Plastic Mulch and In-row Spacing Effects on Sweetpotato Yield in Northwest Washington

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Additional index words. *Agriotes* sp., *Ipomoea batatas*, *Limonius* sp., polyethylene mulch, slips, soil-biodegradable mulch, soil temperature, wireworm

Summary. Sweetpotato (*Ipomoea batatas*) production in the northern United States is limited due to the perceived barriers of a short growing season and relatively cool summer temperatures, yet recent studies have shown yield in northern regions can be greater than the national average when sweetpotatoes are grown with plastic mulch. A study was conducted in northwest Washington to evaluate the productivity of 'Covington' sweetpotato with polyethylene (PE) and soil-biodegradable (BDM) mulches and different in-row spacings (20, 30, and 38 cm) in 2019, and to test accessions resistant to wireworm (*Agriotes* sp. and *Limonius* sp.) in 2020. In 2019, slips were shipped from North Carolina, and after 4 days in transit, 60% to 70% died after transplanting in the field. By the end of the season, BDM deterioration reached 11% compared with 0.4% for PE mulch, but there were no differences due to mulch in plant establishment, growth, yield, or the proportion of storage roots damaged by wireworm. Total storage root yield was 22 t·ha^{-1} with PE mulch and 15 t·ha^{-1} with BDM. Percent canopy cover was greatest at 20-cm spacing later in the growing season, likely due to intermingling of vines from adjacent plants, whereas high percent canopy cover at 38-cm spacing was likely due to increased production of secondary vines per plant. Total yield was greatest with 20-cm plant spacing (20.4 t·ha^{-1}), intermediate with 30-cm spacing (18.0 t·ha^{-1}), and lowest with 38-cm spacing (17.0 t·ha^{-1}). In contrast, the greatest number of storage roots per plant was produced with 38-cm plant spacing (3.4). There were more jumbo sweetpotatoes produced with PE mulch (3.4 t·ha^{-1}) and with 30-cm spacing (3 t·ha^{-1}), and the weight of U.S. No. 2 grade sweetpotatoes was greatest at 20-cm spacing (10.2 t·ha^{-1}). Soil temperature was increased by 3 °C under the PE mulch and 2 °C under the BDM compared with bare ground. However, 98% of storage roots were observed to be severely damaged by wireworm in 2019, with more than 10 to 20 holes per storage root. For wireworm-resistant accessions in 2020, 16% of the storage roots were damaged by wireworm, with 1.7 to 4.0 holes per storage root. Total yield of accessions PI 666141 and 04-791 (45.5 t·ha^{-1} on average) was greater than the national average (24.7 t·ha^{-1}). Overall, sweetpotatoes appear to be suitable for production in northwest Washington, but low yield in 2019 highlights the importance of healthy slips for successful production. Future research should evaluate cultivars with maximum adaptation to the region, techniques to reduce wireworm damage including genetic resistance, and the economics of producing sweetpotatoes in northern regions.

Sweetpotato (*Ipomoea batatas*) is one of the most nutritious root crops, and ranks seventh in world food production after wheat (*Triticum aestivum*), rice (*Oryza sativa*), maize (*Zea mays*), potato (*Solanum tuberosum*), barley (*Hordeum vulgare*), and cassava (*Manihot esculenta*) (Brandenberger et al., 2014; Food and Agriculture Organization of the United Nations, 2019; Johnson et al., 2015; Truong et al., 2018). In the United States, the national average yield of sweetpotato in 2018 was 11 tons/acre (24.7 t·ha^{-1}) [U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS), 2020] and per capita annual consumption was 6.7 lb in 2015. Commercial production of sweetpotato is concentrated in the warmer states, with North Carolina, Louisiana, California, Arkansas, Florida, and Mississippi accounting for 94% of total production in 2018 (USDA, NASS, 2020). Sweetpotato has not been grown commercially in the northern United States because of the perceived limitations of a short growing season and relatively cool summer temperatures. However, PE mulch has been used successfully to increase soil temperatures and productivity for many crops including sweetpotato (Duque, 2020; Sideman, 2015; Wees et al., 2015, 2016). In a cultivar trial in Pennsylvania where all the entries were grown with black PE mulch, the total marketable yields of the highest-yielding sweetpotato cultivars ranged from 548 to 706 50-lb bushels/acre (30.7 to 39.6 t·ha^{-1}) (Duque, 2020). In another cultivar trial grown with black PE mulch in the cool climate and short growing season of Quebec, Canada, Wees et al. (2016) reported sweetpotato marketable yields of 24.4 t·ha^{-1}. Similarly, in a sweetpotato cultivar trial grown with black BDM in New Hampshire, the highest-yielding cultivars included Covington and Beauregard that produced marketable yields ranging from 503 to 887 50-lb bushels/acre (28.2 to 49.7 t·ha^{-1}) (Sideman, 2015). The sweetpotato yields in that study were 17% to 108% greater than the national average. These studies suggest that

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
3.7854	gal	L	0.2642
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.0450	kilocalorie(s)/ft^2	MJ·m^{-2}	22.2044
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha^{-1}	0.8922
25.4	mil(s)	µm	0.0394
2.2417	ton(s)/acre	t·ha^{-1}	0.4461
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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sweetpotatoes may be grown successfully with black plastic mulch in northwest Washington, which has a warm Mediterranean climate (Peel et al., 2007) with an average soil temperature of 18 °C at 20-cm depth during the summer (June through September) growing season [10-year average (AgWeatherNet, 2020)].

