Yield, Quality, and Performance of Organic Sweetpotato Slips Grown in High Tunnel Compared with Open Field

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Summary. Sweetpotatoes (*Ipomoea batatas*) are nutritious, easily stored, and well adapted to a variety of organic farming operations. This widely consumed root crop is propagated through the use of cuttings, known as slips. Slips are commercially grown primarily in the southeastern United States, and growers in the central United States still have limited access to sweetpotato planting material. Production of organic slips in high tunnels (HTs) could be a profitable enterprise for growers in the central United States given the season extension afforded by controlled-environment agriculture, which could allow growers to diversify their operations and facilitate crop rotation. In trials conducted in 2016 and 2017 at two research stations in northeast and south central Kansas, a systems comparison was used to evaluate the yield and performance of organic sweetpotato slips grown in HT as compared with the open field (OF), with four to six replications at each location. Propagation beds planted with 'Beauregard' seed roots in 2016 and 'Orleans' in 2017 were established in HT and OF under similar cultural methods and planting schedules. Slips were harvested from both treatment groups and transplanted to field plots to investigate the impact of production system on transplant establishment and storage root production. Slip yield from HT was greater than OF at both locations in 2016 ($P \leq 0.001$), but this trend was inconsistent in 2017. Slips grown in HT were on average 12% less compact (slip dry weight per centimeter length) with fewer nodes than their OF counterparts in 2016. Nonetheless, mean comparisons for vine length, stem diameter, and total marketable storage root yield were not significant between HT and OF treatments (1.7 and 2.1 lb/plant, respectively). Similarly, the number of marketable storage roots for HT and OF groups was comparable (3.4 and 3.8 storage roots/plant, respectively). Although more research is needed to evaluate the feasibility of slips grown in HT and to determine recommendations for seed root planting densities, results from this study suggest that HT organic sweetpotato slip production could be a viable alternative to OF production as it relates to slip performance. According to this study, HT production could be a useful mechanism for growing sweetpotato slips, which could provide regional growers more control over planting material. Furthermore, HT slip production could promote the adoption of an underused vegetable crop that can be grown throughout many parts of the United States.

In 2016, sweetpotato was the fifth most valuable organic vegetable crop in the United States, generating $101 million in annual sales [U.S. Department of Agriculture (USDA), 2017]. U.S. sweetpotato production is largely concentrated among four states: North Carolina, Louisiana, Mississippi, and California, with more than 50% of domestic production taking place in North Carolina alone (Bond, 2017; USDA, 2018). A tropical crop that does not tolerate frost (Thottappilly, 2009), sweetpotato is propagated vegetatively using 25- to 35-cm stem cuttings known as slips (Boudreaux et al., 2005). Wholesale production of sweetpotato slips is typically done in OF propagation beds, although sweetpotato growers in the colder temperate zones of the United States and Canada are known to use greenhouses and HTs for the production of slips and storage roots (Coleman, 1995; Sand Hill Preservation Center, personal communication; Zvalo, 2017). Likewise, greenhouse production of sweetpotato is widely used by certified seed programs for isolated multiplication of virus-tested foundation plants (Jiang et al., 2017). Even in propagation beds established outdoors, it is common cultural practice to cover bedded seed roots with plastic mulch to warm the soil and promote early sprouting for slip production (Barkley et al., 2017). The plastic is usually removed once slip shoots reach the soil surface and become visible. In place of plastic ground mulch, commercial growers in California use low tunnels that consist of metal wire covered with clear plastic (Smith et al., 2009). Despite the extensive use of plasticulture for sweetpotato slip production, research regarding the effect of propagation beds grown under an elevated polyethylene film such as in low tunnel or HT is lacking.

HTs are impermanent, passively heated, controlled-environment growing structures that typically use evenly spaced arch-shaped pipe frames built from bent steel or plastic, and covered with tightly fastened greenhouse-type polyethylene films (Carey et al., 2009). Similar to greenhouses used in temperate zones, HTs are largely used for their ability to create microclimates, especially those with warmer air and soil temperatures (Wells and Loy, 1993). HT systems allow for season extension and the enclosed growing environment lends itself to organic production, reduced foliar disease, increased crop marketability, and higher yields (Black, 2010; O'Connell et al., 2012).

Considering that many growers propagating slips are routinely importing costly tissue-cultured and virus-tested derived seed stock (La

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
0.0929	ft^2	m^2	10.7639
0.7457	horsepower	$kJ \cdot s^{-1}$	1.3410
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.1	inch(es)/inch	$mm \cdot cm^{-1}$	10
2.54	$inch^2$/inch	$cm^2 \cdot cm^{-1}$	0.3937
0.4536	lb	kg	2.2046
0.0254	mil(s)	mm	39.3701
28.3495	oz	g	0.0353
930.1025	oz/ft	$mg \cdot cm^{-1}$	0.0011
305.1517	oz/ft^2	$g \cdot m^{-2}$	0.0033
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Bonte et al., 2000), production systems that promote high yield and consistency would be ideal for sweetpotato slip production. Nevertheless, the authors are not aware of any reports in the scientific literature that examine the utilization of HT systems for slip production. La Bonte et al. (2000) demonstrated greater and earlier slip production under a low tunnel with black (opaque) polyethylene film applied after the removal of ground mulch; however, subsequent storage root yield from slips grown under plastic was inconsistent in comparison with OF control group and the treatment was not recommended.

La Bonte et al. (2000) removed plastic several days before harvest to de-etiolate plants before transplant, but still found that slips grown under plastic tunnels weighed less on average than the control. Aside from this study, there is little information available to predict how HT slip production influences the plant quality. Plastic films used by HT typically inhibit ultraviolet light transmission and the plants produced under them can be significantly taller and have thinner leaves in comparison with OF production (Tsormpatsidis et al., 2008). Feedback from a sweetpotato nursery in the midwestern United States (Sand Hill Preservation Center, Calamus, IA) that has used an HT for early season production indicated that slips grown in protected culture such as a HT or greenhouse, are sometimes elongated, "leggy," and/or "soft" (overly succulent) when compared with plants produced in the OF. This is consistent with findings from other studies showing the effect of comparative HT production on crops, like cut flowers, where longer stems are preferred (Ortiz et al., 2012). For production of other vegetables, such as those in the mustard (Brassicaceae) and nightshade (Solanaceae) families, growers typically favor a more compact transplant (biomass/length) with a thicker stem to ensure establishment in the field (Latimer, 1998; Vu et al., 2014). Likewise, slip morphology is an important consideration for sweetpotato propagators, and Barkley et al. (2017) identified parameters that can contribute to the quality of slips for commercial production, such as vine length and the presence of nodes, which will subsequently form roots.

