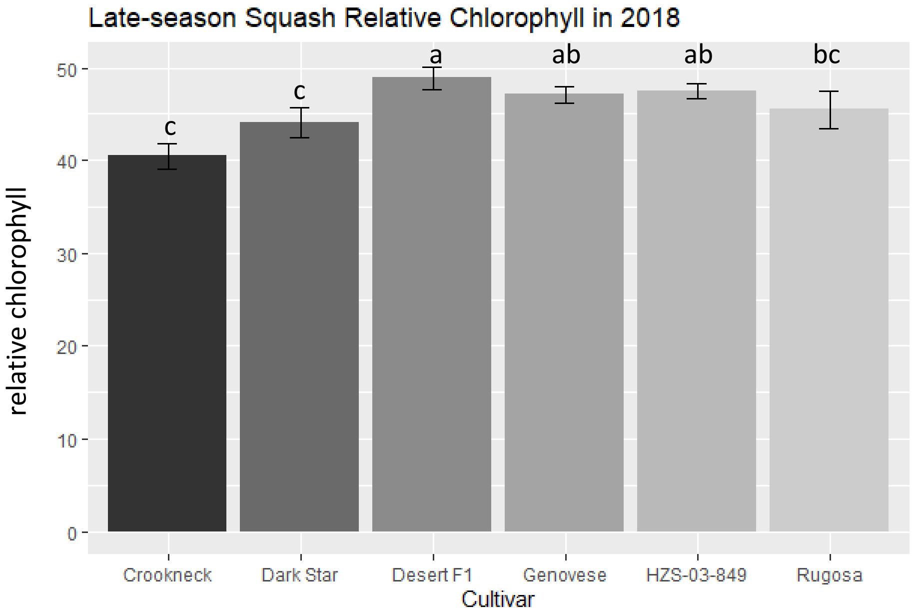


Figure 20- Late-season relative chlorophyll values (SPAD) of six summer squash cultivars in the 2018 field trials measured with a handheld photosynthetic measurement system (MultispeQ).

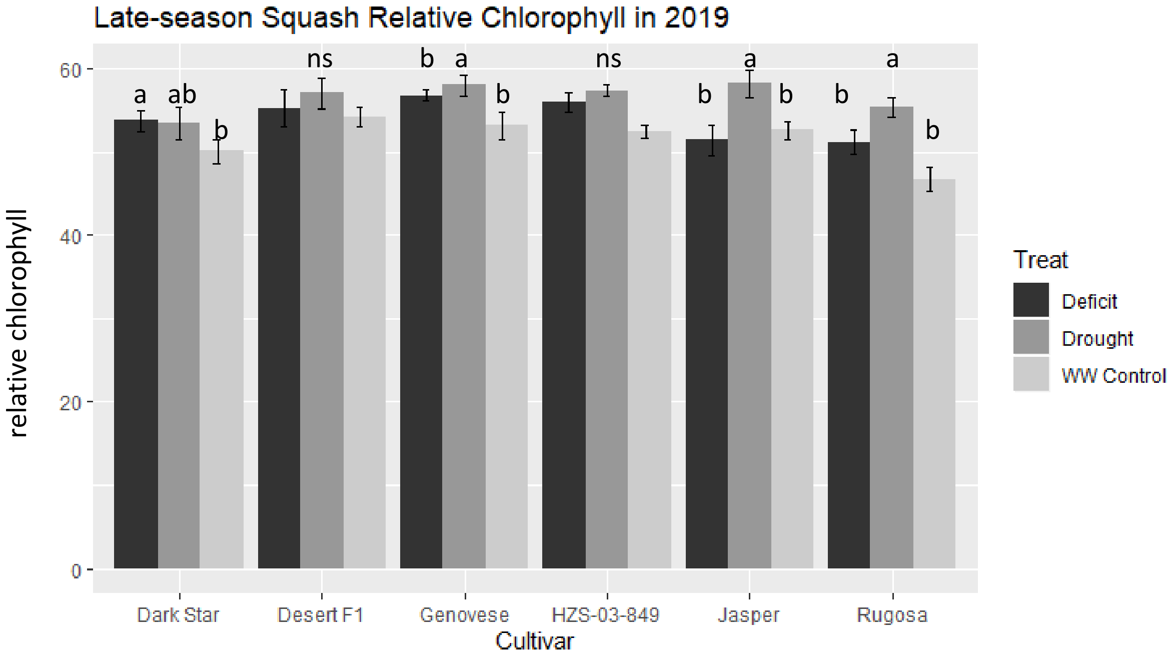


Figure 21- Late-season relative chlorophyll values (SPAD) of six summer squash across treatments within cultivars in the 2019 field trials measured with a handheld photosynthetic measurement system (MultispeQ).

There were no clear trends in Phi2, PhiNO, or PhiNPQ in 2018 or 2019, though there were isolated instances of statistical significance (data not shown). Squash had similar photosynthetic responses to reduced irrigation across treatments and cultivars, both mid and late season, in 2018 and 2019. In 2018, cultivar was the significant predictor of relative chlorophyll, a unitless measure of "greenness", both mid and late season. The ranking of relative chlorophyll values among cultivars changed slightly from mid-season to late season (Figures 18 and 20). In 2019, main effects of treatment and cultivar were significant, with no interaction. Pairwise comparisons were made between treatments within each cultivar (Figures 19 and 21). Differences in relative chlorophyll between treatments in 'HZS-03-849' were not significant at mid-season or late-season. 'Dark Star', 'Desert F1' and 'Rugosa Friulana' had the lowest relative chlorophyll estimate (49.3, 53.1, and 49.1, respectively) in the control treatment mid-season. In the late-season data, 'Rugosa Friulana' and 'Dark Star' continue to follow this trend, only then 'Rugosa Friulana' had similar readings in the deficit plots and only the drought readings could be differentiated as higher. 'Genovese' and 'Jasper' went from being not significantly different between treatments mid-season, to having the highest relative chlorophyll content in the drought plots late-season, at 58 and 57.9, respectively.

3.4 Field Results: Watermelon

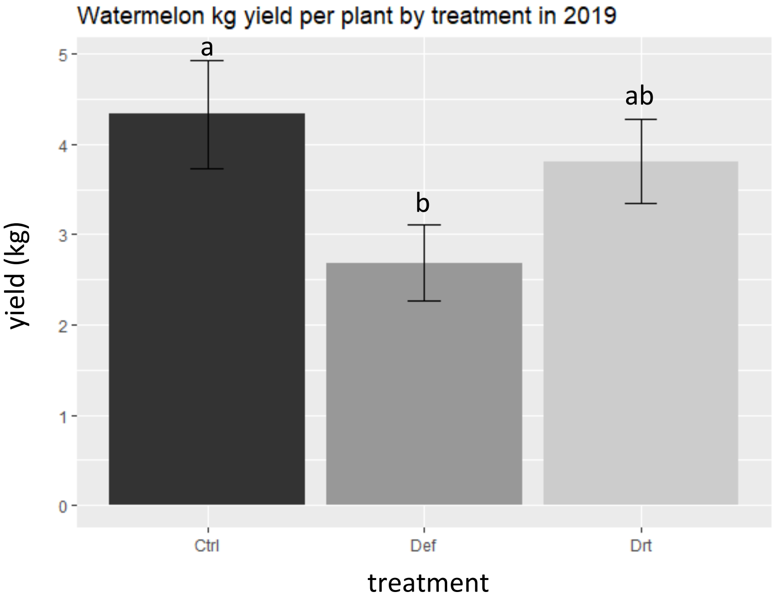


Figure 22- Watermelon yield by irrigation treatment in field trials, 2019.

For watermelon, cultivar was not a significant predictor of yield per plant in 2018 but was a borderline (p=0.0517) significant predictor of yield in 2019. In both years, however, 'Amiga' had the lowest mean yield (1.54 kg/plant in 2018, 2.76 kg/plant in 2019), and 'Tohono O'odham Yellow-Meated' had the highest mean yield (2.85 kg/plant in 2018, 4.75 kg/plant in 2019). 2019 yields more than doubled those of 2018 due to hail damage and severe cucumber beetle damage in 2018. Hail damage also occurred in early July of 2019, but the crop successfully recovered after pruning vines to remove damaged tissue. In 2019, treatment was the significant predictor of yield. The control plots yielded significantly higher than the deficit plots for all cultivars, with a mean yield of 4.33kg/plant vs. 2.69 kg/plant. Drought plot yields could not be differentiated from the other treatments, even though they received the same amount of water as the deficit treatment (55.1 gallons per plant) in 2019. This indicates that the depth and timing of irrigation application may be as consequential as the amount of water applied to these watermelon cultivars, and deep infrequent irrigations are preferable. Irrigation treatment was not a significant predictor of total unmarketable yield in either year, indicating that drought stress alone does not cause an increase in unmarketable fruits. By contrast, in 2018, ‘Rio Grande Red Seeded’ had more unmarketable yield by weight than any of the other cultivars, and in 2019, ‘Desert King’ and ‘Tohono O’odham Yellow Meated’ had the most unmarketable weight per plant. Watermelons were counted as unmarketable most often due to a combination of sunscald, mechanical damage, wildlife/insect feeding, and shriveled/misshapen fruits. ‘Rio Grande Red Seeded’ was a uniquely small, white fleshed watermelon with an average weight of 0.4-0.5 kg per fruit compared to an average weight between 2.0 and 4.0 kg per fruit among all other cultivars evaluated.

°Brix measurements were not impacted by irrigation treatments in 2018. Cultivar main effects were significant, with ‘Amiga’, ‘Ancient’, and ‘TOY’ having the highest °Brix values with averages ranging from 9.3-9.7 (Figure 23). ‘Desert King’ and ‘Jemez’ had mid-range Brix values, and ‘RGRS’ had the lowest °Brix readings with a mean of 6.8, making it an undesirable cultivar for fresh market growers despite its convenient small fruit size.

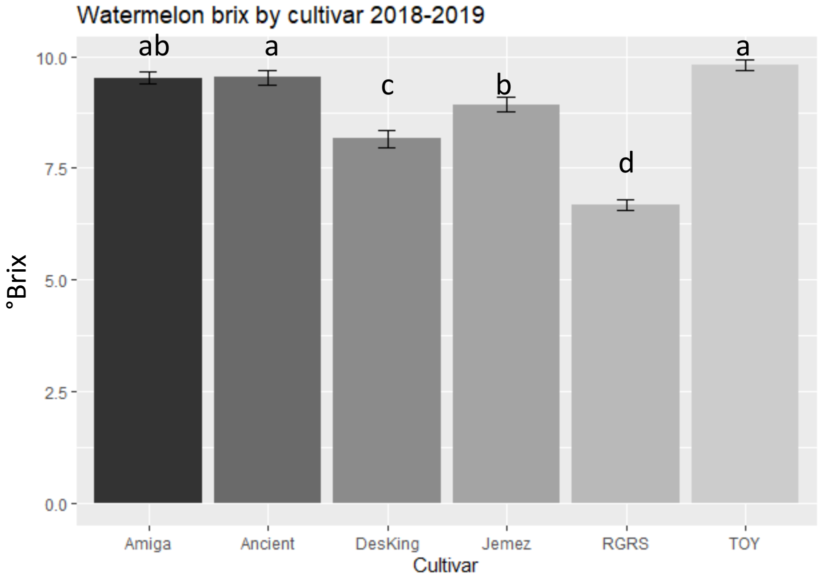
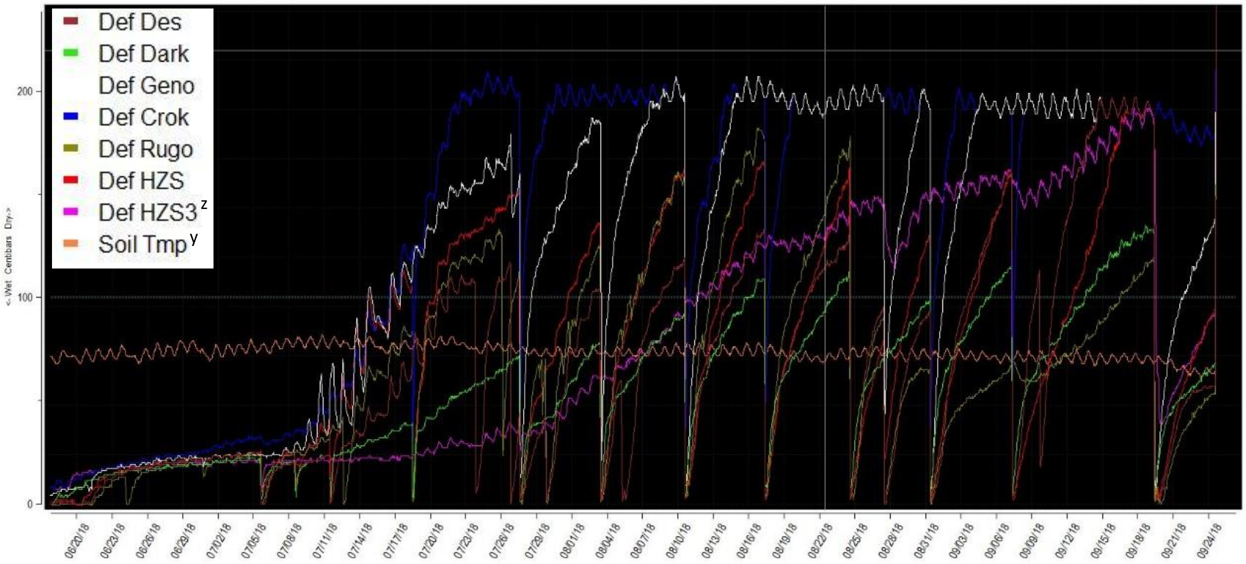


Figure 23: °Brix (total soluble solids) of 6 cultivars of watermelon measured by a digital refractometer in the 2018 and 2019 field trials.

3.5 Environmental Monitoring

Soil moisture readings in centibars from WaterMark monitors (Appendix, Figures 24, 27-34) were soil-temperature calibrated and allowed graphical representation of irrigation events as well as the dry-down pattern of each cultivar in block 2 of the squash plots and the watermelon plots. A horizontal line is marked on each graph at -100 centibars, the recommended threshold for irrigating a high-clay soil (Irrometer, 2019) (Figures 27-34 in appendix, Figure 24 as a representative). Measurements ranged from zero (saturated with water) to -239 centibars. Data from additional WaterMark soil moisture sensors that was manually recorded is presented in Figure 25 and in the Appendix (Figures 33-44). Canopy temperature sensors compared canopy temperatures from each of the treatments in block two of the squash plot, as well as outside of the Cravo. These four temperature measurements are indistinguishable from one another, showing that similar temperature conditions existed in all four locations (Figure 26). In 2019, data from the control plot had to be removed due to a faulty sensor (Figure 52). In the watermelon field, canopy temperature and soil temperature were recorded in both years.