An alternative to PE mulch is desired to reduce agricultural plastic waste, and BDM is suitable as it provides comparable crop production benefits and can be tilled into the soil after use, where it will biodegrade (Cowan et al., 2014; Ghimire et al., 2018; Tofanelli and Wortman, 2020). In studies with pie pumpkin (*Cucurbita pepo*) in northwest Washington, Sintim et al. (2019) reported that soil temperatures at 10- and 20-cm depths were 1 to 5 °C greater under black plastic BDMs and PE mulch compared with no-mulch early in the growing season, when the plant canopy had not fully developed. In two studies with pumpkin at the same location, black plastic BDMs and PE mulch increased the soil temperature by 1 to 1.8 °C at a 10-cm depth compared with no-mulch, and the soil temperature was 0.5 °C higher under black PE mulch than under black BDM (Ghimire et al., 2018; Zhang et al., 2020). Waterer (2010) reported no significant differences in soil temperature and crop yield for clear, black, and wavelength-selective PE mulches (BioWay, Leduc, AB, Canada) and BDMs (DuBois Agrinovation, St. Remi, QC, Canada) in Saskatchewan, Canada. In that study, ‘Navajo’ sweet corn (*Z. mays*), ‘Goldrush’ zucchini (*C. pepo*), ‘Fastbreak’ cantaloupe (*Cucumis melo*), ‘Redstart’ pepper (*Capsicum annuum*), and ‘Dusky’ eggplant (*Solanum melongena*) had similar production across all treatments for three cropping seasons. For tomato (*Solanum lycopersicum*), similar yields were observed when grown with black PE mulch and BDM in Spain and the United States (Anzalone et al., 2010; Cowan et al., 2014; Martin-Closas et al., 2008; Moreno and Moreno, 2008).

Sweetpotato plant growth (i.e., number and length of vines) and root yield (i.e., size, number, and weight) are also strongly influenced by planting density, and optimal spacing can differ based on location (Onunka et al., 2011). The most common plant spacing for sweetpotato in North Carolina is 20 to 36 cm within-row and 91 to 122 cm between-row (Jennings et al., 2019). In Kentucky, the recommended plant spacing is 25 to 36 cm in-row and 91 to 122 cm between-row, whereas in Ontario the recommended plant spacing is 30 to 40 cm in-row and 102 to 112 cm between-row [Coolong et al., 2012; Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA), 2012]. These plant spacings provide planting densities of ≈22,000 to 55,000 plants/ha. Further, as in-row spacing was increased, the total root yield decreased but the yield of jumbo-sized roots increased, which can be desirable for some markets (Anderson et al., 1945). The plant spacing to achieve maximum root yield and size appears to increase as the production moves farther north and may be cultivar dependent; thus, studies are needed to determine optimal plant spacing for each region.

Potential pest issues are another consideration for sweetpotato production in each region. The major soil-dwelling insect pests reported to affect sweetpotatoes in the United States are beetles (Coleoptera), including the spotted cucumber beetle (*Diabrotica undecimpunctata*), banded cucumber beetle (*Diabrotica balteata*), sweetpotato flea beetle (*Chaetocnema confinis*), elongate flea beetle (*Systena elongata*), wireworm larvae (*Conoderus* sp.), white grub larvae (*Phyllophaga* sp. and *Plectris aliena*), sugarcane beetle (*Euetheola rugicepes*), and sweetpotato weevil (*Cylas formicarius*) (Cuthbert, 1967; Smith, 2006; Sorensen, 2009). Sweetpotato weevils and wireworms are reported as the most damaging insect pests worldwide, and of all reported beetle pests, only *Agriotes* and *Limonius* species of wireworm have been reported in northwest Washington (Seal et al., 2020).

The overall goal of this study was to ascertain if sweetpotato could be suitable for production in northwest Washington. Specific objectives were to 1) compare the impacts of PE mulch and BDM and different in-row spacings on productivity in northwest Washington, and 2) identify potential pest threats of sweetpotato production in this region and evaluate resistant accessions to manage the pest problem.

Materials and methods

Experimental location. This study was carried out at Washington State University (WSU) Northwestern Washington Research and Extension Center, Mount Vernon (lat. 48°43′24″ N, long. 122°39′09″ W; elevation 6 m) in the Pacific Northwest in 2019 and 2020. The region has a warm Mediterranean climate, and during the summer growing season (June through September) average air temperature is 15 °C (average maximum 21 °C and average minimum 10.5 °C), precipitation is 170 mm, and relative humidity (RH) is 80% [20-year average (AgWeatherNet, 2020)]. The experimental site has a Skagit silt loam soil with a pH of 6.4 and 2.7% organic matter (USDA, Natural Resource Conservation Service, 1960).

2019 field experiment. The objective of this experiment was to compare the impacts of PE mulch and BDM and different in-row spacings on sweetpotato productivity. The experiment had a randomized complete split plot design with two main plot treatments, three subplot treatments, and four replications (Fig. 1). The main plot treatment was mulch with black BDM (0.7 mil, 4 ft wide; Organix Solutions, Grove, MN) and black PE mulch (1 mil, 4 ft wide; Filmtech, Allentown, PA). The subplot treatment was in-row plant spacing at 20, 30, and 38 cm, which were selected from the range of common sweetpotato in-row spacings (Coolong et al., 2012; Jennings et al., 2019; OMAFRA, 2012). Each subplot was 15 ft long. Subplots with 20-cm in-row spacing had 22 plants/plot, 30-cm in-row spacing had 15 plants, and 38-cm in-row spacing had 11 plants. A nonreplicated single no-mulch reference plot with in-row spacing of 38 cm also was included.