The overall objective of this study was to determine the utility of HT production for growing organic sweetpotato slips, using two complementary experiments to address the research questions. The specific research objectives were as follows: 1) to compare the effect of HT and OF production systems on slip yield and quality, and 2) evaluate the influence of HT and OF production systems on subsequent transplant establishment and storage root production.

Materials and methods

Complementary experiments were conducted in 2016 and 2017 at two research stations operated by Kansas State University: the Olathe Horticulture Research and Extension Center (OHREC) in Olathe, KS [Johnson County (lat. 38.884347°N, long. 94.993426°W, USDA Plant Hardiness Zone 6A)] and the John C. Pair Horticultural Center (JCPHC) in Haysville, KS [Sedgwick County (lat. 37.518928°N, long. 97.313328°W, USDA Plant Hardiness Zone 6B)]. The soil type is a Chase silt loam (pH = 6.3) at OHREC, and a Canadian-Waldeck fine sandy loam (pH = 6.7) at JCPHC.

A propagation bed study compared the yield and quality of slips grown in HT and OF (systems), and a slip performance study, using slips grown in both systems (and at both locations), determined the impact of HT slip production on their performance. Due to flooding and subsequent crop loss at JCPHC in Summer 2016, storage root harvest data for the slip performance study could be collected only from OHREC in 2016. Trial areas at both sites were managed using organic practices.

'Beauregard' seed roots were grown at JCPHC in 2015 and bedded at both sites in 2016. The seed roots were mainly composed of U.S. no. 1 grade (diameter 1.75 to 3.4 inches and length 3 to 9 inches) in 2016. Although weights were recorded only at the OHREC, 'Beauregard' seed roots weighed on average 8.1 oz in 2016. Before bedding, the seed roots were presprouted for ≈4 weeks, a process that subjects seed roots to a period of warm (85 °F), humid (85% relative humidity) storage. This can help induce early sprout formation, increase quantity of slips produced, and speed the time from bedding to slip harvest (Hall, 1993).

Due to the Summer 2016 flooding at JCPHC, 'Beauregard' seed roots were not available for the 2017 trials. Instead, Generation 1 (G1) 'Orleans' seed roots were purchased and shipped in from a commercial nursery (Jones Farm, Bailey, NC) to plant propagation beds at both locations. Both of these cultivars are alike in average propagation bed vigor, canopy biomass, leaf size, days to harvest, storage root yield, appearance, and composition (La Bonte et al., 2012). The 'Orleans' seed roots used in 2017 were predominantly canner grade (diameter 1 to 1.75 inches), and weighed on average 3.5 oz at JCPHC and 3 oz at OHREC. 'Orleans' was otherwise similar to 'Beauregard'. Also in the second trial year (2017), the later delivery of purchased seed roots shortened the length of time available for presprouting, which was done for only 2 weeks.

PROPAGATION BED STUDY. In both years and locations, a "systems" experimental design was used, similar to the approach described in O'Connell et al. (2012). This method offers a more representative comparison by applying cultural management practices that are specific to each system (e.g., planting dates, duration of

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mulch application, days to harvest) rather than controlling for all variables. Whole seed roots, free of decay, rot, and/or other deformity were selected for planting into propagation beds. Beds were planted when soil temperature was consistently above 55 °F. Except for the 2016 JCPHC trial, propagation bed plots were 2 m long × 1 m wide and seed roots were weighed and planted at 65 seed roots/m^2. In the 2016 JCPHC trial, seed roots were planted mechanically, and in all other trials, they were laid by hand. In all cases, seed roots were distributed evenly within the plot dimensions without overlapping or stacking seed roots, given that stacking can diminish the sprouting potential of seed roots and increase likelihood of decay in propagation beds (Barkley, 2015). Each OF and HT plot was replicated at least four times. Plastic mulch, applied at bedding, was then removed from all replications when shoot emergence was observed. Slips were harvested when slip canopy reached ≈12 inches in length. In both OHREC trials and in the 2017 JCPHC trial, plots were harvested by laying a 1-m^2 polyvinyl chloride (PVC) quadrat over the center of the replicated plots and manually cutting vine stems ≈1 inch above soil line. In the 2016 JCPHC trial, a 1-m^2 PVC quadrat was placed randomly in four locations distributed over one contiguous row in the HT, as well as the OF. In all trial years and locations, plots were marked so that a second harvest could be conducted at the exact same location. All treatment plots within the same row or replication were harvested on the same day. Whenever possible, plots were harvested twice each year at each location in accordance with the regional planting window for sweetpotato slips. Data were collected in the same manner at both sites and are outlined as follows.

John C. Pair Horticultural Center. At JCPHC in both years, HT plots were planted in 20 × 100-ft HT (Stuppy Greenhouse Manufacturing, North Kansas City, MO) with no end walls and open sidewalls. HT and OF bedding areas were prepared with a disc followed by a spring-tooth harrow before planting. In 2016 and 2017, bedding soil was irrigated 2 d before laying seed roots. In 2016, seed roots were laid using a tractor-pulled hopper and conveyor belt and were placed at soil grade. Planting density in 2016 in both HT and OF plots was solely determined by the number of seed roots required to fill bedding rows as densely as possible without stacking or layering, which is typical of commercial production at the site. The mechanical seed root layer at JCPHC made a narrower bed (about 74 cm wide) compared with the plots that were laid by hand at OHREC in 2016 (1 m wide). Once the seed roots were placed on the ground, a custom-made, power takeoff–driven implement was used to pull soil from the edges to cover roots and build a uniform rectangular raised bed (≈25 cm tall and 150 cm wide). Next, 2-mil clear polyethylene mulch (Mid South Extrusion, Monroe, LA) was placed over the beds with a tractor-drawn implement. Following the removal of plastic mulch, overhead irrigation was applied as needed.