[z] "Def HZS3" soil moisture sensor buried at 90cm depth instead of 30cm depth in 'HZS-03-849'.
[y] "Soil Tmp" soil temperature sensor buried at 30cm depth and used to calibrate soil moisture readings.
Figure 24: Soil moisture in centibars at 30cm (12") depth in the deficit squash plot in 2018.

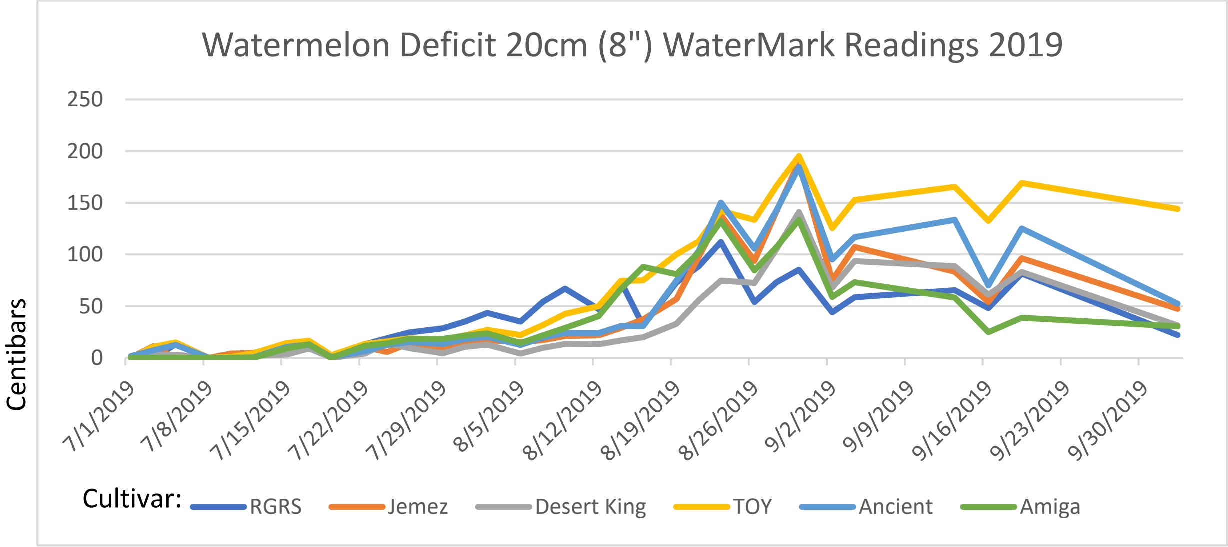


Figure 25: Soil moisture in centibars at 20cm (8") depth in block two of the deficit watermelon plot in 2019.

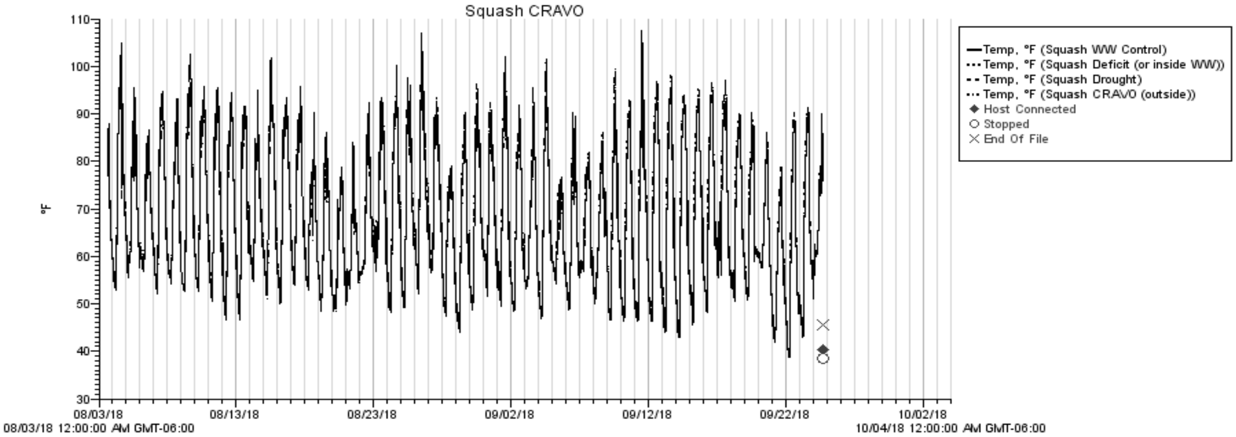


Figure 26: Canopy temperature of squash plots inside and outside of Cravo in 2018.

4. DISCUSSION

In this series of experiments, differences can be identified between cultivar reports from seed companies, overall cultivar performance in the greenhouse, and yield success under sustained deficit irrigation in the field trials. Based on seed company reports and OSU DFC trials, ‘Desert King’ watermelon was expected to be the most successful in drought conditions, and because of the lack of reports of drought-resistance, ‘Amiga’ was included as a presumably drought-sensitive modern hybrid check cultivar. Among the summer squash cultivars, the organic hybrid ‘Desert F1’ zucchini was the only cultivar claimed to be “drought tolerant”. ‘HZS-03-849’ our conventional hybrid zucchini, had reports of high yield potential, but no claims related to drought response and so was hypothesized to be sensitive to drought conditions.

‘Rugosa Friulana’ was more successful than all other squash cultivars in the greenhouse trials in terms of the number of days it survived. This cultivar also had the greatest ability to extract moisture from the substrate and to persist in low moisture conditions. However, this survivability did not correspond to statistically greater overall root growth. Two of the cultivars with the most extensive (longest) root systems in the dry down study (‘Jasper’ in both years, and ‘HZS-03-849’ in 2019) tended to die faster (37 days in 2018, 62-63 days in 2019) than ‘Rugosa Friulana’ (48 days in 2018, 93 days in 2019), and had a significantly higher percent soil moisture at death in 2019. There appeared to be a tradeoff between survivability and root system development, as ‘Jasper’ and ‘HZS-03-849’ had better yield in the field studies than ‘Rugosa Friulana’. This was not always the case, though, as ‘Genovese’ had similar root growth and survivability in the greenhouse studies but comparably low yields in the field studies.

Overall yield averages were slightly lower in the field in 2019, likely due to severe pest pressure from squash bugs (*Anasa tristis)*. Populations were controlled by physical removal and destruction of eggs, nymphs, and adults. Powdery mildew, grasshopper feeding, cucumber beetle feeding, root rot, and rodent feeding caused additional damage to the squash crop in both years. Damage was quantified and accounted for where possible. Late in the 2019 growing season, squash bug damage prevented the growth of some developing fruits, but incomplete pollination or lack of pollination was the primary cause of unmarketable fruits in the squash crop.

Control treatments received an average of 5.9 inches of water per season, and the drought and deficit treatments received an average of 5.1 inches of water. This difference of 0.8 inches was enough to result in yield differences in some cultivars (‘Rugosa Friulana’ and ‘Genovese’ in 2018, and ‘Desert F1’ in 2019) due to the extended period that the treatment interval lasted, more than two months. Only between 0.7-1.6 inches of water were applied based on treatment over the course of drought-sensitive period of flowering and reproductive growth. The conventional hybrid ‘Jasper’ was the most successful cultivar overall, with an average yield of 1.9 kg/plant in 2019, but organic hybrid ‘Desert F1’ had statistically similar yields overall (1.7 kg/plant in 2018, 1.4 kg/plant in 2019), though this was impacted by treatment. A similar, but not statistically significant trend was observed in ‘Desert F1’ in 2018. ‘Jasper’ and ‘Dark Star’ also remained more tender at a larger size than ‘Desert F1’, which was generally firmer than the check cultivar, ‘HZS-03-849’ at a smaller average size. Even though ‘Desert F1’ was one of the few cultivars to experience a statistically significant yield penalty in the deficit treatment and a decreased mean yield in the drought treatment, this cultivar is a good choice for reduced moisture conditions due to its ability to reach its high yield potential in the control plot, in which irrigation was still restricted to an average of 5.9 inches of water per season. The highest yielding open-pollinated cultivar was ‘Dark Star’, which had a lower mean yield but was statistically similar to ‘Desert F1’ in 2018 and 2019. This cultivar’s yield was not impacted significantly by the different irrigation treatments, and neither was ‘Jasper’. Among the seven cultivars total evaluated in the field trials, only ‘Desert F1’ had reports of drought resistance. The success of ‘Jasper’, ‘Dark Star’, and ‘HZS-03-849’ shows that currently available cultivars without reports of drought resistance have an ability to succeed under sustained deficit conditions that was previously unknown. It is also evident that high-yielding cultivars with drought-sensitive responses may still be preferable to lower-yielding cultivars that are more resilient to additional water deficits.

Greenhouse performance of the watermelon cultivars was inconclusive. Differences in root:shoot ratio were not significant in 2019, but in 2018 ‘TOY’ had a significantly higher root:shoot ratio than ‘Desert King’. Due to field conditions in 2018, no yield differences could be identified, but in 2019 all cultivars had a similar response to deficit irrigation treatments. While cultivar variation for root:shoot ratio was significant in 2018, differences in total root length and fine root length were not. In 2019, ‘TOY’ had significantly more total root length and fine root length than ‘Kaho’ and ‘Amiga’. ‘Kaho’ was not included in the field trials, but those that were, ‘TOY’ and ‘Amiga’, had statistically similar yield and °Brix. The traits evaluated in the greenhouse had no assumed relationship to °Brix, and this quality measure ended up being the best tool to identify suitable cultivars in the field studies since yield responses were similar across cultivars.

Though the watermelon cultivars included in these studies were from different regions and had individual reports of unique traits, there were no statistically significant interactions between the main effects of treatment and cultivar for any of the response variables evaluated. In most cases (Figures 17, 18, 20, and 23), cultivar was the significant predictor of crop success, or cultivar and treatment were significant as main effects, without an interaction between the two variables. However, in the case of the 2019 watermelon crop (Figure 22) only the treatment main effect was significant which indicates that all cultivars behaved similarly in response to treatment despite differences in genetics and historical management.

Sustained deficit irrigation conditions of 50% or more below recommended season-long rates (4.7 inches vs. 12 inches of water) did not prevent marketable yield from being obtained from any plots, indicating that a sustained irrigation deficit of over 50% may not be detrimental to the quality of watermelon fruits in general, but can cause yield reductions. In 2019, when yields were higher and all plots received on average 0.7 inches of additional water, the deficit treatment plots yielded significantly lower than the control or drought plots in all cultivars. Deficit plots received a nearly identical overall amount of water to the drought plots in both years (46 vs. 47.1 GPP in 2018, 55.1 GPP in 2019), and it is important to note that the deficit plots received more frequent, shallow irrigations than the drought plots, which led to a yield penalty. Therefore, it appears that when water resources are scarce, fewer, deeper irrigations are preferable to more frequent shallow irrigations in both modern hybrids and open pollinated heirloom watermelon crops, whether these cultivars have reports of drought resistance or not.

While the watermelon field data does not conclusively suggest that any of the cultivars studied are preferable from a yield standpoint, the °Brix data indicates that ‘Amiga’, ‘Ancient’, and ‘TOY’ produced watermelon fruits with the highest total soluble solids in both years. In 2019, none of the ‘Ancient’ watermelons ripened until the final harvest, nearing the frost date, making it less suited to Northern Colorado growing conditions. It was also observed that, though ‘TOY’ began flowering later than other cultivars, it reached maturity within the same time frame, and this late flowering resulted in less mechanical hail damage to fruit from early season hail storms. ‘TOY’ also yielded fruits with a more uniform shape and size than some other cultivars, such as ‘Amiga’ and ‘Desert King’. Ripeness was easiest to determine for ‘TOY’, based on size for weight, rind feel, and sound. However, this cultivar was the most prone to splitting if mishandled. The orange-fleshed ‘Desert King’ experienced the most plant losses resulting from hail damage in 2018. Though it produced a wide range of sizes of watermelons, and some of them were misshapen, it ripened consistently within the same time frame regardless of size. ‘Jemez’ had lower °Brix than ‘Ancient’ and ‘TOY’, but higher than ‘Desert King’ and ‘RGRS’. However, this heirloom cultivar produced watermelons with five or more different rind patterns seen across the plot. A single vine regularly produced three watermelons with three distinct rind patterns. Flesh was pink-red in general, but a few watermelons with yellow flesh were also found. The inconsistency of this cultivar’s phenotype, combined with its lower °Brix value, makes it less desirable as a crop for market growers. ‘RGRS’ was another very unusual cultivar, with fruits ripening at the size of a softball. It was white-fleshed, red-seeded, and not very sweet, so though its size makes it an interesting novelty, this cultivar would be difficult to market. Many of these cultivars were still flowering at the last harvest and had young pollinated fruits that would not reach maturity. Though our season began in early June with month-old transplants, early frost dates on the Front Range make it difficult to bring a watermelon crop to its full yield potential. This may not have been the case if the vines and early fruits had not needed to be pruned due to hail damage, but because of the frequency of hail storms in Northern Colorado this must be take into account. Physiological leaf roll was observed to a greater extent in some cultivars than others, namely ‘Desert King’ and ‘Ancient’, but there were no yield differences between these cultivars and the others. All things considered, the red-fleshed hybrid ‘Amiga’ and the yellow-fleshed open-pollinated ‘Tohono O’odham Yellow-meated’ had some of the highest °Brix and were observed to perform more consistently than the four other cultivars in the field trials.

All soil moisture readings revealed that soil dried beyond recommended thresholds for both crops (Figures 24, 25, 27-50), and in many cases reached the driest reading measurable with this sensor, without resulting in crop loss. However, WaterMark sensors can lose soil contact in clay-dominant soils that become very dry and shrink, and therefore these sensors may not be ideal for drought studies in such conditions. An alternate soil moisture measurement system using Time Domain Reflectometry (TDR) to measure volumetric soil moisture content was tested during 2019 field trials and is being evaluated for use in future studies, though the shrinking of high-clay soils in very dry conditions can become problematic with any type of soil moisture sensor. The squash were grown in a Cravo which was used for rain and hail exclusion, and inside and outside canopy temperature data reveal that the use of the Cravo did not lead to differences in environmental conditions and therefore is a good choice for future studies on drought response and deficit irrigation.