Fertilizer (16N–7P–13K; Wilbur-Ellis, San Francisco, CA) was applied to the center of the row at the rate of 100 lb/acre of nitrogen with a 6-ft drop-spreader (Gandy, Owatonna, MN) just before the beds were formed 1 week before planting. Raised beds were 15 to 20 cm high and 0.8 m wide, spaced 3 m center-to-center. Beds were spaced wide apart to allow for mechanical cultivation of weeds early in the season. Drip irrigation tape [8 mil, 8-inch emitter spacing, 0.34 gal/min per 100 ft flowrate (T-Tape model 508-08-340;

Fig. 1. 'Covington' sweetpotato grown with polyethylene (PE) and soil-biodegradable plastic mulch (BDM) at three plant spacings (20, 30, and 38 cm) (left) and without mulch as a nonreplicated reference plot at 38-cm plant spacing (right) at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, on 19 Aug. 2019; 1 cm = 0.3937 inch.

Rivulis, San Diego, CA)] was laid during bed shaping simultaneously with mulch.

Slips of 'Covington' sweetpotato (Jones Family Farm, Bailey, NC) arrived on 7 June 2019 and were transplanted on the same day. Slips took 1 d longer in shipping than arranged (4 d rather than 3 d) and were in very poor health on arrival, which negatively affected survival and establishment in the field. Remaining slips were placed in shallow plastic bulb crates with moist potting mix (Sunshine #3 N&O; Sun Gro Horticulture, Agawam, MA) in a shaded high tunnel and were used to replace dead plants in the field. Many slips (60% to 70%) did not survive the first transplanting and were replaced throughout the field experiment on 10 and 17 June. Weeds were managed in the alleyways by rototilling, and bed edges, planting holes, and the no-mulch reference plot were hand-weeded as needed throughout the growing season. No pesticides were applied to the experiment so that any potential pest issues could be observed.

2020 FIELD EXPERIMENT. The objective of this experiment was to evaluate wireworm-resistant accessions, as only this pest severely affected the 2019 experiment. On 11 Feb. 2020, eight wireworm-resistant sweetpotato accessions (PI 666139, PI 666141, W382, W388, 04-136, 04-284, 04-791, and 09-130) were received from the USDA, Agricultural Research Service (P.A. Wadl) (Table 1). Plant material arrived as tissue culture plantlets, and on arrival were washed and transplanted into sterilized 4-inch pots filled with autoclaved potting mix (same product as in 2019) that was lightly moistened. Pots were placed in a humidity box in the greenhouse, the plants and inside of the box were slightly misted before closing the box, and the box was covered with shade cloth to maintain 50% to 70% light. The environment within the box was maintained at 25 to 27 °C and 80% to 85% RH. The shade cloth cover was removed from one side of the box on the third day, from two sides of the box on the fourth day, and from three sides on the fifth day. On the sixth day, the cloth was completely removed, and the plants were placed on the greenhouse bench. Two of the accessions, PI 666139 and W388, did not survive. The remaining six accessions were propagated by vine cuttings in the greenhouse. On 8 June, the plants were placed in the same field where sweetpotatoes were grown in 2019.

Fertilizer (same product as in 2019) was applied at the rate of 100 lb/acre of nitrogen and beds were formed following the same procedures as in 2019. Beds were mulched with BDM (same product as in 2019) and spacing between plants was 38 cm based on 2019 results to provide the maximum number of storage roots per plant to assess wireworm incidence. The experiment included a single plot of each accession due to low plant numbers and the number of plants per accession varied due to propagation differences. Field data that were collected in 2019 were not collected in 2020 because of limited ability to carry out research experiments during the Coronavirus Disease 2019 (COVID-19) pandemic.

WEATHER DATA. Air temperature, RH, solar radiation, and rainfall data during the cropping season of both years were collected from the WSU AgWeatherNet station (AgWeatherNet, 2020) located ≈140 m from the experimental field plots. Soil temperature was measured every 15 min using data loggers (HOBO; Onset Computer Corp., Bourne, MA). A temperature probe (S-TMB-M002; Onset Computer Corp.) was placed at a 10-cm depth under the plastic mulch in the center of both main plots in the second replicate and in the center of the no-mulch reference plot in 2019, and under the BDM in the center of the third plot in 2020.

MULCH DETERIORATION. In 2019, mulch deterioration was measured visually during the crop growing season in the center 1 m of each plot at the beginning of each month from July through September. Mulch deterioration was assessed as percent soil exposure (PSE) where 0% represents completely intact mulch and 100% represents fully exposed soil (Cowan et al., 2014). Ratings were done in 1% increments until 20% exposure, and 5% increments thereafter. The PSE region was visualized in a grid of 100 (10 × 10) boxes, and the mulch deterioration in the grid was noted. Further, visual rating of mulch

Table 1. Number of sweetpotato plantlets per accession, number of plants transplanted per accession per plot, and length of each plot at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2020.[z]

Accession no.	Plantlets (no.)	Plants (no./plot)	Plot length (ft)[y]
PI 666139	1	–[x]	–
PI 666141	1	18	23
W382	1	35	44
W388	1	–	–
04-136	2	11	14
04-284	2	20	25
04-791	1	13	16
09-130	2	28	35

[z] Plants obtained from the U.S. Department of Agriculture, Agricultural Research Service (P.A. Wadl).