To follow the same methods used at OHREC, seed roots were planted manually in 2017. The number of replications and arrangement of the blocks was the same as in 2016, except that there were two rows of propagation bed plantings centrally located within the HT, with 1 m of space between each row. The experimental replications were centered over the length and width of the tunnel to reduce interference from the edges and ends of the HT. Each row contained two replications with 1 m of space in between. Each plot was 2 m long × 1 m wide. OF plots were seeded in an adjacent 100-ft section of row that was planted within an ≈1/4-acre OF planting that is used for commercial production. Plots that were 2 m long × 1 m wide were distributed over the length of the row for data collection.

In the 2016 trial, JCPHC HT and OF plots were planted on 15 Apr. First harvest of all HT and OF plots was conducted on 31 May [46 d after planting (DAP)]. The second harvest for 2016 HT and OF plots was performed on 28 June (74 DAP). Plastic mulch was removed ≈14 DAP in both years. In 2017 HT and OF were planted on 17 Apr. and first harvests were conducted 13 June (57 DAP). The second harvest for 2017 was on 10 July (84 DAP).

Olathe Horticulture Research and Extension Center. HT and OF treatments were replicated six times at the OHREC. In both 2016 and 2017, plots were planted in six identical 20 × 32-ft Quonset-style, four-season HT (Stuppy Greenhouse Manufacturing), and equivalent and adjacent OF plots. The OF and HT plots were nested within a long-term, systems comparison of HT and OF production (Knewtson et al., 2012; Zhao et al., 2007). OF plots had maintained the same orientation, spacing between replicates, and cropping history as the HT for more than 10 years.

Soil in HT and OF bedding areas was prepared with a tiller driven by a two-wheel tractor (model 732; BCS America, Portland, OR). Individual plot dimensions in both years were 2 m long × 1 m wide and planted at a 65-seed root/m^2 planting density. Unplanted buffer (0.5 m) was left between the plots as well as the edges and end walls of the OF and HT plots to reduce interplot interference and edge effects of the HT system.

In 2016, seed roots were laid below soil grade in HT and OF plots by manually digging a large trench with shovels, ≈5 cm deep, throughout the plot area. Conversely, in 2017, seed roots were laid at grade level and were covered with 5 cm of soil dug from outside of the plot dimensions. In both years, temperature data loggers (EL-USB-1; Lascar Electronics, Erie, PA) housed inside protective metal cases were placed in each plot alongside seed roots and recorded soil temperature every 30 min throughout the production period. The propagation beds were irrigated and a generic 6-mil transparent polyethylene plastic sheeting (HDX; The Home Depot, Atlanta, GA) was installed over the plots to stimulate shoot growth. Although the plastic sheeting was not vented before its removal in 2016, four 25-cm vents were cut in each main treatment plot in 2017 at 10 DAP based on recommendations in Coolong et al. (2012).

In 2016, OHREC HT and OF plots were planted on 11 May and 20 May, respectively. HT plastic sheeting was removed 16 DAP. The average HT soil temperature recorded by the logger during this period was 76.8 °F. Concurrent weather data collected by a weather station on site (Kansas State University, 2018) shows that the average soil temperature (at 5 cm depth on unplanted ground) during that same period was 62.1 °F. Although the 2016 OF plots showed little to no shoot emergence, plastic mulch was removed from propagation beds 25 DAP. The average recorded soil temperature was 86.6 °F during the mulch-covered period. Weather station on site averaged 72 °F during that time. Because of the large volume of slip measurements that were required, the first harvest of HT plots in 2016 took place on 17 June and 20 June (37 and 40 DAP, respectively) with three replications harvested each day. Due to slow shoot emergence, the 2016 OF plots were harvested only once, which occurred on 11, 12, and 13 July (52, 53, and 54 DAP) and rotting seed roots were observed below the soil line. The average recorded soil temperature from plastic mulch removal to first harvest in OF was 83.9 °F. Weather station on site averaged 80.4 °F for soil temperature during that period. The second harvest in the 2016 HT plots was conducted on 6 and 7 July (56 and 57 DAP). The average recorded soil temperature from plastic removal to second harvest in HT plots was 76.5 °F. The weather station averaged 77.7 °F for soil temperature during that period.

In 2017, HT and OF plots were planted on 28 Apr. and 8 May, respectively, and plastic mulch for both HT and OF was removed on 25 and 15 DAP. The average soil temperature in HT plots from bedding to plastic removal was 78.8 °F. The weather station probe averaged 62 °F for soil temperature during that period. The average soil temperature recorded by the loggers in OF plots from bedding to plastic removal was 79.6 °F. The weather station averaged 67.9 °F for the corresponding period. First harvest in 2017 of HT subplots was conducted on 16 June and OF plots on 19 June (49 and 42 DAP). The second HT harvest in 2017 was conducted on 12 and 13 July (75 and 76 DAP). The average recorded soil temperature from plastic removal to second harvest in HT was 76.6 °F. Weather station on site average 76.2 °F for soil temperature during that period. The OF plots were harvested a second in 2017 time on 17 July (70 DAP). The average recorded plot soil temperature from plastic removal to second harvest in OF was 76.6 °F. Weather station on site read 76.6 °F for average soil temperature during that period.

PROPAGATION BED STUDY DATA COLLECTION. Harvesting was performed manually by cutting slips 1 inch above the soil surface. In addition to slip yield, slip quality parameters were measured on 15 individual, randomly selected slip subsamples per plot in 2016 and on 10 subsamples per plot in 2017 to reduce labor. Otherwise, all data collection was identical at both locations and in both years.

Slips were harvested in the morning and data collection was conducted on the same day. Harvests from HT and OF were sorted and measured to determine the number of marketable slips produced per square meter, total marketable fresh and dry weights, as well as total cull fresh and dry weight. Marketability was based on on-farm standards used at JCHPC for commercial production of organic sweetpotato slips. Slips were considered marketable if they were free from visible disease or deformity and larger than 13 cm. Slips ≤5 inches long (≈13.0 cm) were not considered viable because plants are unable to survive when planted completely below soil (Barkley et al., 2017). Marketable and cull fresh weight were determined before drying. Dry weight was determined after drying for 70 °C for at least 72 h in a forced-air drying oven (SC-350 Electric Shelf Oven; The Grieve Corp., Round Lake, IL).