These results demonstrate that the most successful cultivars of summer squash in these experiments experience an approximate yield penalty of 30% in conditions of more than 50%

water reduction from average recommended rates. While a yield penalty was incurred, no significant changes in quality or marketability were observed. All watermelon cultivars were equally sensitive to irrigation reductions from the control in 2019, and even in the control plot yields per plant and per area were below the range of expected watermelon yields. However, the consequences of drastically reduced irrigation in these cultivars are now known, along with which cultivars are the best fit if irrigation inputs are reduced.

5. CONCLUSIONS

These results indicate that more summer squash cultivars than originally assumed have the potential to produce acceptable levels of marketable yield with drastically reduced irrigation. In the case of the watermelons, this crop was surprisingly resilient to decreases in quality as a result of sustained irrigation deficits. However, cultivars with a reputation for drought resistance, such as ‘Desert King’, did not out-perform cultivars without any drought-related claims and fell short in other measures such as °Brix. Cultivars without claims of drought resistance need to be evaluated on a case-by case basis in field trials, as cultivar greenhouse outcomes did not always align with field trial outcomes. Strong drought-resistant traits may exist in cultivars that have already been bred for overall vigor and high yields, such as in the open-pollinated ‘Dark Star’ and hybrid ‘Jasper’ zucchinis. While selective breeding for drought resistance would likely give us new cultivars that are successful with severe water deficits, other cultivars already on the market may have undiscovered potential in these conditions.

The difference in total root growth and average days to death between the 2018 and 2019 greenhouse studies reaffirms the importance of consistent environmental conditions (light, temperature, humidity) in greenhouse studies. However, the sensitivity of these studies to environmental conditions makes it even less likely that they will produce results that align with season-long field performance. Neither year of the greenhouse study produced results that were consistent with both seed company reports of drought resistance and field outcomes, however total root length was a better indicator of field success than metrics related to survivability. Because of the weak relationship between cultivars that were successful in greenhouse trials and those that yielded highest in field trials, it is important to continue to rely on field studies to identify crop cultivars with season-long success under drought.

Prior to planting, growers may have limited information on how much water will be available to them throughout the growing season, and while ideal irrigation amounts may vary from year to year depending on rainfall and average temperatures, crop producers do not necessarily have an extra supply of irrigation water to respond to these changing conditions. Crop producers may be able to reduce irrigation in summer squash crops beyond what was applied in this study by including rainfall for the full growing season. Growing summer squash cultivars such as ‘Jasper’, ‘Desert F1’, or ‘Dark Star’, and watermelon cultivars such as ‘Tohono O’odham Yellow-meated’ and ‘Amiga’ can help ensure growers that they will still harvest marketable yields, and in the case of the squash, acceptable overall yields, even in years of low precipitation or limited irrigation water availability. These results demonstrate that growers may plant ‘Desert F1’, ‘Dark Star’, or ‘Jasper’ zucchini, and apply an average of 19.9 gallons/plant (5.4 inches) including rainfall, and expect yields of 1.2-1.9 kg/plant over the course of the growing season.

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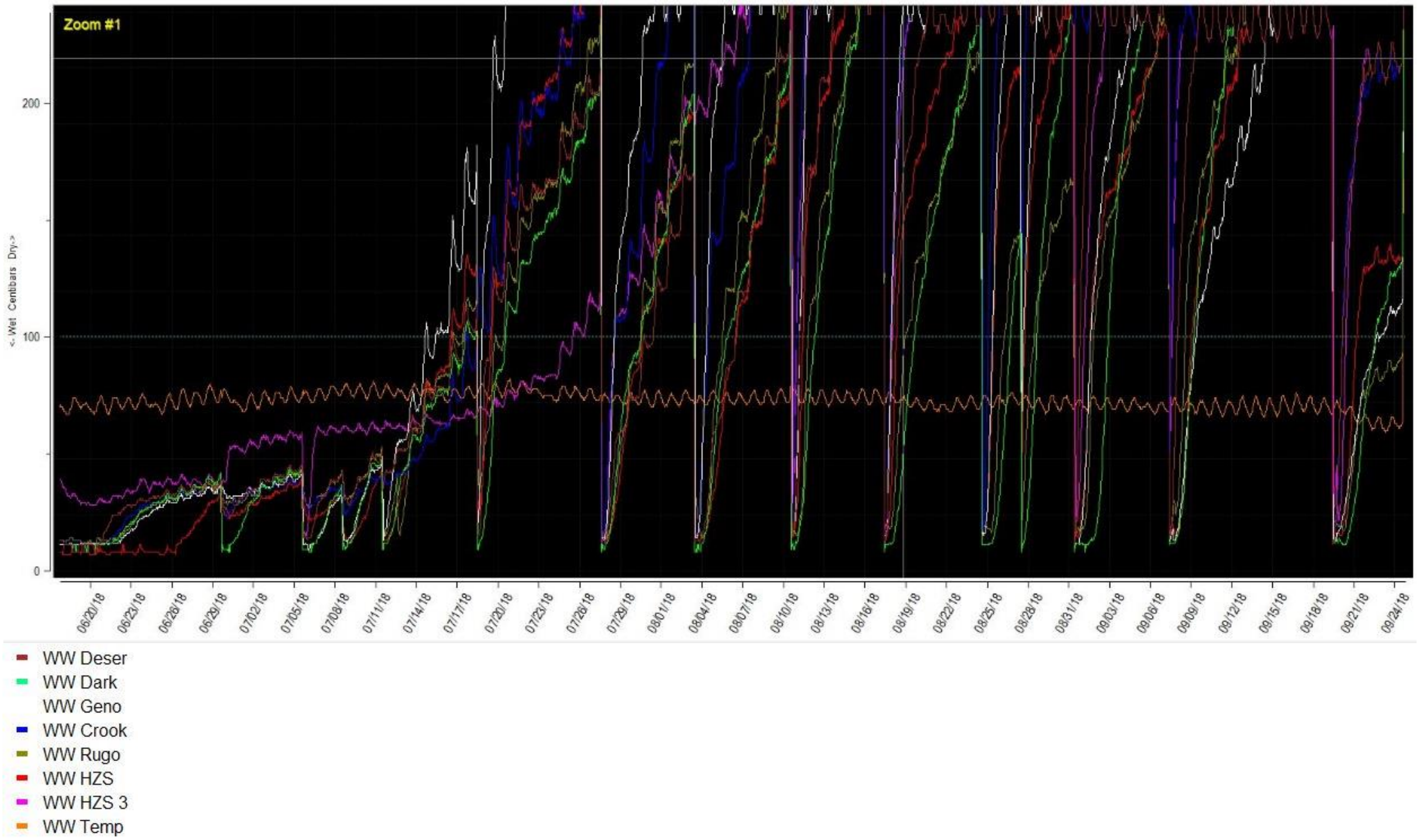


Figure 27- Soil moisture in centibars for squash control plot in 2018, 20cm (8”) depth unless otherwise stated.

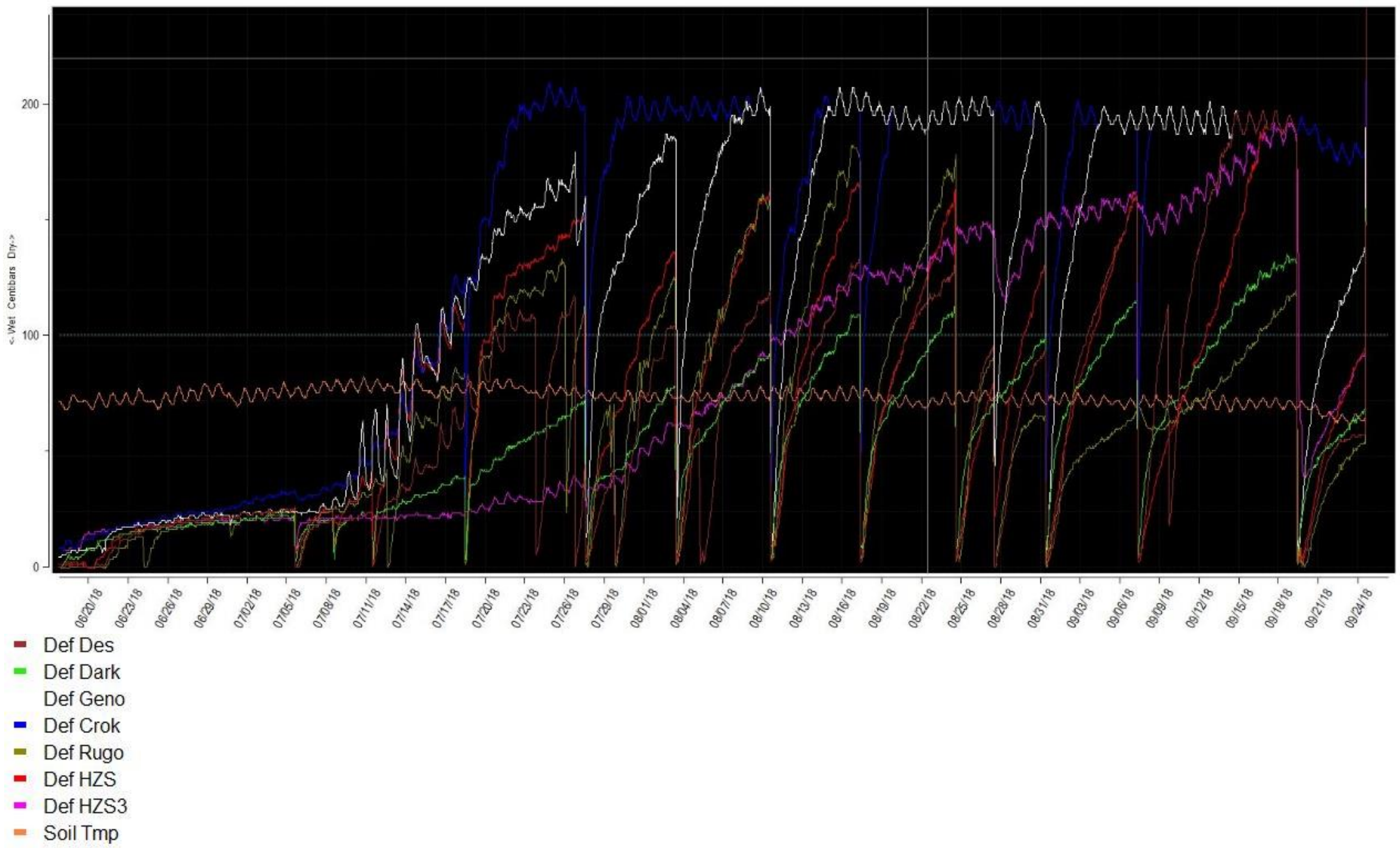


Figure 28- Soil moisture in centibars for squash deficit plot 2018, 20cm (8”) depth unless otherwise stated.

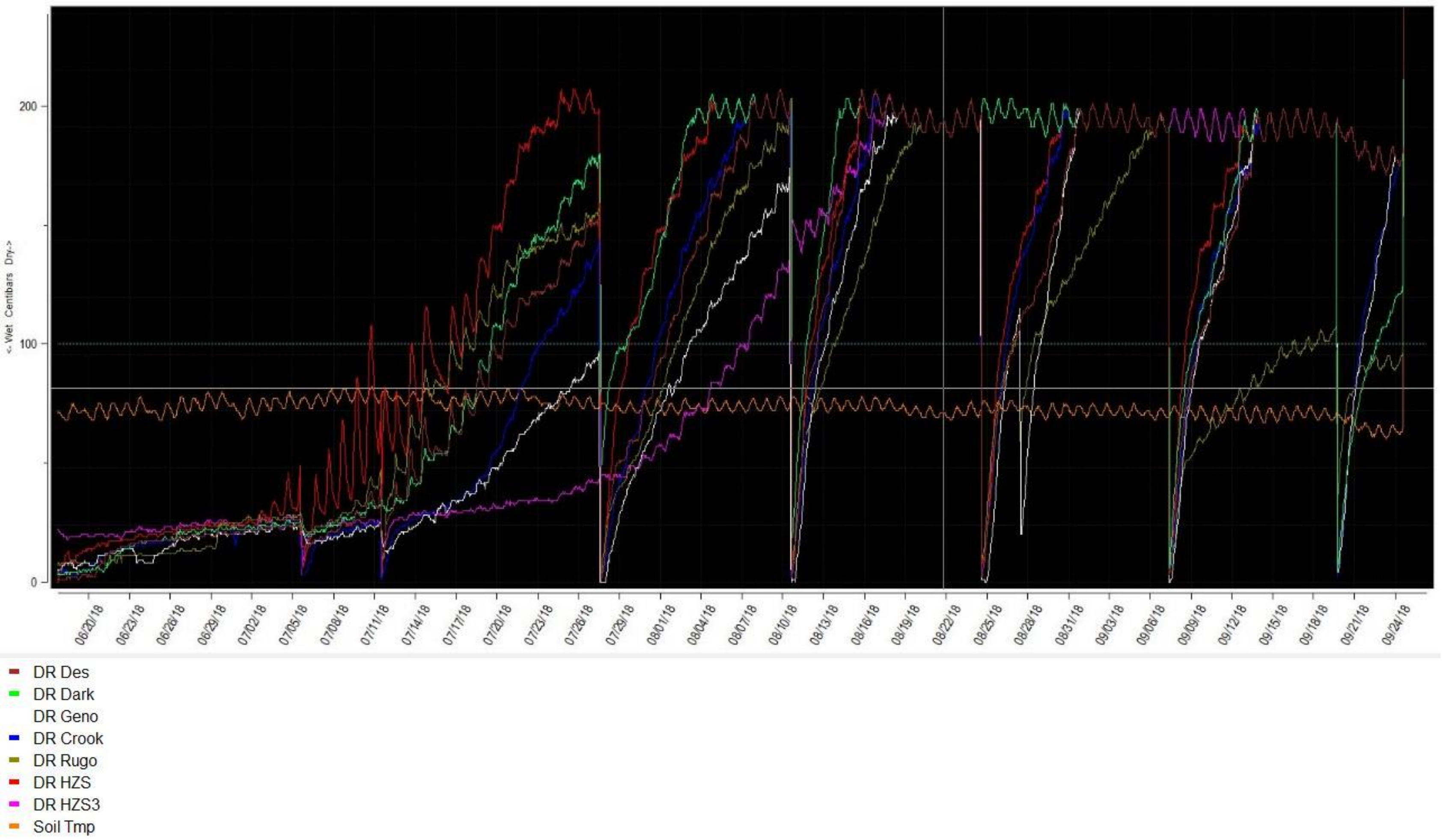


Figure 29- Soil moisture in centibars for squash drought plot 2018, 20cm (8”) depth unless otherwise stated.