[y] Plants were transplanted at 38-cm (15.0 inches) in-row spacing; 1 ft = 0.3048 m.

[x] Accession did not survive in the greenhouse.

deterioration is subjective, and the same person was responsible for this data collection throughout the experiment to maintain consistency.

Plant establishment and growth. In 2019, plant establishment was measured as the total number of live plants per plot and was recorded at 3 weeks (27 June) and 7 weeks (25 July) after transplanting. The length of the longest vine was measured from the base to the tip of the vine for the center six plants in each plot at 7 weeks (25 July) and 11 weeks (22 Aug.) after transplanting. Percent canopy cover was measured on 30 July and then twice per month until 10 Sept. using digital photographs and a green canopy cover measurement tool (Canopeo version 2.0; Canopeo, Stillwater, OK) developed by the Soil Physics Research Group at Oklahoma State University (Patrignani and Ochsner, 2015) (Fig. 2). Photographs were taken at a 1-m height centered above the central plant in each plot, and included an area ≈130 cm long and 75 cm wide. Beds were hand-weeded before each measurement so that no weeds were in the images. Canopy cover was calculated as the percentage of foliage in the image.

Yield and wireworm damage. In 2019, sweetpotato roots were harvested on 9 and 10 Oct., and in 2020 harvest was on 7 Oct. In both years, harvest was before the soil temperature was below 13 °C to maintain storability of the roots (Brandenberger et al., 2014). Vines were cut and removed from all plots the day before harvest each year to prevent interference with harvesting, and PE mulch was removed from all respective plots. The center 6 ft of each plot in 2019 and the center 5 ft of each plot in 2020 was hand harvested for yield and wireworm damage measurements. The remaining area of each plot was harvested using a single-row potato digger (model D-10M; U.S. Small Farm Equipment Co., Worland, WY).

In 2019, total root weight and marketable root weight per hectare and number of storage roots per plant were calculated for each plot; marketable yield was based on storage roots that had shape and size that would have been considered marketable if they were not damaged by wireworm.

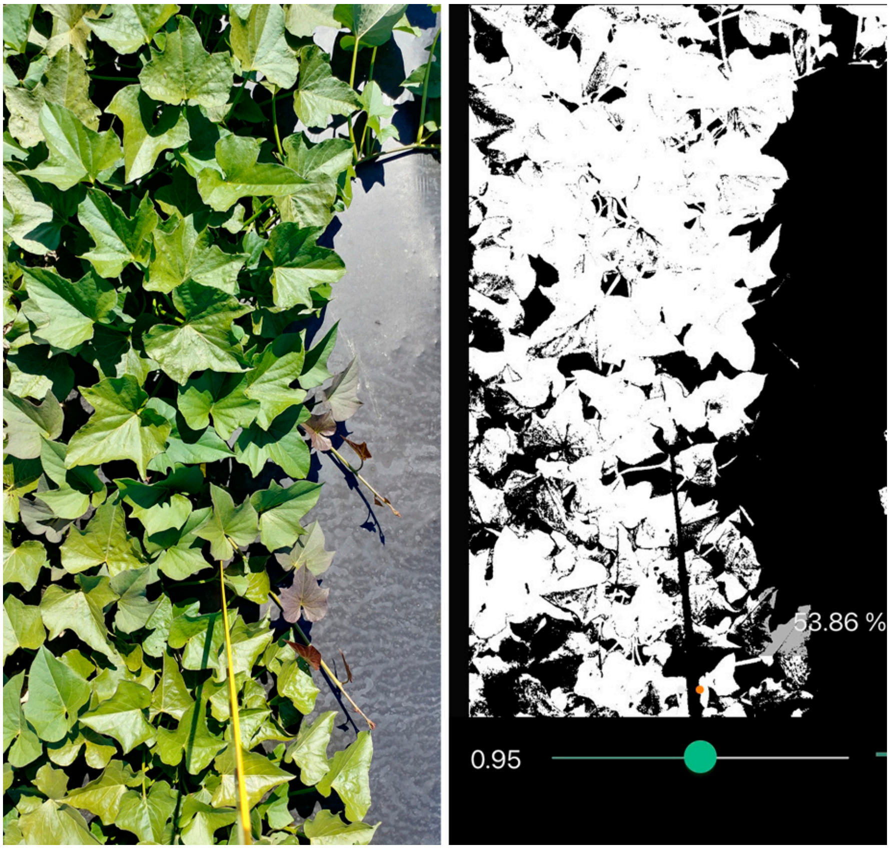

Fig. 2. Measurement of percent canopy cover of 'Covington' sweetpotato grown with polyethylene (PE) and soil-biodegradable plastic mulch (BDM) at three plant spacings (20, 30, and 38 cm) using digital photographs and a green canopy cover measurement tool (Canopeo version 2.0; Canopeo, Stillwater, OK) at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, on 30 July 2019; 1 cm = 0.3937 inch.