Slip quality measurements (length, fresh and dry weight, stem diameter, number of plant nodes, and leaf area) were performed on a randomly selected subsample of individual slips. Slip length was determined by measuring from the cut end to the apical meristem. The nodes of each subsample were counted from the cut end to the apex, but did not include the growing point. Slip stem diameter was measured, using a caliper tool, within 1 cm of cut end and nodes were avoided. Leaf area was measured using a leaf area meter (LI-3100C; LI-COR, Lincoln, NE) by placing whole leaf blades, separated from the petiole at their base by hand, with the adaxial surface laid downward.

SLIP PERFORMANCE STUDY. To further evaluate the effect of the HT and OF system on sweetpotato propagation beds, slips produced in both systems from both locations were planted at each trial site to determine treatment effect on transplant performance. The four treatments implemented in this experiment included slips that were grown in JCPHC HT, JCPHC OF, OHREC HT, OHREC OF, a two-way factorial at each trial location of slip origin (JCPHC and OHREC) and treatment (HT and OF). In both years and locations, trials were planted in a randomized complete block. Each plot was 25 ft long and had 25 slips, which were transplanted by hand at 12-inch in-row spacing and a planting depth of approximately three nodes (Thompson, 2014). Transplant establishment data were collected by taking plant growth measurements from three random subsamples within each treatment and replication every week from 3 to 7 weeks after planting (WAP). Flooding experienced at JCPHC in 2016 resulted in complete crop loss, therefore, storage root harvest data could be collected only at OHREC during the 2016 season. In 2017, storage root harvests were recorded from both the OHREC and JCPHC.

JOHN C. PAIR HORTICULTURAL CENTER. The JCPHC site was planted in a Randomized Complete Block Design (RCBD) with three replications using three adjacent 200-ft rows (≈60-inch row centers) for transplant establishment. In 2017, RCBD was conducted over two adjacent, 255-ft rows. Two replications were planted per row, with a 25-ft sweetpotato buffer separating the 100-ft-long replications and a 15-ft buffer at the end of each row. The field was prepared by dicing twice, and the soil was leveled by a single pass with a spring-tooth harrow. A bed shaper implement (described previously) was used to build an ≈25-cm-tall raised bed for transplanting.

Slips were watered by hand immediately following transplanting. Overhead irrigation was applied using a traveling irrigation system (B-140; Kifco, Havana, IL) as needed to prevent wilting. Cultivation was performed as needed to control weeds either manually or with a tractor-mounted cultivator. In 2016, HT and OF slips (a random effect termed slip origin) were harvested on 28 June from OHREC and on 29 June from JCPHC. The slips were then planted on 29 June at JCPHC. Initial transplant growth measurements were recorded as described later in this article. In 2017, HT and OF slips were harvested on 10 July from OHREC and JCPHC, and planted the same day. In 2017, the only year root harvest data could be collected, storage roots were machine harvested on 12 Oct. (94 DAP) with a chain digger (D-10T; US Small Farm Equipment Co., Worland, WY).

Olathe Horticulture Research and Extension Center. In both years at OHREC, replications consisted of four, 100-ft rows (≈50-inch row centers). The field was rototilled with a 55-horsepower tractor, and a disc hiller implement (FarmMaxx URH-100; Unifarm Machinery Corp., Wilson, NC) was used to build 7-inch-tall raised beds for transplanting. The four treatments were randomly assigned to each block/row with at least 25 ft of planted buffer areas on the ends of each row. A single row of drip tape was run over the length of each row. Beds were irrigated immediately following transplanting and as needed (first 2 inches of soil surface was dry to touch), which was ≈1.25 times per week. Cultivation for weed control was performed as needed with hand tools for the first few WAP. In 2016, HT and OF slips from JCPHC were harvested on 28 June. OHREC slips were harvested 30 June and planted the same day. In 2016, the storage roots from OHREC slip performance study were harvested on 4 Oct. (96 DAP). In 2017, HT and OF slips were harvested from JCPHC on 10 July and harvested then planted from OHREC on 12 July. The trial storage roots were harvested on 20 Oct. (100 DAP).

Slip performance study data collection. Each propagation bed plot was evaluated weekly for plant growth from 3 to 7 WAP. Three subsample plants were selected at random from each plot and measured to determine main stem diameter at the soil interface. The length of the main stem was measured to the apical meristem. At harvest, 10 ft of row (10 plants) in the middle of the 25-plant plot was harvested manually with a spade fork, and plant survival was recorded. Harvested storage roots from both sites were cleaned to remove excess soil and sorted as either marketable or cull. Storage roots were culled if they were damaged, diseased, irregular shape, malformed, and/or not meeting size requirements of marketable grades. Marketable storage roots were graded according to La Bonte et al. (2012), counted, and weighed. Marketable grades consisted of U.S. no. 1 (diameter 1.75 to 3.4 inches and length 3 to 9 inches), medium or canner (diameter 1 to 1.75 inches), and jumbo storage roots (diameter >3.5 inches).

Statistical analysis. The plot yield data in the propagation bed study was normalized to standard 1-m^2 plot dimension used in most trial years and locations. All individual slip quality measurements were normalized by slip length. Slip quality parameters were averaged from subsamples and the mean of the subsamples served as the experimental unit for analysis. Homogeneity of variance and normality of data from both studies were verified using Levene and Shapiro-Wilk tests, respectively. Multiple regression with standard least squares fitting was used to identify any significant interactions between fixed effect (production system), random effects (year, trial site, slip origin), and repeated measure (harvest). Based on the presence of significant interactions involving the fixed effect, or in some cases an unbalanced factorial design, the analysis and presentation of data were separated. Analysis of variance (ANOVA) was performed to separate means and determine significance of production system effect on all parameters. Statistical analyses were carried out using JMP software (version 13.2.0; SAS Institute, Cary, NC).

Results

Slip yield. When considering each harvest event, we had an unbalanced factorial design due to having only one harvest in the OF at OHREC in the 2016 trial. Therefore, individual harvests were analyzed and reported separately. Similarly, the multiple regression with standard least square fitting for 2017 showed a significant three-way interaction for location × harvest × production system for marketable fresh weight and dry weight, and total fresh weight and dry weight parameters. Cumulative yield data from both years showed significant interactions for year × production system (Table 1). Therefore, the results of each year, trial site, and harvest are shown independently in Table 2.