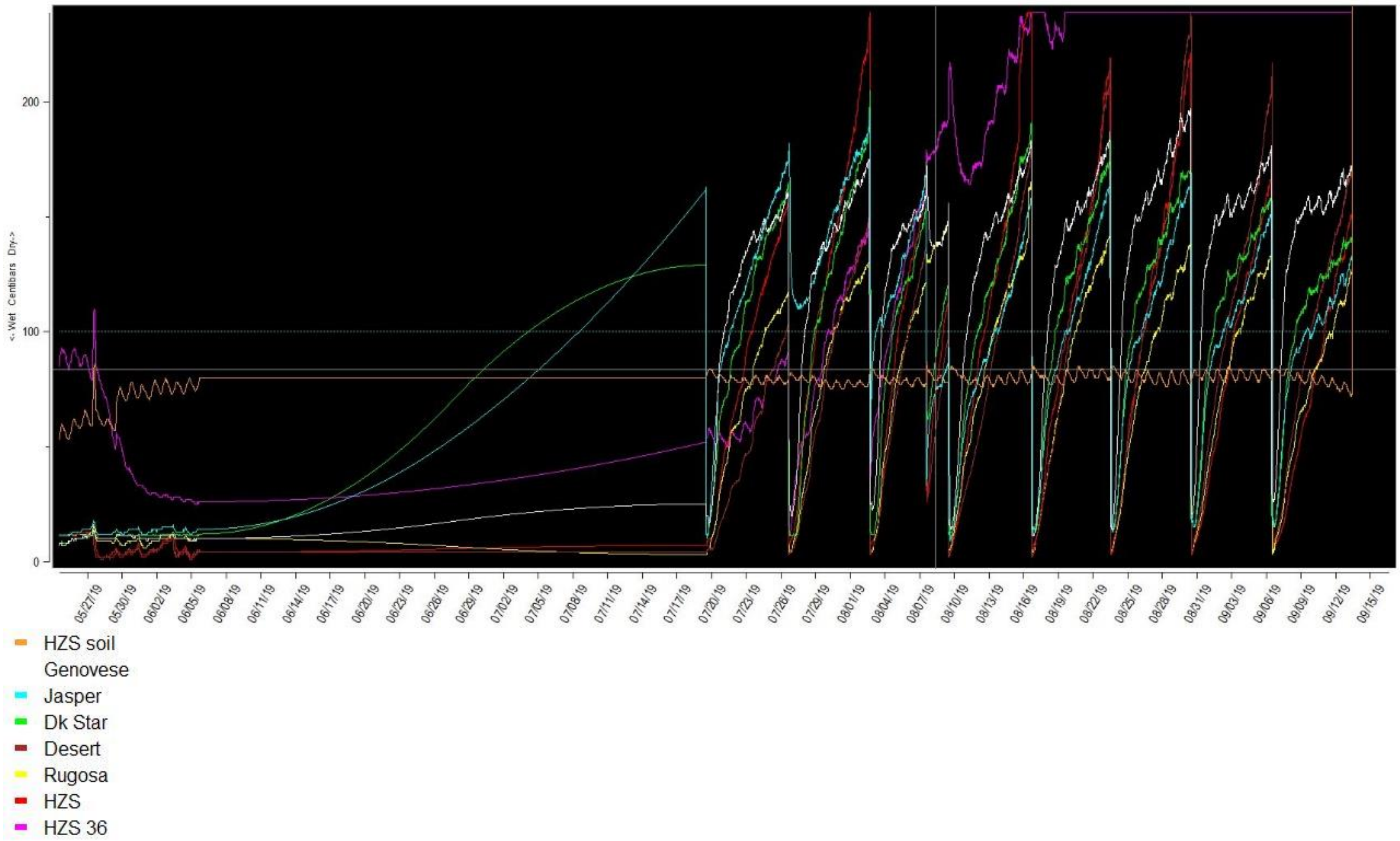


Figure 30- Soil moisture in centibars for squash control plot in 2019, 20cm (8”) depth unless otherwise stated.

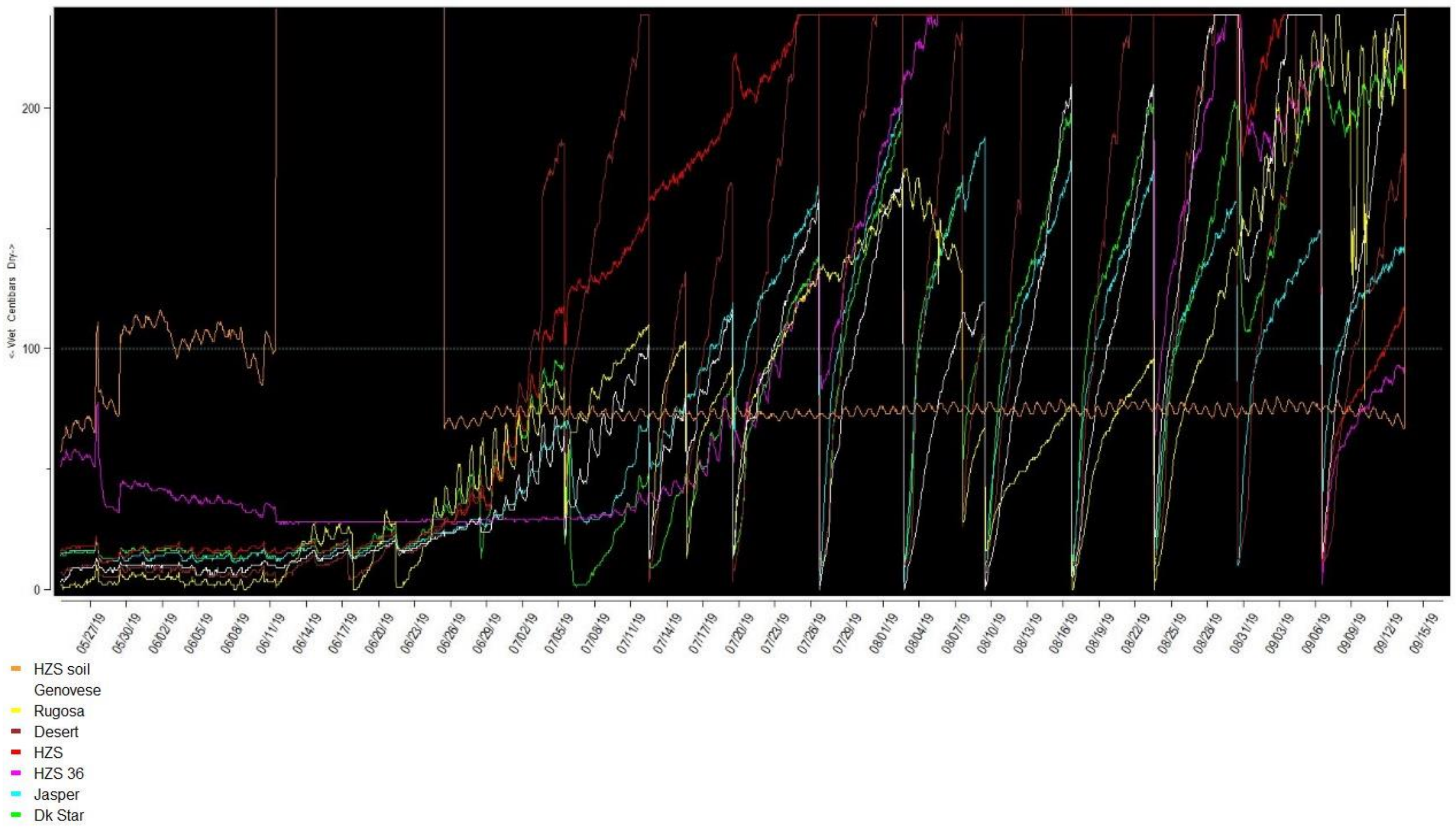


Figure 31- Soil moisture in centibars for squash deficit plot in 2019, 20cm (8") depth unless otherwise stated.

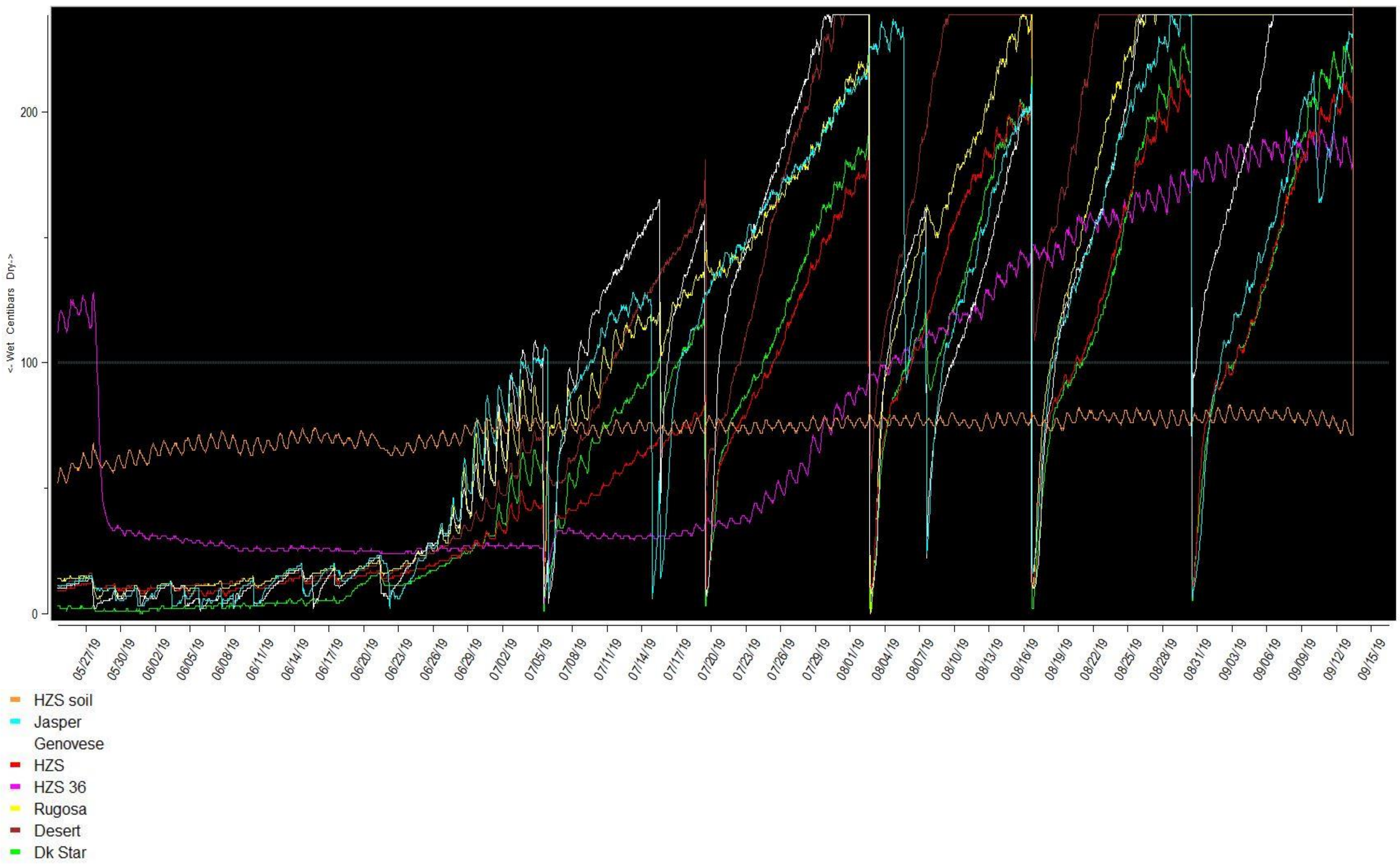


Figure 32- Soil moisture in centibars for squash drought plot in 2019, 20cm (8”) depth unless otherwise stated

2. Manually Recorded WaterMark Soil Moisture Readings: Squash

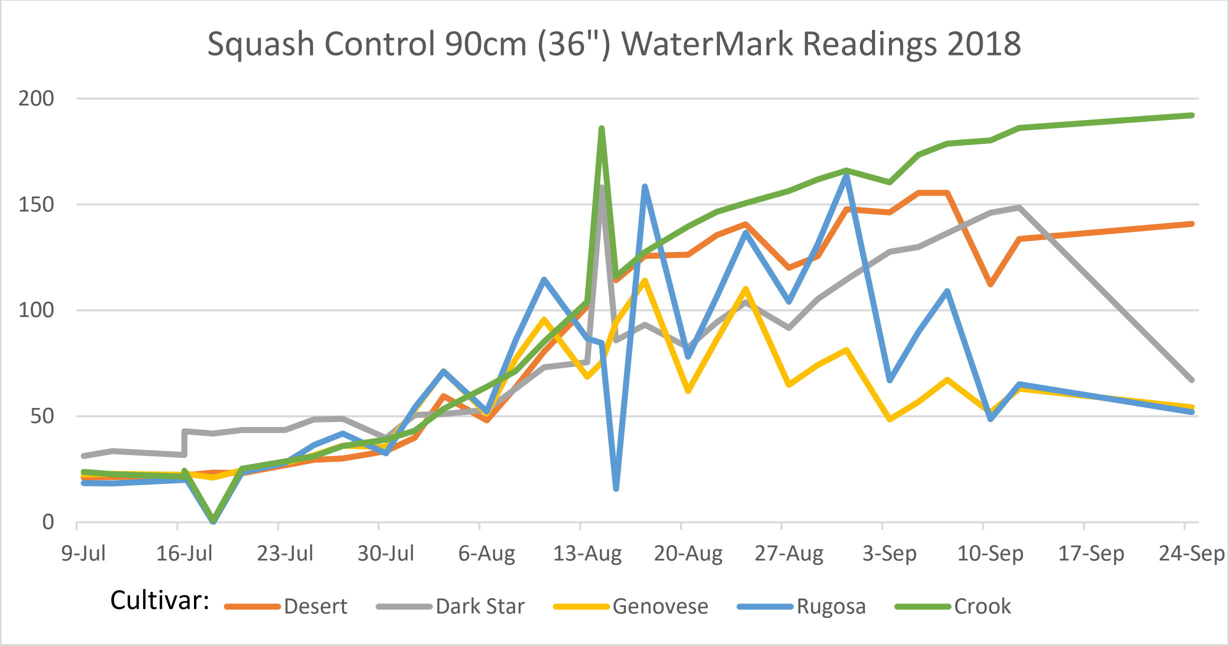


Figure 33- Season long soil moisture in centibars at 90cm depth in block two of the squash control plot in 2018.