Sweetpotatoes were then sorted into size categories, and total root weight in each grading category was calculated per plot. Grading followed U.S. standards for grades of sweetpotatoes (USDA, Agricultural Marketing Service, 2005): Jumbo (>9 inches length and >3.5 inches diameter), U.S. No. 1 (3–9 inches length and 1.75–3.5 inches diameter), U.S. No. 2 (≥1.5 inches diameter), and cull (storage roots of any size with off-shapes). Sweetpotatoes were not sorted into categories in 2020 because of work restrictions caused by the COVID-19 pandemic, and only total root number and weight were measured for each plot and yield per hectare was calculated.

Yield per hectare in both years was calculated based on the mean yield per plant for each treatment (which took into account reduced plant stand) by multiplying with a correction factor of 1.7 to convert the wide row-to-row spacing of 3 m that was used in this study to 6-ft spacing that is common for commercial production using mulched beds. In both years, the percentage of sweetpotato roots that had one or more holes indicative of wireworm damage was calculated for each plot, and in 2020 the number of holes caused by wireworm damage per storage root was recorded for each plot.

Data analysis. All data were analyzed using statistical analysis software (R version 1.4.1106-5 for Windows; RStudio, Boston, MA; SAS version 9.4 for Windows; SAS Institute, Cary, NC). The assumptions of normality and homogeneity of variance were tested using the Shapiro-Wilk test (α = 0.05) and the Levene's test (α = 0.05), respectively, and the data were subjected to analysis of variance. A nonparametric transformation was applied using PROC RANK in SAS to the data that did not satisfy the assumptions of normality with any transformation. All means presented are nontransformed, and means were separated using Tukey's honestly significant difference at a significance level of $\alpha < 0.05$.

Table 2. Environmental and soil conditions during the growing season (7 June to 10 Oct. 2019 and 8 June to 7 Oct. 2020) at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2019 and 2020.[z]

Environmental variables[y]	2019	2020
Average daily air temperature (°C)	16	16
Average daily maximum air temperature (°C)	21	22
Average daily minimum air temperature (°C)	11	11
Total solar radiation ($MJ \cdot m^{-2}$)	1434	2175
Relative humidity (%)	61	79
Total rainfall (mm)	229	127
Soil temperature (°C)[x]		
Polyethylene mulch[w]	21	–[v]
Soil-biodegradable plastic mulch	20	20
No-mulch	18	–

[z] Data from Washington State University Ag WeatherNet Station located 140 m (459.3 ft) from the field site.

[y] (°C × 1.8) + 32 = °F, 1 $MJ \cdot m^{-2}$ = 22.2044 kilocalories/ft^2, 1 mm = 0.0394 inch.

[x] Measured every 15 min at 10-cm (3.9 inches) depth with data loggers (HOBO; Onset Computer Corp., Bourne, MA).

[w] Polyethylene mulch was 1 mil (Filmtech, Allentown, PA) and soil-biodegradable plastic mulch both years was 0.7 mil (Organix Solutions, Grove, MN); 1 mil = 25.4 μm.

[v] Polyethylene mulch and no-mulch treatments were not included in 2020.

Results

ENVIRONMENTAL AND SOIL CONDITIONS. During the growing season both years (June through September), the average air temperature was 16 °C (range 5 to 21 °C in 2019 and 11 to 22 °C in 2020) (Table 2). The average minimum air temperature was 11 °C in both years (range −1 to 17 °C in 2019 and 9 to 16 °C in 2020), and average maximum air temperature was 21 °C for 2019 (range 11 to 30 °C) and 22 °C for 2020 (range 14 to 32 °C). Average daily RH was 61% in 2019 (range 3% to 91%) and 79% in 2020 (range 56% to 98%). Overall, 2019 had 80% greater precipitation and 34% lower total solar radiation (229 mm and 1434 $MJ \cdot m^{-2}$, respectively) than 2020 (127 mm and 2175 $MJ \cdot m^{-2}$, respectively). Average soil temperature at 10-cm depth in 2019 was greatest under PE mulch [21 °C (range 8 to 31 °C)], intermediate under BDM [20 °C (range 7 to 26 °C)], and lowest in no-mulch [18 °C (range 7 to 27 °C)]. In 2020, the average soil temperature under BDM at 10-cm depth was also 20 °C (range 13 to 28 °C).

PERCENT SOIL EXPOSURE. In July, Aug., and Sept. 2019, PSE differed due to mulch ($P \leq 0.0003$ for all) but not due to plant spacing ($P \geq 0.48$ for all) (Table 3), and there was no interaction between mulch and plant spacing ($P = 0.54$, $P = 0.29$, and $P = 0.30$, respectively). PSE remained constant over time for PE mulch (0.4%) but increased for BDM, and was ≈2% in July and August, and 11% in September.

PLANT ESTABLISHMENT AND GROWTH. Average plant stand in 2019 was 68% at week 3 after transplanting and 76% at week 7 after transplanting, and did not differ due to mulch ($P = 0.26$ and $P = 0.40$, respectively) or plant spacing ($P = 0.58$ and $P = 0.26$, respectively) (Table 4). There also was no interaction between mulch and plant spacing (week 3 $P = 0.61$, week 7 $P = 0.08$). In the no-mulch reference plot, plant stand was 28% less on average than with mulch at 3 and 7 weeks after transplanting (49% and 55%, respectively). At week 3 after transplanting, some plants were defoliated and appeared necrotic, and hence were counted as dead. However, after a few weeks, these plants resprouted from below-ground causing an increase in the recorded plant stand.