Comparing data from all years, locations, and harvests, the HT plots averaged 226.7 slips/m^2 compared with 147.8 slips/m^2 in the OF. Of the eight harvests that are shown on Table 2, the mean in the HT was higher in six of them, but only two showed significantly higher marketable slip yield. Interestingly, the results of the 2 years indicate that there was a stronger benefit of using the HT system in 2016 compared with 2017. This is verified by the presence of a significant year × system interaction (Table 1). There were no significant increases in slip yield seen in 2017 as the result of implementing the HT system (Table 2). Mean HT and OF marketable slip yield in 2017 across all sites and harvests were nearly the same (HT = 120.3 slips/m^2 vs. OF = 123.3 slips/m^2). In 2016, the utilization of the HT system increased slip number by 49% to 199% and averaged 82% more slips than in the OF. Conversely, in 2017, slip yield difference ranged from –63% to 25% and averaged –8% in the HT as compared with the OF.

Sweetpotato slip biomass production in the HT followed a similar trend to slip number. In 2016, all 12 comparisons of marketable and total, fresh, and dry weights were higher in the HT plots compared with the OF. All but two were statistically significant [$P < 0.05$ (Table 2)]. In 2017, none of the HT vs. OF comparisons showed a significant benefit of using the HT system as they relate to overall biomass production and plant growth. In contrast to slip number and biomass production, slip marketability (percent by weight) was consistently higher in the HT as compared with the OF, but it was only statistically significant in the first harvest at JCPHC.

Slip quality. Multiple regression with standard least square fitting test for interactions of year × system effect on slip quality was significant for all parameters except fresh weight. The three-way interaction of fixed effect (HT and OF systems) and random effects (year and location) was significant for stem diameter and slip length (Table 3). Based on the regression model results, data were separated by trial year and location and a second regression was run on each year and location combination separately, testing for significant interaction of harvest × system on all

Table 1. Probability for slip yield as influenced by trial year, location, and production system (high tunnel and open field) from organic sweetpotato propagation beds grown in Haysville, KS, and Olathe, KS, in 2016 and 2017.

	Slip yield parameters[y]					
Interactions[z]	Marketable slips	Marketable fresh wt	Marketable dry wt	Total fresh wt	Total dry wt	Marketable % by wt
Year (Y)	<0.001	<0.001	<0.001	<0.001	<0.001	NS[x]
Location (L)	NS	NS	NS	NS	<0.05	<0.05
System (S)	<0.001	<0.01	<0.05	<0.01	<0.05	NS
Y × L	<0.001	<0.001	<0.001	<0.001	<0.001	NS
Y × S	<0.001	<0.001	<0.001	<0.001	<0.001	<0.05
L × S	NS	NS	NS	NS	NS	NS
Y × L × S	NS	NS	NS	NS	NS	NS

[z]Multiple regression analysis with least squares fitting used to test which factors and interactions between factors had significant effect on slip yield parameters ($\alpha = 0.05$).
[y]Slips were harvested once canopy reached ≈12 inches (30.5 cm). Yield includes two harvests per plot for all trials except the Olathe open-field system in 2016, which was only harvested once.
[x]Not statistically significant.

slip quality parameters. These tests showed significant interactions for fresh weight, dry weight, and leaf area for the JCPHC trial location in 2016 (data not shown). The same two-way interaction regression was significant for nodes and stem diameter at the OHREC in 2017 (data not shown). Based on the presence of significant interactions, the quality data were further separated to compare HT with OF treatment groups by year, site, and harvest (Table 4).

Fresh and dry weights, which have been normalized by slip length (milligrams per centimeter), are indicators of plant compactness (Vu et al., 2014). Ten of the 16 comparisons showed higher compactness values from slips grown in the OF and five of these were statistically significant [$P < 0.05$ (Table 4)]. Compactness of slips grown in the OF was on average 25% greater than slips grown in HT.

In 2016, the leaf area of slips grown in the OF was significantly greater at first harvest in both locations, but was not significant during the second harvest at JCPHC. In 2017, there were no statistically significant effects of the HT system on leaf area, but higher values were found on slips grown in the HT. A similar trend was observed in the number of plant nodes as well. In 2016, there were significantly more nodes on slips grown in the OF than in the HT [$P < 0.05$ (Table 5)]. This contrasts with 2017, when the number of nodes was generally higher for slips grown in the HT and was statistically significant in the second harvest at JCPHC and the first harvest at OHREC. When averaged across all data, the stem diameter of slips grown in the two systems was similar (HT = 0.17 mm vs. OF = 0.16 mm). Interestingly, the slips grown in the OF at JCPHC had significantly greater stem diameters than the ones grown in the HT in 2016. This contrasts with 2017, when the stem diameter of slips grown in the HT was generally higher across both locations and was statistically significant in the first harvest at both locations [$P < 0.05$ (Table 4)]. Due to the need for coordinated data collection and the differential growth rate in the HT compared with OF, the slip length for each system is somewhat arbitrary. However, the slip length in HT was statistically greater at JCPHC in 2016 during both harvests and was higher at OHREC during the first harvest. Similar to slip number, the average length of the slips at combined trial locations was greater in the OF for 2017.

SLIP PERFORMANCE. The average plant survival for slips that were grown in the HT and OF was 94% and 96%, respectively, and the effect of production system was not significant. Plant growth data were collected from 3 to 7 WAP. Multiple regression with standard least square fitting tested for significant interaction of year × trial location × origin × slip production system (HT and OF) × WAP on the transplant establishment parameters (stem diameter and stem length). The model resulted in a significant effect of year × location × WAP ($P < 0.001$); however, there were no significant interactions involving the fixed effect (production system) and so ANOVA was performed on data from each WAP interval to compare HT and OF for combined years, locations, and slip origin. Although fixed treatment effect (HT vs. OF) was not statistically significant for stem diameter or vine length across all WAP intervals, the values are reported to demonstrate average plant growth in the trials (Table 5).

Due to flooding at JCPHC in 2016, the yield data set was unbalanced for analysis of the yield data that was generated in the slip performance study. Therefore, each year and location (2016 OHREC, 2017 JCPHC, and 2017 OHREC) was analyzed as a single factor (trial) similarly but independently. The multiple regression testing for significant interactions of trial × origin × treatment for all storage root yield (pound per plant and number per plant) and marketability parameters showed no significant interaction between fixed and random effects. Therefore, ANOVA means comparison was performed on HT and OF treatment groups combined for year, location, and origin (Tables 6 and 7). Based on the combined data from the three trials, the slips grown in OF had greater mean values for all storage root yield parameters but were not statistically significant. The slips grown in the OF plots averaged nearly 20% higher marketable storage roots by weight than the plots planted with slips grown in HT. However, ANOVA testing to compare HT and OF means was not significant for any of the specific yield or grade parameters (Tables 6 and 7).