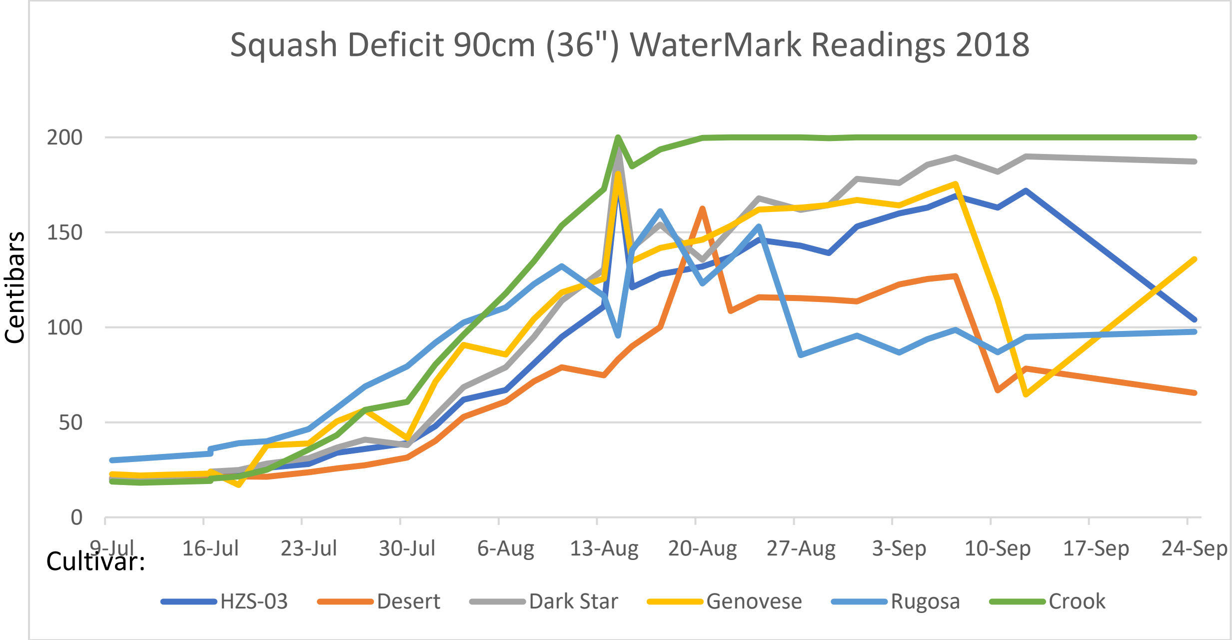


Figure 34- Season-long soil moisture in centibars at 90cm depth in block two of the squash deficit plot in 2018.

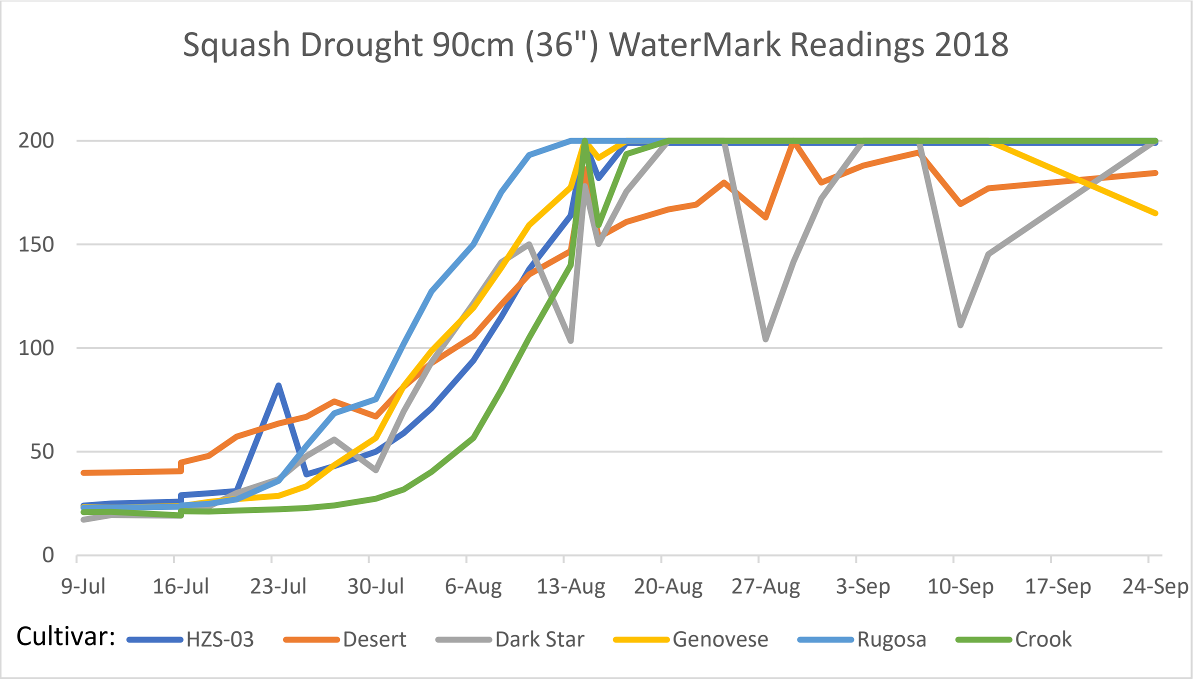
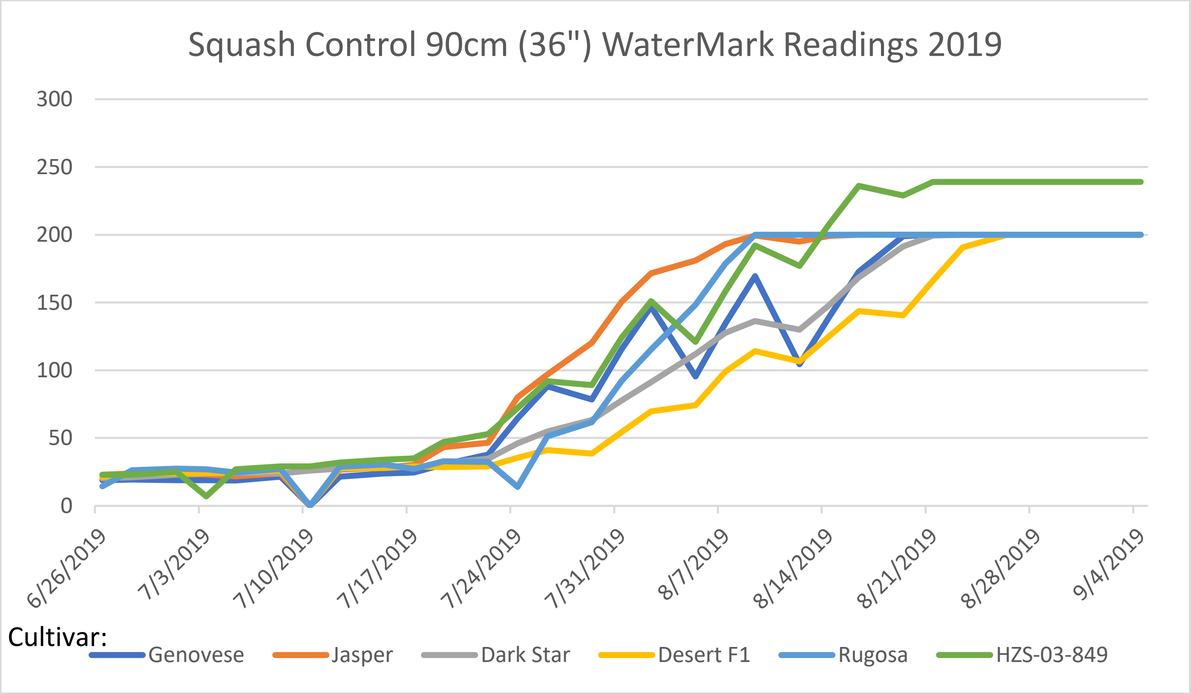


Figure 35- Season-long soil moisture in centibars at 90cm depth in block two of the squash drought plot in 2018.



Figures 36- Season-long soil moisture in centibars at 90cm depth in block two of the squash control plot in 2019.

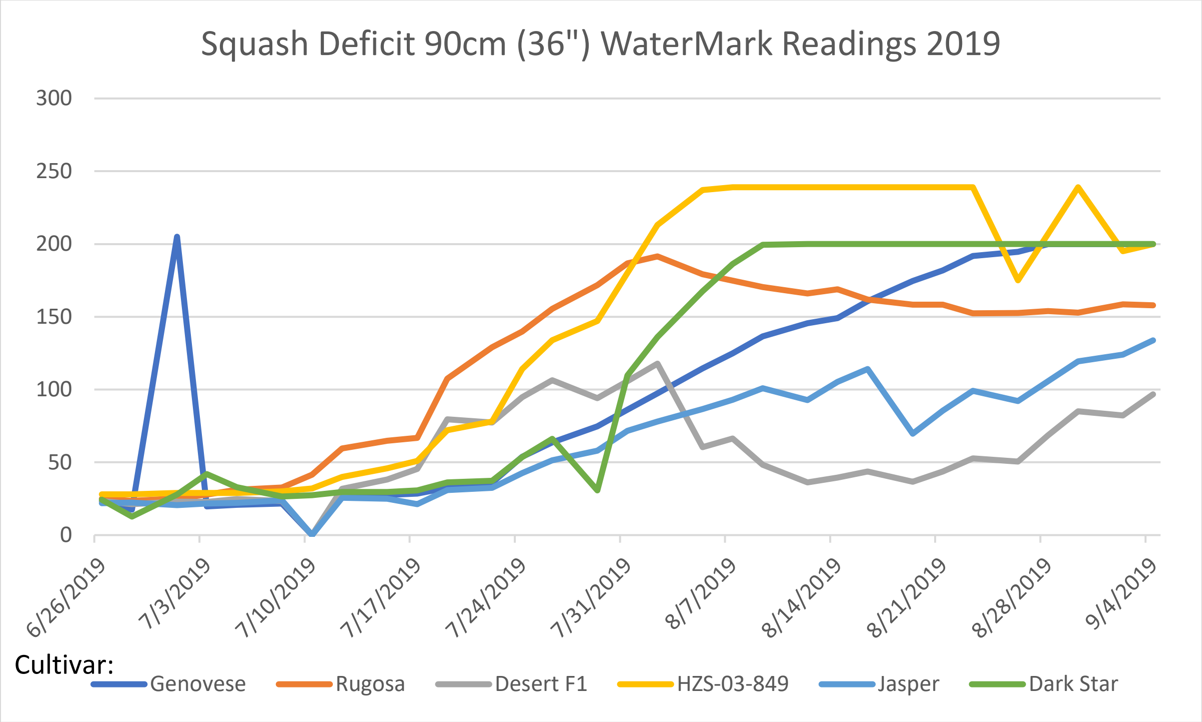


Figure 37- Season-long soil moisture in centibars at 90cm depth in block two of the squash deficit plot in 2019.

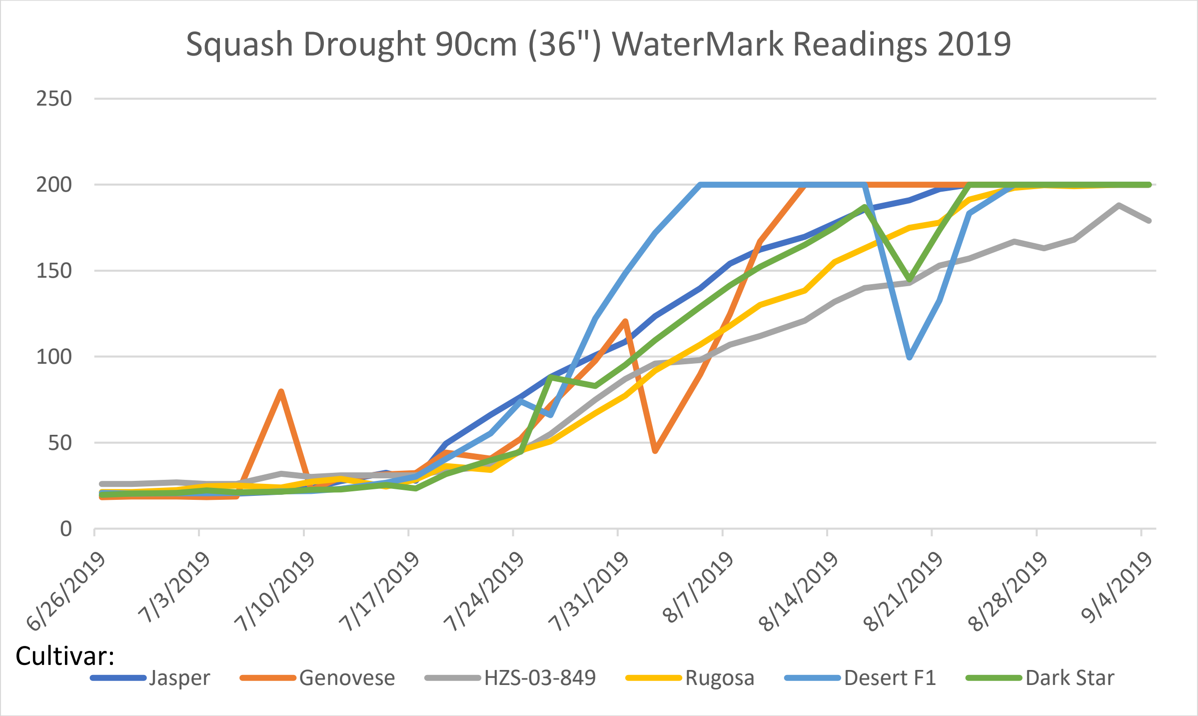


Figure 38- Season-long soil moisture in centibars at 90cm depth in block two of the squash drought plot in 2019.