Average length of the longest vine was 20 cm at week 7 after transplanting, and 113 cm at week 11 after transplanting, and did not differ due to mulch ($P = 0.32$ and $P = 0.68$, respectively) or plant spacing ($P = 0.28$ and $P = 0.60$, respectively) (Table 4). The length of the longest vine in the no-mulch reference bed was 60% and 29% less at 7 and 11 weeks after transplanting, respectively, when compared with the mulched beds. There was an interaction between mulch and plant spacing for vine length at week 7 ($P = 0.03$) but not at week 11 ($P = 0.31$). At week 7, vine length was greatest with PE mulch at 38-cm spacing (24.7 cm) (data not presented).

Canopy cover did not differ due to mulch at any measurement time after transplanting in 2019 (Table 4) and was 19% at week 8 ($P = 0.88$), 51% at week 10 ($P = 0.66$), 60% at week 12 ($P = 0.84$), and 83% at week 14 after transplanting ($P = 0.34$). In the no-mulch reference plot, canopy cover was 73%, 65%, 32%, and 24%

Table 3. Mulch deterioration measured as percent soil exposure (PSE) once per month in the center 1 m (3.3 ft) of each plot of 'Covington' sweetpotato grown with polyethylene (PE) and soil-biodegradable plastic mulch (BDM) at different plant spacings (20, 30, and 38 cm) at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2019.

	PSE (%)[z]		
Treatment	July	August	September
Mulch[y]			
PE mulch	0.4	0.4	0.4
BDM	2.0	2.6	11.0
P value	0.0003	<0.0001	<0.0001
Spacing (cm)[x]			
20	1.6	1.8	5.8
30	1.3	1.4	5.4
38	0.9	1.4	6.0
P value	0.48	0.97	0.87

[z] 0% PSE denoted mulch that was completely intact, and 100% PSE denoted fully deteriorated mulch. Ratings were in 1% increments up to 20% PSE, and in 5% increments thereafter.

[y] PE mulch was 1 mil (Filmtech, Allentown, PA) and BDM was 0.7 mil (Organix Solutions, Grove, MN); 1 mil = 25.4 μm.

[x] 1 cm = 0.3937 inch.

Table 4. Average plant stand, longest vine length, and canopy cover of 'Covington' sweetpotato grown with polyethylene (PE) and soil-biodegradable plastic mulch (BDM) at three plant spacings (20, 30, and 38 cm) at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2019.

	Plant stand (%)		Longest vine length (cm)[z]		Canopy cover (%)			
Treatment	3 WAT[y]	7 WAT	7 WAT	11 WAT	8 WAT	10 WAT	12 WAT	14 WAT
Mulch[x]								
PE mulch	73[w]	79	22	116	19	53	61	84
BDM	63	72	18	110	18	49	59	82
P value	0.26	0.40	0.32	0.68	0.88	0.66	0.84	0.34
Spacing (cm)[z]								
20	73	80	22	120	23	59	67 a[v]	89 a
30	61	70	18	109	16	47	54 b	79 b
38	70	77	19	110	16	47	58 ab	82 ab
P value	0.58	0.26	0.28	0.60	0.09	0.06	0.03	0.004
No-mulch[u]	49	55	8	80	5	18	41	63

[z] 1 cm = 0.3937 inch.

[y] WAT = weeks after transplanting.

[x] PE mulch was 1 mil (Filmtech, Allentown, PA) and BDM was 0.7 mil (Organix Solutions, Grove, MN); 1 mil = 25.4 μm.

[w] All means presented are nontransformed. No transformation satisfied the assumptions of normality for analysis of variance for plant stand at 3 WAT, longest vine length at 11 WAT, and canopy cover at 14 WAT; therefore, data were nonparametrically transformed using PROC RANK test in SAS (version 9.4 for Windows; SAS Institute, Cary, NC). Data for all other measurements were normally distributed and no transformation was needed.

[v] Means followed by the same letter in the same column are not significantly different at $P < 0.05$; means were separated using Tukey's honestly significant difference.

[u] No-mulch was a nonreplicated reference plot with 38-cm in-row spacing between plants.

less than with mulch at weeks 8, 10, 12, and 14 after transplanting, respectively. Percent canopy cover did not differ due to plant spacing at weeks 8 and 10 after transplanting ($P = 0.09$ and $P = 0.06$, respectively); however, there was a difference at weeks 12 and 14 after transplanting ($P = 0.03$ and $P = 0.004$, respectively) when canopy cover was greater for 20-cm spacing than 30-cm spacing and intermediate for 38-cm spacing (Table 4). There was no interaction between mulch and plant spacing at weeks 8 ($P = 0.19$), 10 ($P = 0.12$), and 12 ($P = 0.15$) after transplanting, but there was an interaction at week 14 after transplanting ($P = 0.01$). At week 14, the greatest canopy cover (90%) was with PE mulch at 38-cm spacing (data not presented).