Discussion

The overall objective of these trials was to evaluate the utility of slip propagation in HT and compare

Table 2. Effect of high tunnel (HT) and open-field (OF) production systems on slip yield from organic sweetpotato propagation beds grown in Haysville, KS (JCPHC), and Olathe, KS (OHREC), in 2016 and 2017.

	Marketable plot yield[y]			Total plot yield		Marketable
Treatment[z]	Slips (plants/m²)	Fresh wt ($g \cdot m^{-2}$)	Dry wt ($g \cdot m^{-2}$)	Fresh wt ($g \cdot m^{-2}$)	Dry wt ($g \cdot m^{-2}$)	Total (% by wt)
			2016 JCPHC first harvest			
HT	395.7	3511	353	5053	479	69.3
OF	138.5	1331	140	3390	366	39.8
P value[x]	<0.001	<0.001	<0.01	<0.001	NS[w]	<0.01
			2016 JCPHC second harvest			
HT	437.1	6606	603	8055	802	80.8
OF	293.6	3058	343	4150	470	71.5
P value	NS	NS	<0.05	<0.05	<0.05	NS
			2016 OHREC first harvest			
HT	414.5	5048	0.434	5912	494	74.0
OF	138.5	1603	0.152	2190	215	73.8
P value	<0.001	<0.001	<0.01	<0.001	<0.01	NS
			2016 OHREC second harvest			
HT	140.8	1348	94	2635	177	83.2
OF	n/a[v]	n/a	n/a	n/a	n/a	n/a
P value	n/a	n/a	n/a	n/a	n/a	n/a
			2017 JCPHC first harvest			
HT	50.0	893	91	1065	110	64.0
OF	40.0	635	84	840	112	71.8
P value	NS	NS	NS	NS	NS	NS
			2017 JCPHC second harvest			
HT	22.8	420	40	0.598	52	75.8
OF	62.0	1660	178	1.798	187	80.5
P value	<0.01	<0.001	<0.001	<0.01	<0.001	NS
			2017 OHREC first harvest			
HT	167.0	2002	130	2462	151	71.5
OF	174.3	2627	208	2885	227	61.8
P value	NS	NS	<0.01	NS	<0.01	NS
			2017 OHREC second harvest			
HT	185.5	2765	214	3272	252	84.3
OF	168.5	2717	238	3108	269	87.3
P value	NS	NS	NS	NS	NS	NS

[z]Data are separated by year, location, and harvest due to imbalanced data set (e.g., missing second harvest at OHREC 2016) and significant interactions observed between fixed effect (HT and OF systems), random effects (year, location) and repeated measure (harvest).
[y]1 plant/m² = 0.0929 plant/ft², 1 $g \cdot m^{-2}$ = 0.0033 oz/ft².
[x]Analysis of variance was used to determine the significance of mean differences between HT and OF treatment groups ($\alpha = 0.05$).
[w]Not statistically significant.
[v]Not applicable (i.e., data could not be collected).

Table 3. Probability for slip quality as influenced by trial year, location, and production system (high tunnel and open-field) from organic sweetpotato propagation beds grown in Haysville, KS (JCPHC), and Olathe, KS (OHREC), in 2016 and 2017.

	Slip quality parameters[y]					
Interactions[z]	Fresh wt	Dry wt	Leaf area	Nodes	Stem diam	Slip length
Year (Y)	NS[x]	<0.001	<0.001	<0.001	<0.001	<0.001
Location (L)	NS	<0.001	<0.001	<0.001	<0.001	<0.01
System (S)	NS	<0.001	NS	<0.001	NS	NS
Y × L	NS	<0.001	<0.001	<0.001	NS	NS
Y × S	NS	<0.001	<0.001	<0.001	<0.001	<0.001
L × S	NS	NS	NS	NS	NS	NS
Y × L × S	NS	NS	NS	NS	<0.001	<0.05

[z]Multiple regression analysis with least squares fitting used to test which factors and interactions between factors had significant effect on slip yield parameters ($\alpha = 0.05$).
[y]Slips were harvested once canopy reached ≈12 inches (30.5 cm). Slip quality parameters and statistical analysis include two harvest per plot for all trials except Olathe open-field production in 2016.
[x]Not statistically significant.

them with slips grown in the OF. Previous studies conducted on other fruit and vegetable crops have demonstrated that HT systems can achieve higher yields and produce marketability that is significantly greater than OF production (Janke et al., 2017; Kadir et al., 2006; O'Connell et al., 2012). In La Bonte et al. (2000), the yield of sweetpotato propagation beds grown under low tunnels covered with black polyethylene film varied depending on cultivar and harvest, but were significantly greater than those grown in the OF in multiple trial year and location combinations. Similarly, the results from our trials varied over the course

Table 4. Effect of high tunnel (HT) and open-field (OF) production systems on slip quality from organic sweetpotato propagation beds grown in Haysville, KS (JCPHC), and Olathe, KS (OHREC), in 2016 and 2017.