3. Manually Recorded WaterMark Readings: Watermelon

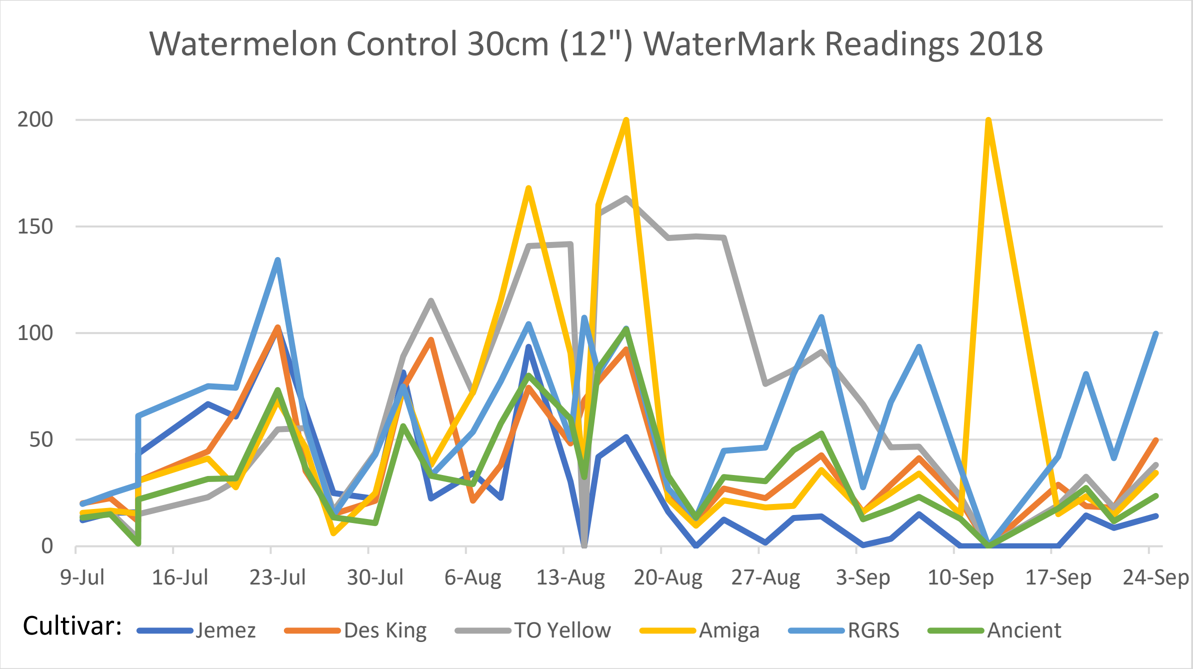


Figure 39- Season-long soil moisture in centibars at 30cm depth in block two of the watermelon control plot in 2018.

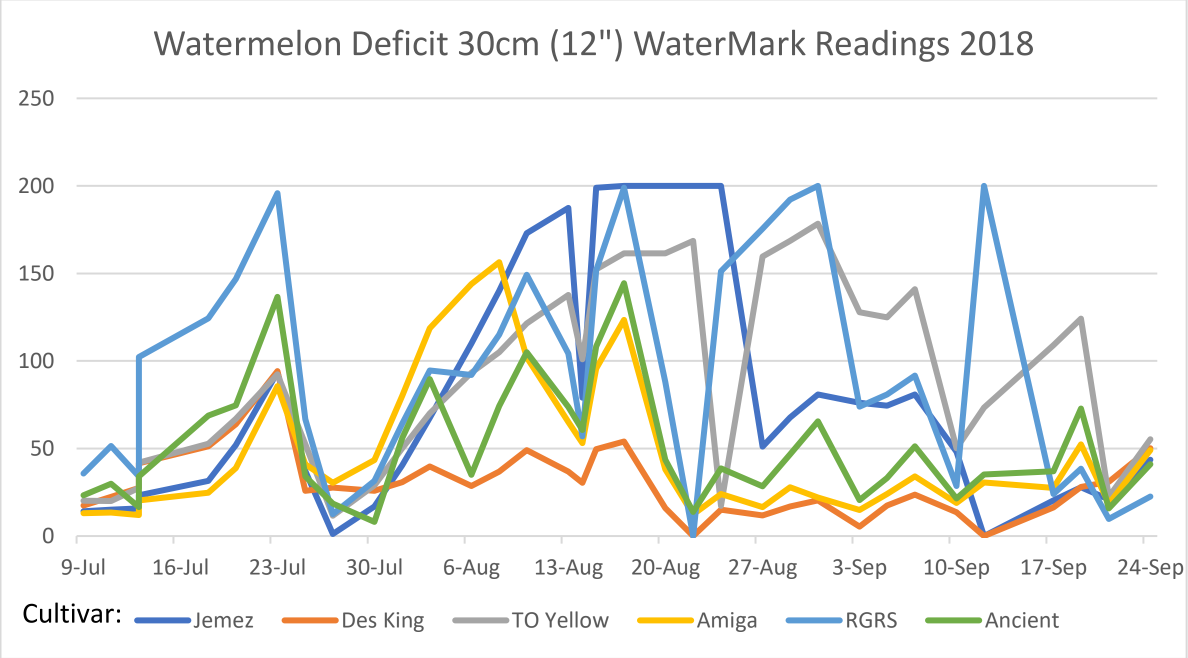


Figure 40- Season-long soil moisture in centibars at 30cm depth in block two of the watermelon deficit plot in 2018.

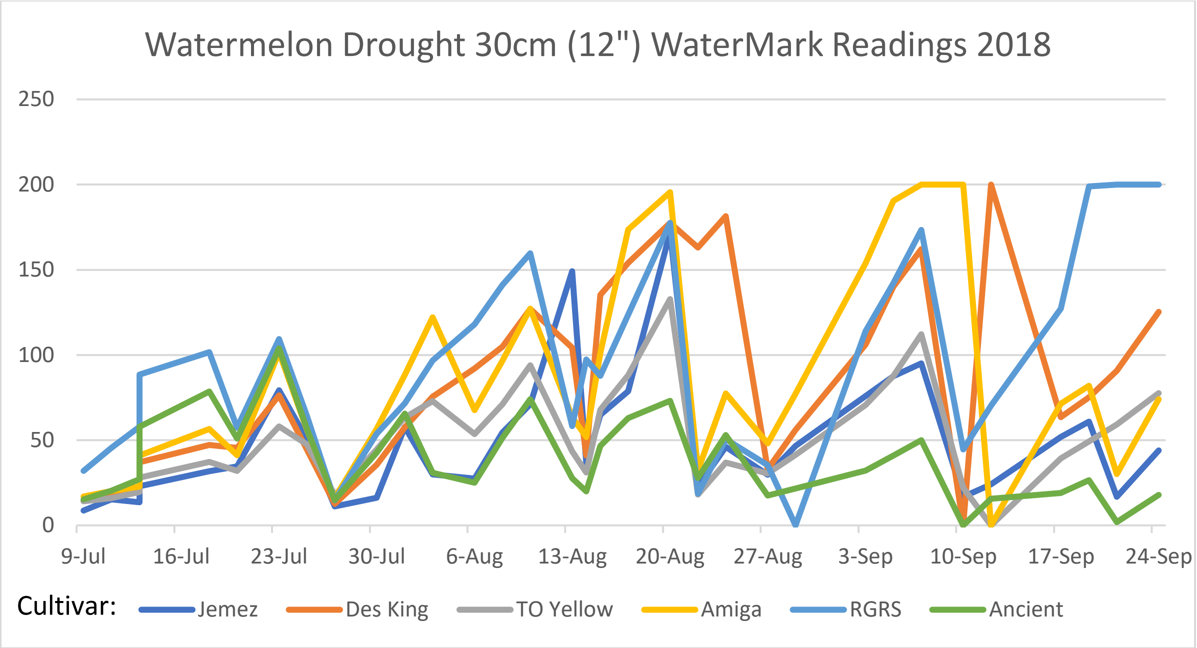


Figure 41- Season-long soil moisture in centibars at 30cm depth in block two of the watermelon drought plot in 2018.

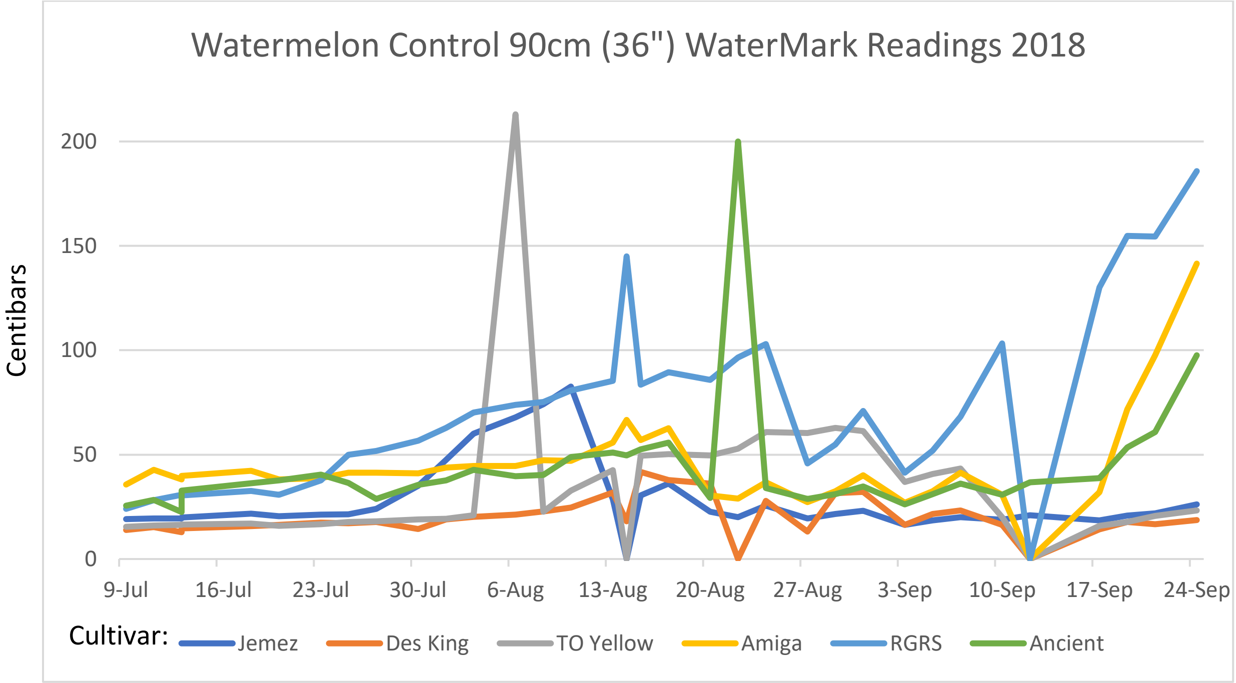


Figure 42- Season-long soil moisture in centibars at 90cm depth in block two of the watermelon control plot in 2018.

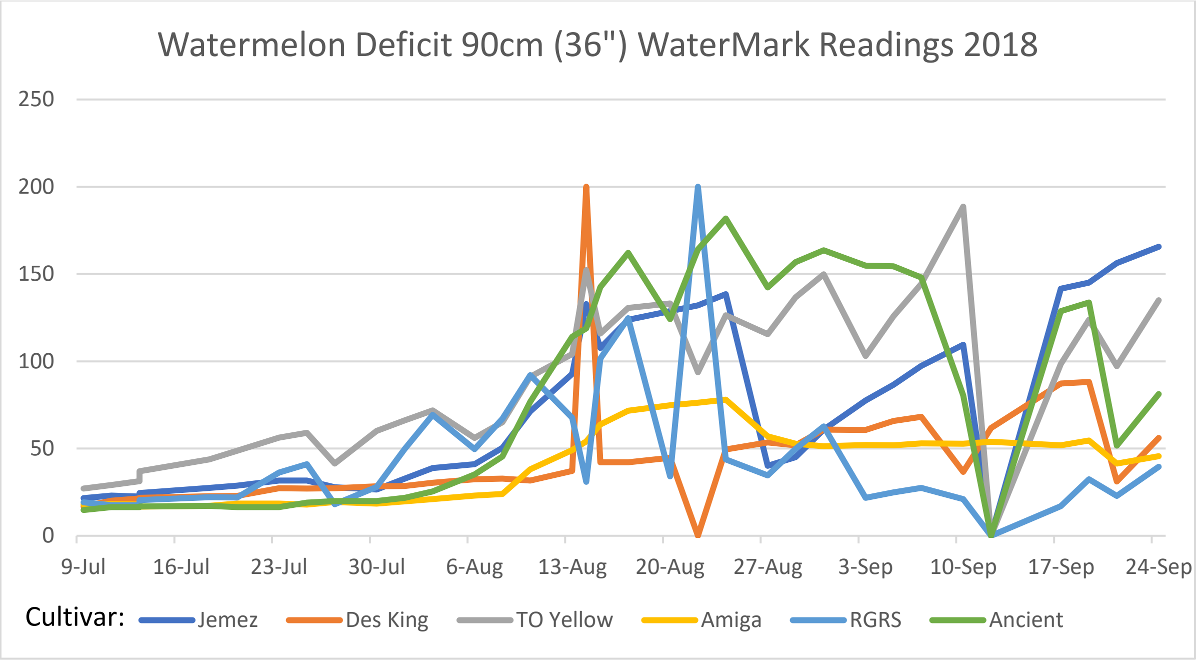


Figure 43- Season-long soil moisture in centibars at 90cm depth in block two of the watermelon deficit plot in 2018.