Yield and wireworm damage. In 2019, total storage root yield was 22 t·ha^{-1} with PE mulch and 15 t·ha^{-1} with BDM ($P = 0.06$) (Table 5). Although not statistically different due to variability among plots, there was a 47% difference between yield with PE mulch and BDM. There was a difference in total root yield due to plant spacing ($P = 0.03$) and 20-cm spacing had the greatest total yield

Table 5. Total yield, marketable yield, storage root number per plant, jumbo yield, U.S. No. 1, U.S. No. 2, and number of storage roots with wireworm damage of 'Covington' sweetpotato grown with polyethylene (PE) and soil-biodegradable plastic mulch (BDM) at different plant spacings (20, 30, and 38 cm) at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2019.[z]

Treatment	Total yield (t·ha^{-1})[y]	Marketable yield (t·ha^{-1})	Storage roots (no./plant)	Jumbo (t·ha^{-1})[x]	U.S. No. 1 (t·ha^{-1})[x]	U.S. No. 2 (t·ha^{-1})[x]	Wireworm damage (%)
Mulch[w]							
PE mulch	22.0	17.0	3.3	3.4	5.0	8.5	98
BDM	15.0	10.7	2.6	0.5	3.2	7.0	97
P value	0.06	0.06	0.18	0.004	0.30	0.39	0.80
Spacing (cm)[v]							
20	20.4 a[u]	15.1	2.6 b	0.2 b	4.6	10.2 a	95
30	18.0 ab	13.4	2.9 b	3.0 a	3.4	7.0 b	99
38	17.0 b	12.8	3.4 a	2.5 ab	4.1	6.1 b	98
P value	0.03	0.25	0.006	0.04	0.64	0.008	0.38
No-mulch[t]	5.8	2.9	1.2	0	0	2.8	100%

[z] All means presented are nontransformed. No transformation satisfied the assumptions of normality for analysis of variance for jumbo and wireworm damage; therefore, data were nonparametrically transformed using PROC RANK test in SAS (version 9.4 for Windows; SAS Institute, Cary, NC). Data for all other measurements were normally distributed and no transformation was needed.

[y] Yield per hectare was calculated by multiplying yield with the correction factor of 1.7 to convert the wide row-to-row spacing of 3 m (9.8 ft) that was used in this study to 6-ft (1.8 m) spacing that is common for commercial production using mulched beds; 1 t·ha^{-1} = 0.4461 ton/acre.

[x] Jumbo category sorted as >9 inches length and >3.5 inches diameter. U.S. No. 1 sorted as 3–9 inches length and 1.75–3.5 inches diameter. U.S. No. 2 sorted as ≥1.5 inches diameter; 1 inch = 2.54 cm.

[w] PE mulch was 1 mil (Filmtech, Allentown, PA) and BDM was 0.7 mil (Organix Solutions, Grove, MN); 1 mil = 25.4 μm.

[v] 1 cm = 0.3937 inch.

[u] Means followed by the same letter in the same column are not significantly different at $P < 0.05$; means were separated using Tukey's honestly significant difference.

[t] No-mulch was a nonreplicated reference plot with 38-cm in-row spacing between plants.

Table 6. Storage root yield per plant, total yield, number per plant, percent of storage roots with wireworm damage, and number of holes per storage root caused by wireworm, for six sweetpotato accessions planted at Washington State University Northwestern Washington Research and Extension Center, Mount Vernon, WA, in 2020. Because the study was not replicated, data are not statistically analyzed.

Accession no.[z]	Yield per plant (kg)[y]	Total yield ($t \cdot ha^{-1}$)[x]	Storage roots (no./plant)	Wireworm damage (%)	Wireworm holes (no./root)
PI 666141	2.22	32.5	4	14	3.4
W382	0.73	10.7	5	11	2.4
04-136	0.42	6.1	4	7	1.7
04-284	0.87	12.7	5	40	2.8
04-791	4.00	58.5	4	4	4.0
09-130	0.91	13.3	10	22	4.0

[z] Accessions obtained from the U.S. Department of Agriculture, Agricultural Research Service (P.A. Wadl).

[y] Plants were spaced 38 cm (15.0 inches) apart in a single row; 1 kg = 2.2046 lb.

[x] Yield per hectare was calculated assuming 38-cm in-row and 6-ft (1.8 m) row-to-row spacing, thus 14,620 plants/ha (5924.6 plants/acre); 1 $t \cdot ha^{-1}$ = 0.4461 ton/acre.

(20.4 $t \cdot ha^{-1}$), 38-cm had the lowest total yield (17.0 $t \cdot ha^{-1}$), and 30-cm was intermediate (18.0 $t \cdot ha^{-1}$). There was no interaction between mulch and plant spacing ($P = 0.19$). Average marketable yield was 13.9 $t \cdot ha^{-1}$ and did not differ due to mulch or plant spacing [$P = 0.06$ and $P = 0.25$, respectively (Table 5)], and there was no interaction between mulch and plant spacing ($P = 0.28$). In the no-mulch reference plot, total storage root yield (5.8 $t \cdot ha^{-1}$) and marketable root yield (2.9 $t \cdot ha^{-1}$) were 69% and 79% less than with mulch, respectively. Average storage root number per plant was 3.0 and did not differ due to mulch ($P = 0.18$), there was a difference due to plant spacing ($P = 0.006$), but there was no interaction between mulch and plant spacing ($P = 0.15$). The greatest number of storage roots was produced at 38-cm spacing (3.4) (Table 5). In the no-mulch reference plot, average storage root number per plant was 59% less than with mulch.