	Slip quality					
Treatment[z]	Fresh wt ($mg \cdot cm^{-1}$)[y]	Dry wt ($mg \cdot cm^{-1}$)	Leaf area ($cm^2 \cdot cm^{-1}$)[y]	Nodes (no./cm)[y]	Stem diam ($mm \cdot cm^{-1}$)[y]	Slip length (cm)[y]
			2016 JCPHC first harvest			
HT	417.5	33.6	5.4	0.37	0.20	19.1
OF	612.5	63.6	8.1	0.55	0.29	15.8
P value[x]	<0.01	<0.001	<0.05	<0.001	<0.001	<0.01
			2016 JCPHC second harvest			
HT	557.5	43.8	7.1	0.29	0.14	32.3
OF	545.0	58.1	7.5	0.46	0.22	20.8
P value	NS[w]	<0.05	NS	<0.01	<0.01	<0.01
			2016 OHREC first harvest			
HT	505.0	39.3	5.3	0.34	0.16	30.5
OF	548.3	53.8	7.8	0.43	0.15	26.8
P value	NS	<0.05	<0.01	<0.01	NS	NS
			2016 OHREC second harvest			
HT	475.0	33.7	5.9	0.32	0.16	23.4
OF	n/a[v]	n/a	n/a	n/a	n/a	n/a
P value	n/a	n/a	n/a	n/a	n/a	n/a
			2017 JCPHC first harvest			
HT	712.5	79.0	11.1	0.45	0.24	22.5
OF	550.0	69.6	8.3	0.41	0.14	35.3
P value	<0.05	NS	NS	NS	<0.05	NS
			2017 JCPHC second harvest			
HT	545.0	73.1	10.9	0.39	0.18	29.8
OF	485.0	76.5	10.5	0.34	0.15	38.4
P value	NS	NS	NS	<0.05	NS	NS
			2017 OHREC first harvest			
HT	618.3	38.1	7.2	0.31	0.16	31.3
OF	696.7	43.7	6.4	0.25	0.12	39.6
P value	NS	<0.05	NS	<0.01	<0.01	<0.05
			2017 OHREC second harvest			
HT	403.3	35.2	6.0	0.22	0.13	37.4
OF	420.0	39.8	5.7	0.23	0.13	35.6
P value	NS	NS	NS	NS	NS	NS

[z]Data are separated by year, location, and harvest due to imbalanced data set (e.g., missing second harvest at OHREC 2016) and significant interactions observed between fixed effect (HT and OF systems), random effects (year, location), and repeated measure (harvest).
[y]1 $mg \cdot cm^{-1}$ = 0.0011 oz/ft, 1 $cm^2 \cdot cm^{-1}$ = 0.3937 $inch^2$/inch, 1 node/cm = 2.54 nodes/inch, 1 $mm \cdot cm^{-1}$ = 0.1 inch/inch, 1 cm = 0.3937 inch.
[x]Analysis of variance was used to determine the significance of mean differences between HT and OF treatment groups (α = 0.05).
[w]Not statistically significant.
[v]Not applicable (i.e., data could not be collected).

of 2 years, locations, and repeated harvests. In 2016, we observed significantly greater slip yields from plots grown in the HT. In 2017, yields in the HT and OF were similar, excluding second harvest at the JPCHC site. The mean values for all yield parameters at the JCPHC in 2017 were dramatically lower than the three other site and year combinations (Table 2). During the second harvest at this site in 2017, significant burrowing of the plots was observed from rodents, and it is likely that this issue led to confounding effects. And although every effort was made to trial the same or similar cultivars across both years, the use of 'Beauregard' in 2016 and 'Orleans' in 2017 was a limitation of this study. Nonetheless, careful review of the trial data across both years and locations suggests that the yield potential of HT slip production may be at least similar to that of the OF, and could be greater depending on cultivar, environment, and management practices.

Previous research indicates that HT systems often provide a more consistent growing environment that can lead to more convenient production schedules (Knewtson et al., 2010). In the case of our trials at OHREC in 2016, excessive rain and poor growing conditions led to only one harvest in the OF, whereas the HT was harvested twice. Shoot emergence under the plastic in the OF was inconsistent and the plastic was removed 25 DAP even though emergence had not yet occurred. Following the removal of the plastic sheeting, the slip canopy in the OF plots was observed to be patchy and less vigorous. It is likely that by planting seed roots in shallow trenches in combination with the location's higher clay soil content and heavy rain that was received just after planting, the seed roots did not have sufficient gas exchange. The accumulation of carbon dioxide and largely hypoxic conditions are known to cause tissue decay in propagation beds (North Carolina Sweet Potato Commission, 2018). Because they have a closed roof and were constructed at an elevated grade, the HT

Table 5. Effect of high tunnel (HT) and open-field (OF) production of slips from organic sweetpotato propagation beds grown in Haysville, KS (JCPHC), and Olathe, KS (OHREC), on transplant establishment by weeks after planting (*P* = NS) in 2016 and 2017.

Slip establishment[z]	Treatment[y]	Weeks after planting 3	4	5	6	7
Vine length (cm)	HT	36.9	62.5	91.1	115.6	118.6
	OF	35.4	60.8	85.8	108.4	110.3
	P value[w]	NS[v]	NS	NS	NS	NS
Stem diameter (mm)	HT	5.3	6.0	7.4	8.3	9.3
	OF	5.2	6.1	7.4	8.6	9.3
	P value	NS	NS	NS	NS	NS

[z]1 cm = 0.3937 inch, 1 mm = 0.0394 inch.
[y]Data are combined by year (2016 and 2017) and trial location (JCPHC and OHREC).
[w]Analysis of variance tested for significant mean differences between HT and OF treatment ($\alpha = 0.05$).
[v]Not statistically significant for all comparisons at all intervals.

Table 6. Effect of high tunnel (HT) and open-field (OF) production of slips from organic sweetpotato propagation beds grown in Haysville, KS (JCPHC) and Olathe, KS (OHREC) on storage root yield (all grades by weight and number) after transplanting in JCPHC in 2017 and OHREC in 2016 and 2017.

	Yield (lb/plant)[y]			Yield (no./plant)		
Treatment[z]	No. 1	Canner	Jumbo	No. 1	Canner	Jumbo
HT	0.72	0.35	0.20	0.89	2.38	0.16
OF	0.90	0.37	0.27	1.05	2.52	0.21
P value[x]	NS[w]	NS	NS	NS	NS	NS

[z]Data are combined by year (2016 and 2017), location (JCPHC and OHREC) every yield parameter.
[y]Seed roots were harvested by hand and graded either U.S. No. 1 (diameter of 1.75 to 3.4 inches and length of 3 to 9 inches), canner storage roots (diameter 1 to 1.75 inches), and jumbo storage roots (diameter >3.5 inches); 1 inch = 2.54 cm, 1 lb = 0.4536 kg.
[x]Analysis of variance tested for significant mean differences between HT and OF treatment ($\alpha = 0.05$)
[w]Not statistically significant.

Table 7. Effect of high tunnel (HT) and open-field (OF) production of slips from organic sweetpotato propagation beds grown in Haysville, KS (JCPHC), and Olathe, KS (OHREC) on storage root yield (marketable and total by weight and number) after transplanting in JCPHC in 2017 and OHREC in 2016 and 2017.