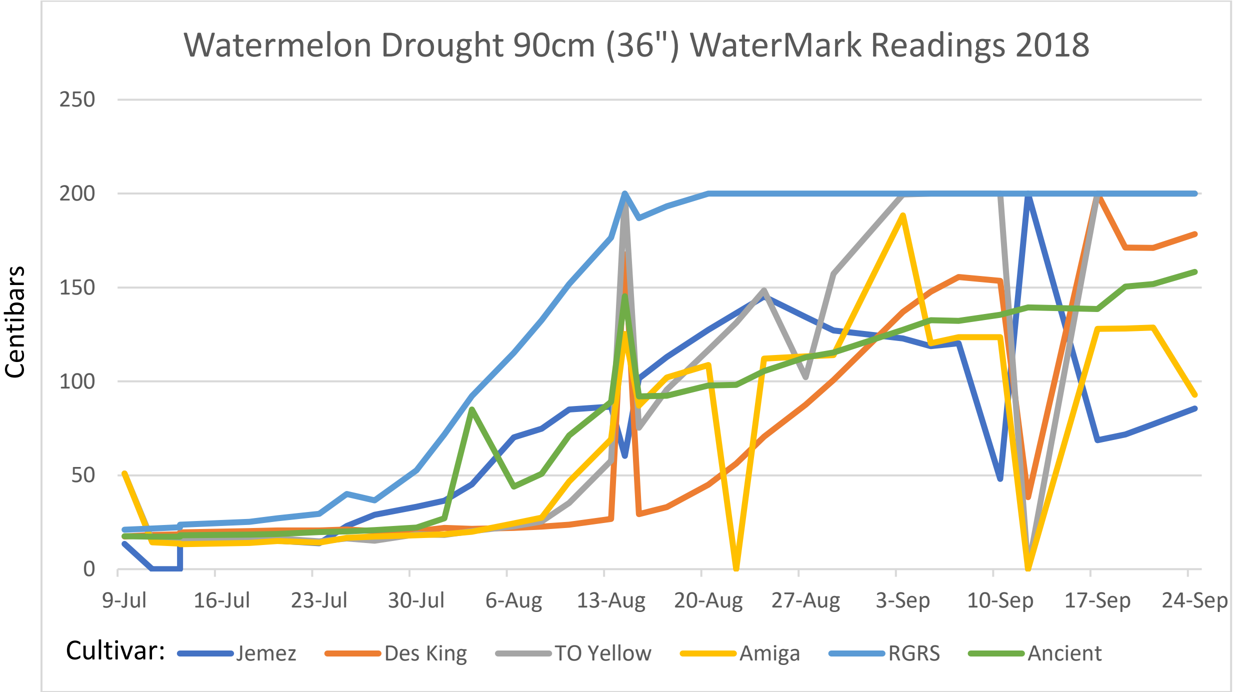
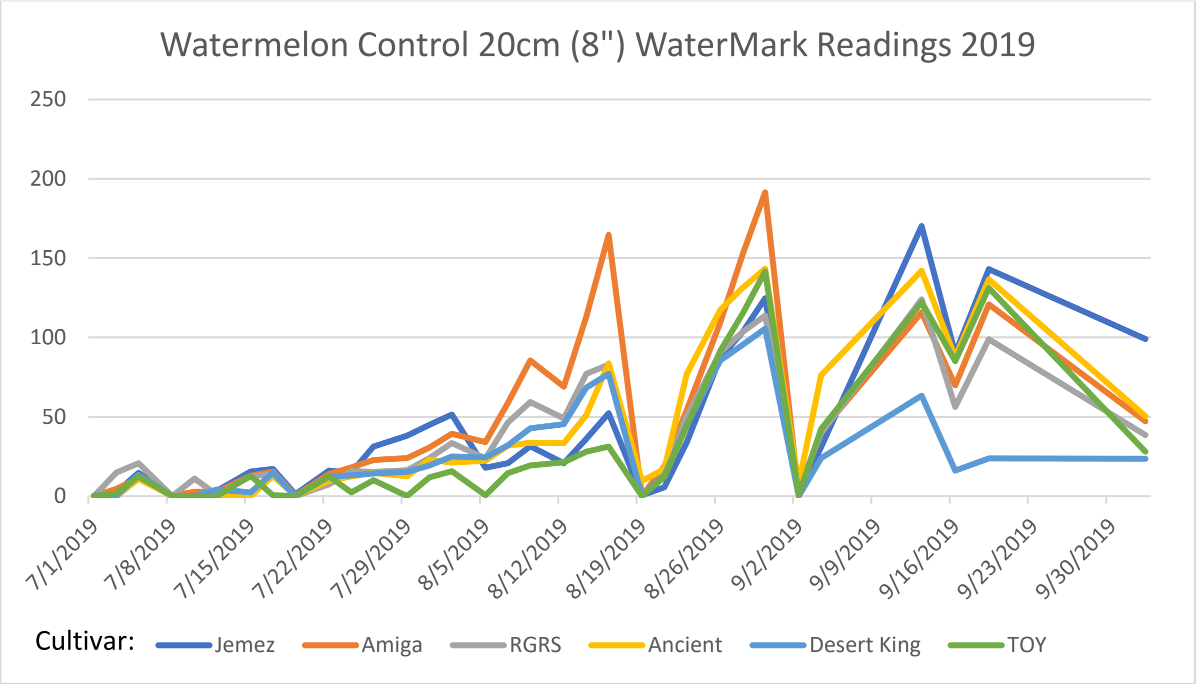


Figure 44- Season-long soil moisture in centibars at 90cm depth in block two of the watermelon drought plot in 2018.



Figures 45- Season-long soil moisture in centibars at 20cm depth in block two of the watermelon control plot in 2019.

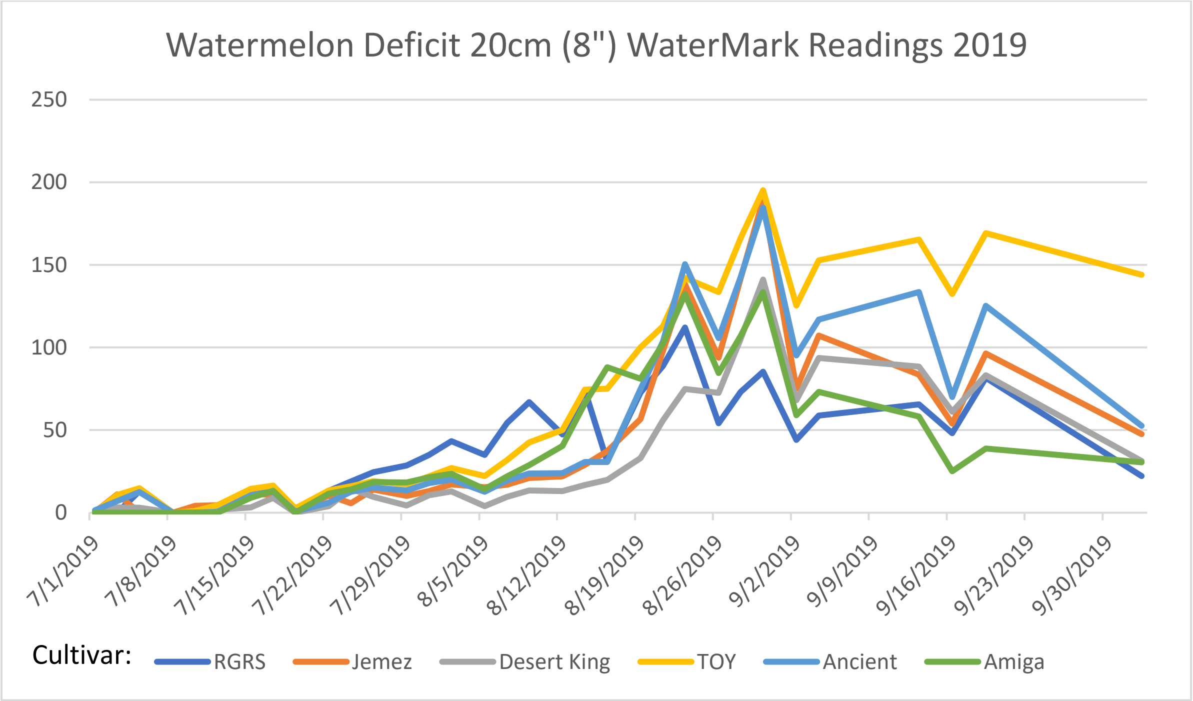


Figure 46- Season-long soil moisture in centibars at 20cm depth in block two of the watermelon deficit plot in 2019.

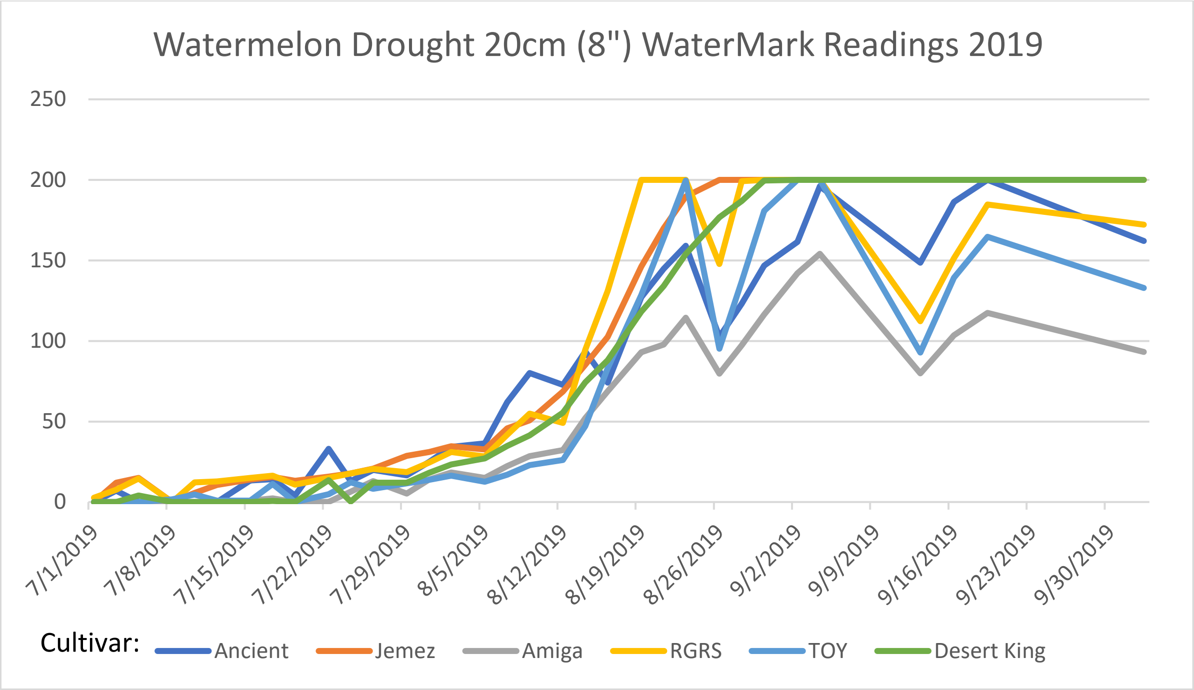


Figure 47- Season-long soil moisture in centibars at 20cm depth in block two of the watermelon drought plot in 2019.

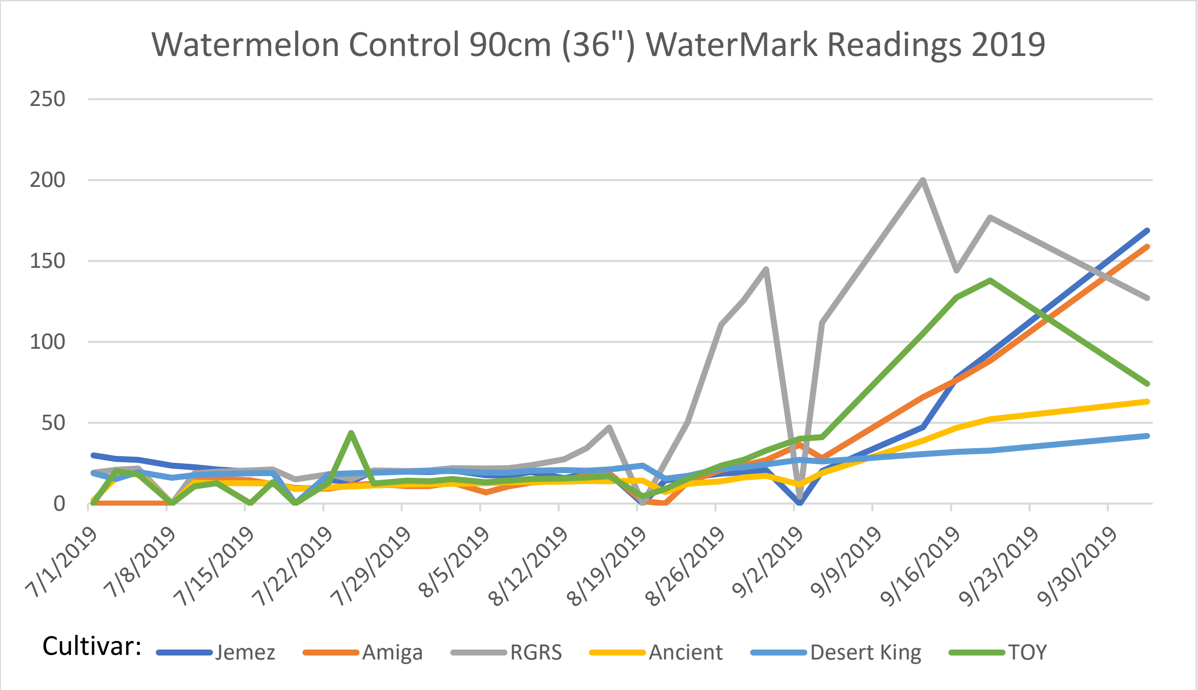


Figure 48- Season-long soil moisture in centibars at 90cm depth in block two of the watermelon control plot in 2019.

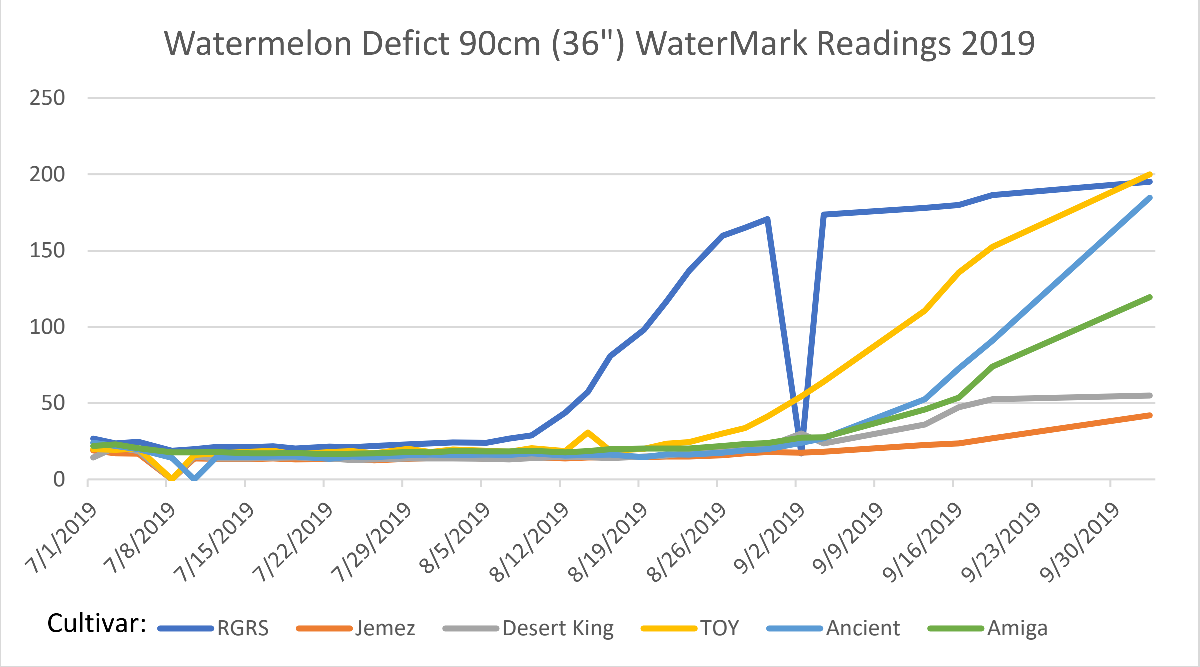


Figure 49- Season-long soil moisture in centibars at 90cm depth in block two of the watermelon deficit plot in 2019.

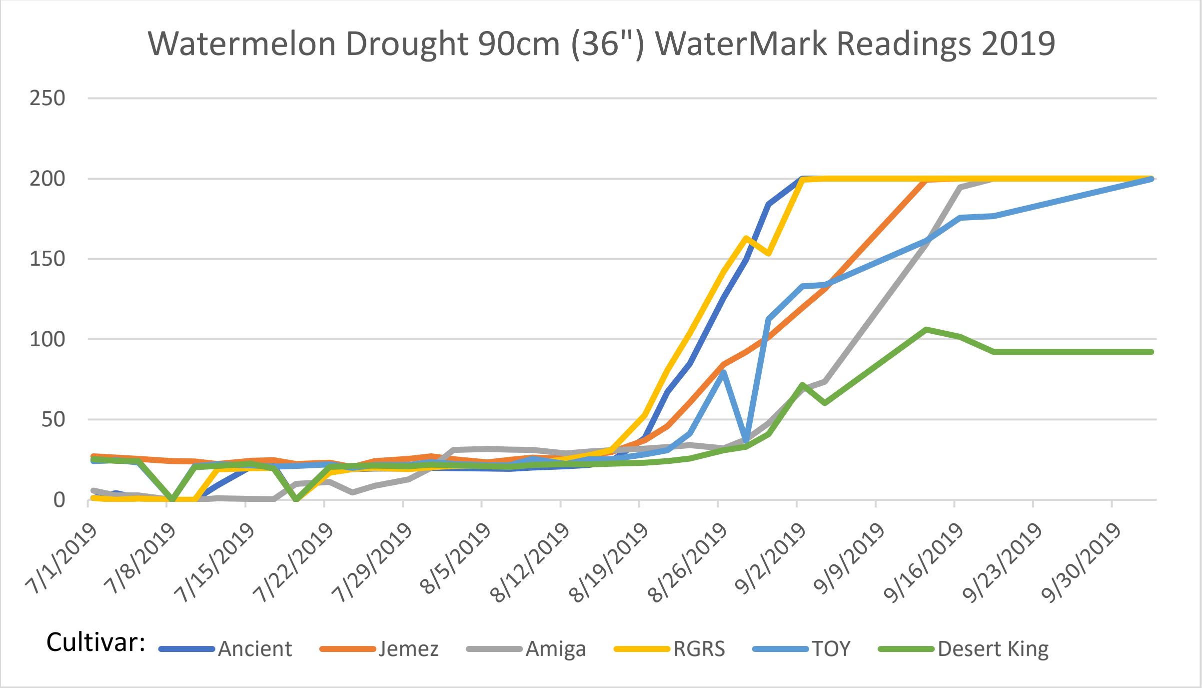


Figure 50- Season-long soil moisture in centibars at 90cm depth in block two of the watermelon drought plot in 2019.

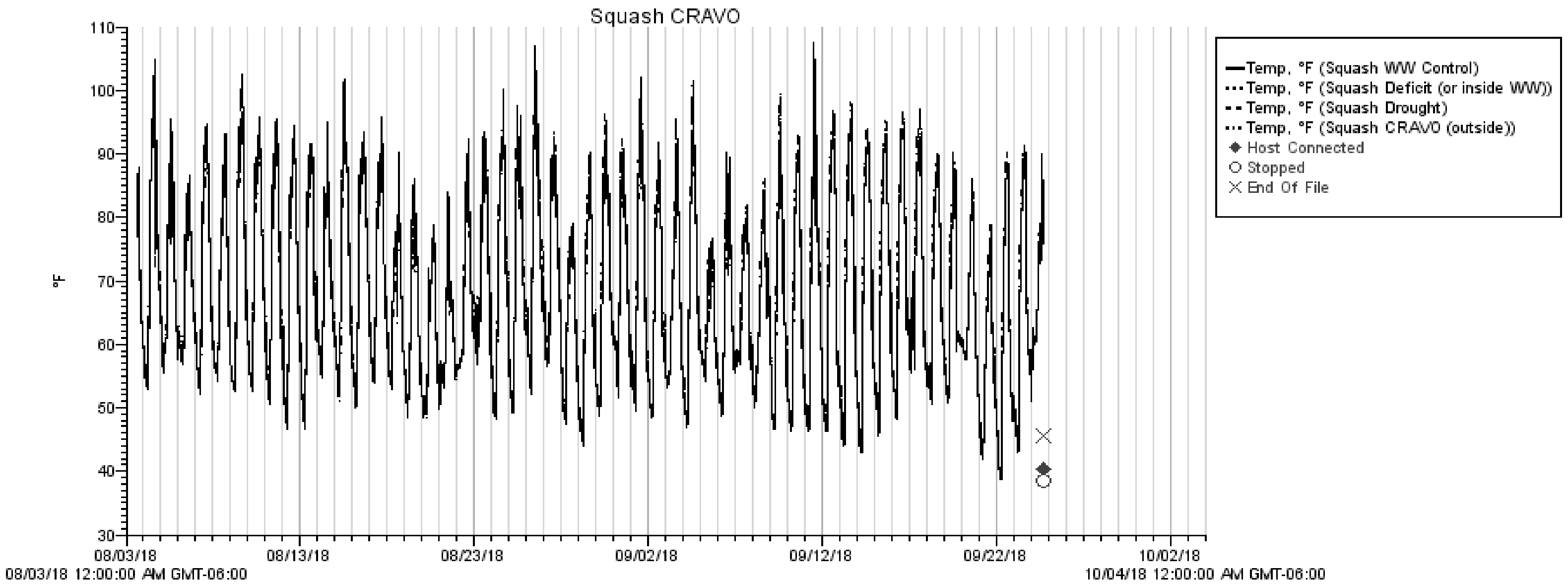


Figure 51- HOBO canopy temperature readings inside and outside of squash Cravo in 2018.

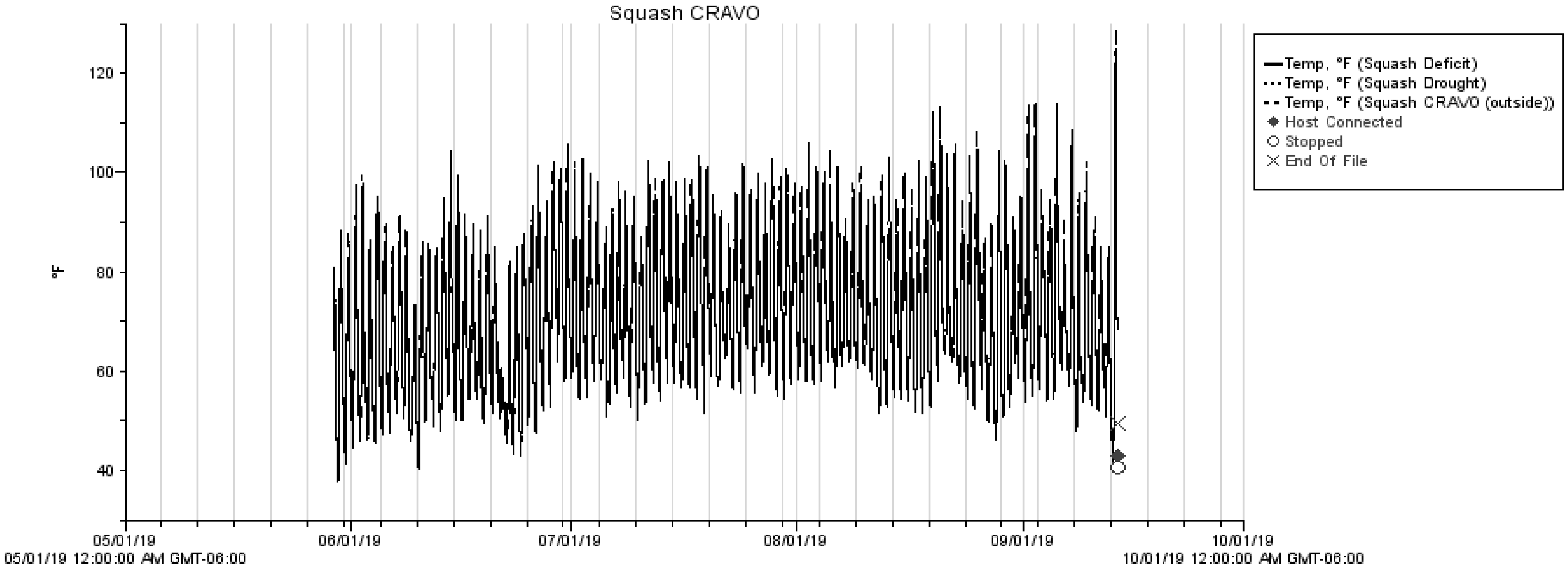


Figure 52- HOBO canopy temperature readings inside and outside of squash Cravo in 2019.
*control treatment inside Cravo malfunctioned, data removed.

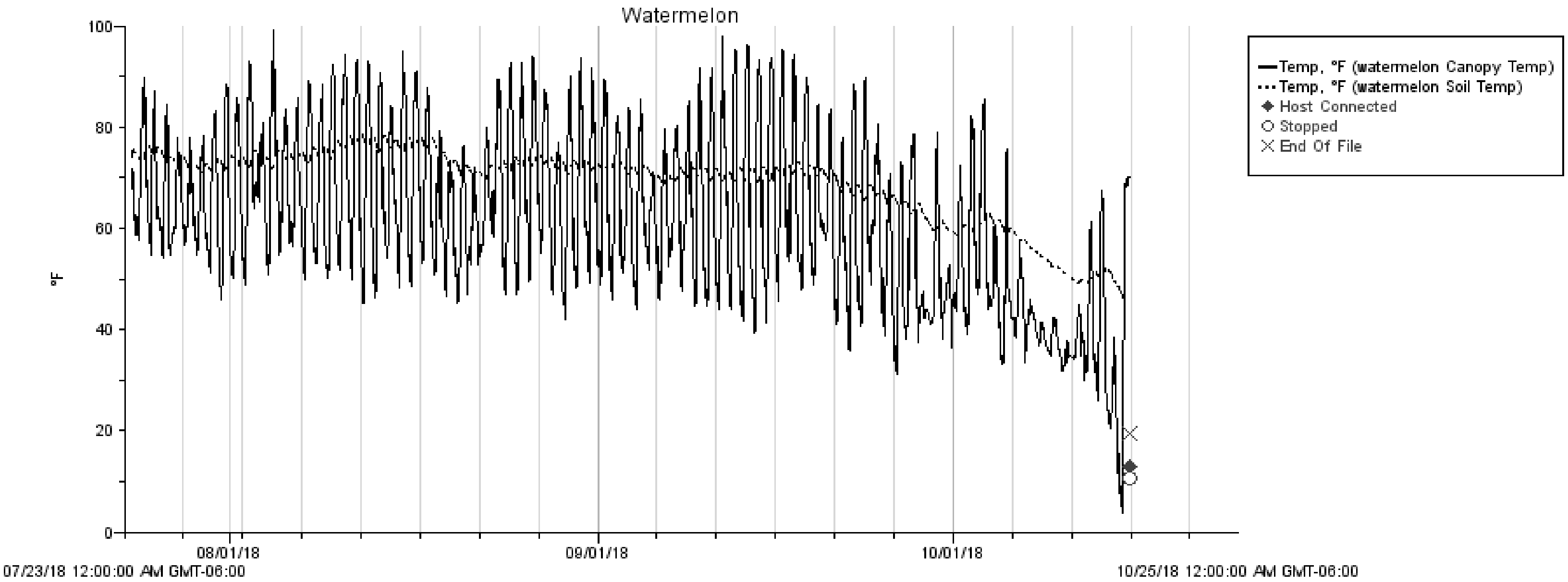


Figure 53- HOBO air and soil temperature readings in watermelon field in 2018.

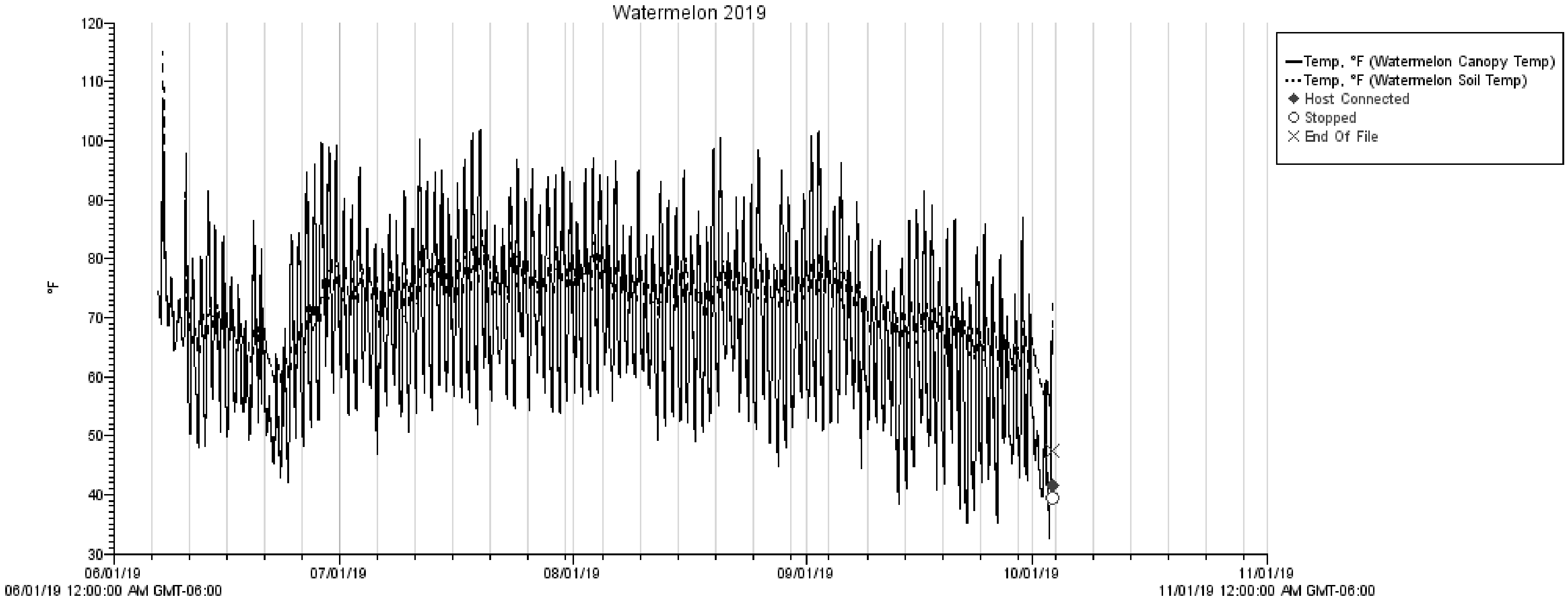


Figure 54- HOBO air and soil temperature readings in watermelon field in 2019.