	Yield (lb/plant)[y]		Marketable yield	
Treatment[z]	Marketable[x]	Total	(% by wt)	(roots/plant)
HT	1.74	2.64	65.3	3.43
OF	2.07	2.81	71.7	3.78
P value[w]	NS[v]	NS	NS	NS

[z]Data are combined by year (2016 and 2017) and location (JCPHC and OHREC) for every yield parameter.
[y]1 lb = 0.4536 kg.
[x]Marketable roots were free of disease or deformity and conformed to U.S. No. 1 (diameter of 1.75 to 3.4 inches and length of 3 to 9 inches), canner (diameter 1 to 1.75 inches), and/or jumbo grade (diameter >3.5 inches); all other roots were considered unmarketable; 1 inch = 2.54 cm.
[w]Analysis of variance tested for significant mean differences between HT and OF treatment ($\alpha = 0.05$)
[v]Not statistically significant.

plots did not experience this situation and may have allowed for improved slip production and early growth. Spring and early summer rain events can seriously limit OF production in the central United States, and the results of our trials reflect the impact of erratic weather on OF production compared with the HT system.

Although the goal of this study was not to determine the differences between microclimates of the two growing systems, collected soil probe data may provide some valuable insight to producers. The use of polyethylene film mulches alone resulted in higher average soil temperatures for OF plots compared with uncovered soil temperature recorded by nearby weather station in an unplanted field. Like the polyethylene mulch, plastic covers on HT trap heat by preventing convective cooling. Combining the use of mulch and HT over the same period is likely to multiply the soil warming effect. Despite that they were recorded over different periods and lengths of time, the average soil temperature increase from bedding to plastic removal in the earlier planted OHREC 2017 HT was ≈10% higher than OHREC 2017 OF when compared with the concurrent weather station data, respectively. More research is required to determine the necessity and value of polyethylene mulches for HT production of slips; however, this combined management practice may facilitate greater season extension for seed root bedding in colder climates.

In addition to measuring slip yield, the propagation bed trials in HT and OF systems sought to compare the individual slip quality of plants grown in the HT with those in OF system. Slip quality has not been defined in the literature for sweetpotato like it has for other crops (Latimer, 1998; Meyer et al., 2017; Vu et al., 2014), but Barkley et al. (2017) identified slip length and the number of nodes as being important quality factors, especially for mechanical planting. Plant compactness has also been identified for transplanted crops such as tomato (Meyer et al., 2017) and is generally preferred for vegetable crops grown in the OF (Latimer, 1998). HT production has been shown to influence the morphology of plants and certain aesthetic quality parameters in cut flower crops (e.g., stem length and stem diameter) (Ortiz et al., 2012). There is little known about the impact of the HT production system on the physical characteristics of propagules or nursery plants of horticultural food crops grown for field planting. The methods used by La Bonte et al. (2000) were distinct from typical HT production and black polyethylene film was used to construct a low tunnel. Furthermore, there were few data presented regarding the physical or quality-related characteristics of slips from the low tunnel and OF treatments (La Bonte et al., 2000).

In 2016, the slips grown in the OF generally produced higher mean values for the defined quality parameters, and in 2017, the opposite trend occurred. Despite the inconsistent differences in physical characteristics, neither plant growth or storage root harvest data were significantly different for transplanted slips grown under the two systems regardless of trial or location. The mean stem diameter and vine length of transplanted HT and OF slips were very comparable through the first 7 weeks of plant growth. The storage root harvest data showed that the OF slips produced higher average storage root yield for all grades as well as percent marketability; however, the mean comparisons were not statistically significant and so it is unclear whether the production treatments and their corresponding slip morphology trends influenced the yield potential. Future slip performance studies comparing transplant potential may benefit from more standardized factors like holding days between propagation bed harvest and slip planting, as was done in Thompson et al. (2017).

We saw significant differences between slip yields in 2016 and 2017. It is important to note that we were working with different, albeit similar, cultivars each trial year. Moreover, the seed root grade and average weight per seed root was dramatically different. 'Beauregard' seed roots that were planted in 2016 were planted at 33.5 lb/plot, whereas in 2017, the smaller 'Orleans' seed roots averaged 13.1 lb/plot. Furthermore, the 'Orleans' seed roots from 2017 were shipped more than a thousand miles via standard freight shipping and likely experienced suboptimal handling and storage conditions. When seed roots arrived in 2017, the presence of what appeared to be Rhizopus soft rot (*Rhizopus stolonifera*) was pronounced and required sorting and culling. The diminished quality of the imported seed roots reduced time for presprouting and required careful sorting of individual seed roots destined for propagation bed plots. Seed roots that were free of decay were used. However, it is possible that seed root quality was an influencing factor in the 2017 propagation beds. Because of the critical nature of repeating our experiment, we needed to import seed roots in 2017. Nonetheless, the phytosanitary issues associated with shipping seed roots long distances is an issue a grower may want to avoid. Seed programs that originate from imported virus-tested mericlones (e.g., G1 slips) rather than early generation root stock have resulted in higher yields and lower incidence of disease in previous studies (Bryan et al., 2003).

Conclusion

The results of this study suggest that slip production in HT may be a comparable alternative to the more widely used OF method. To our knowledge, this is the first report of sweetpotato slips being propagated in HT and provides data that could be very valuable to established slip propagators as they consider adopting HT production systems. Moreover, HT production of sweetpotato slips in the central and northern growing regions of the United States may permit sufficient season extension for farmers to produce their own slips regionally for storage root production. Considering that the time to maturity for storage roots produced from slips can be 90 d or more, HT systems could support the additional growing time required to also propagate slips in regions with fewer frost-free days. Likewise, the protection afforded by HT also could prevent crop loss or delay caused by extreme weather events (e.g., flooding). These considerations might justify the added cost of HT production and consequently promote improved control over local sweetpotato planting without compromising slip yield, quality, or performance. Small-acreage sweetpotato growers could dedicate a small portion of a HT to produce all the slips they need on-farm. Alternatively, a grower could dedicate an entire tunnel to slip production and distribute those slips regionally, providing an alternative source of farm gate revenue and a potential high-value crop while supporting crop diversity in the HT. Clearly, an economic analysis of this production system will be critical to determining its sustainability. However, our data suggest that propagating sweetpotato slips in the HT is a viable way to grow slips that perform well in the OF, and the HT system may be a mechanism to diversify the geographic range of this valuable crop.

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