When storage roots were sorted by size, the weight of storage roots in the jumbo category differed due to mulch and spacing ($P = 0.004$ and $P = 0.04$, respectively), but there was no interaction between mulch and spacing ($P = 0.17$). There were more jumbo sweetpotatoes with PE mulch (3.4 $t \cdot ha^{-1}$) and with 30-cm spacing (3 $t \cdot ha^{-1}$). Average yield of U.S. No. 1 grade and U.S. No. 2 sweetpotatoes was 4.1 and 7.8 $t \cdot ha^{-1}$, respectively, and there were no differences due to mulch ($P = 0.30$ and $P = 0.39$, respectively). The weight of U.S. No. 1 grade sweetpotatoes also did not differ due to spacing ($P = 0.64$); however, the weight of U.S. No. 2 grade was greatest with 20-cm spacing [10.2 $t \cdot ha^{-1}$ ($P = 0.008$)]. There was no interaction between mulch and plant spacing ($P = 0.27$ and $P = 0.54$, respectively) for total yield. In 2020, the greatest total yield of storage roots was obtained for accession 04-791 (4 kg per plant, 58.5 $t \cdot ha^{-1}$) and was lowest for accession 04-136 (0.42 kg per plant, 6.1 $t \cdot ha^{-1}$) (Table 6). The greatest storage root number per plant was obtained for accession 09-130 (10), and the storage root number per plant was comparable for all other accessions (4.4 on average).

In 2019, the proportion of storage roots with wireworm damage did not differ due to mulch ($P = 0.80$) or plant spacing ($P = 0.38$) (Table 5), and there was no interaction between mulch and plant spacing ($P = 0.81$). Average wireworm damage was 98% overall and essentially all storage roots were observed to be severely damaged, with more than 10 to 20 wireworm holes per storage root (data not shown). In 2020, accession 04-284 had the greatest proportion of storage roots with wireworm damage (40%) and accessions 04-791 and 04-136 had the least damage (4% and 7%, respectively). For the storage roots that had wireworm damage, the average number of holes per root was greatest for accessions 09-130 and 04-791 (4.0 for both) and lowest for accession 04-136 (1.7), followed by W382 (2.4). Four accessions produced marketable storage roots, whereas accessions 04-136 and 04-791 produced irregularly shaped storage roots that would not be marketable.

Discussion and conclusions

This study demonstrates there is potential to grow sweetpotatoes in northwest Washington for local fresh and processing markets; however, there are several limitations to production that must be addressed. First, a reliable supply of sweetpotato slips is needed for the region. Sweetpotato slips were 4 d in transit from North Carolina to Mount Vernon in 2019; they arrived in very poor condition, and 60% to 70% died after transplanting in the field. Slips likely were damaged during transport because of tissue desiccation and/or extreme temperatures (Gilbertson and Bradshaw, 1985; McKay, 1996). For sweetpotato production to be a viable crop, slips must be sourced closer to our region, for example from California where sweetpotatoes are being grown commercially. It also may be economically effective for growers to produce their own slips or arrange to have them produced in their region.

A second limitation to sweetpotato production in the region was severe wireworm damage that caused the crop to be nonmarketable in 2019 in this study. There was less wireworm damage to sweetpotatoes in 2020, suggesting the wireworm-resistant accessions were effective. In 2019, 98% of storage roots were observed to be severely damaged, with more than 10 to 20 wireworm holes per storage root. In 2020, 16% of the storage roots were damaged on average, with 1.7 to 4.0 holes per storage root. Both years, other crops such as lettuce (*Lactuca sativa*) and potatoes had extensive wireworm damage in plots adjacent to this study; therefore, wireworm damage in 2019 was not likely due to poor slip condition. Accessions PI 666141, W382, 04-284, and 09-130 produced marketable storage roots, whereas accessions 04-136 and 04-791 produced irregularly shaped storage roots that would not be marketable. In addition to causing sweetpotatoes to be nonmarketable, wireworm feeding holes can be an entry point for plant pathogens that cause root rot (Ester and Huiting, 2007). Wireworms are difficult to manage, as their behavior can be unpredictable and the most effective insecticides were deregistered because they were persistent chlorinated hydrocarbons (Kuhar et al., 2003; Kwon et al., 1999; Parker and Howard, 2001; Schalk et al., 1993). Currently, growers depend solely on chemical insecticides that do not provide complete control of wireworm (Jackson et al., 2012; Lawrence et al., 2005). Another consideration is the mode of pesticide application, as the choice of products that would be applied in-season are limited by the production system. For example, if plastic mulch is in place, products that can be applied through the drip irrigation system can be used, or products can be target sprayed over the bed if soil is exposed in the transplant hole and before the canopy becomes too large. Breeding for pest resistance is one of the fundamental approaches to pest management, and results of this study suggest that resistant accessions may provide effective control of wireworm damage in sweetpotatoes. However, additional studies of these accessions to test their wireworm resistance are needed.

A third consideration for successful sweetpotato production in northern regions of the United States is increasing field soil temperature. PE mulch and BDM raised soil temperature by 2 to 3 °C at 10-cm depth compared with the no-mulch reference bed in this study. This result is in line with other studies at this location (Cowan et al., 2014; Ghimire et al., 2018, 2020; Miles et al., 2012). Plant stand, the length of the longest vine, canopy cover, total storage root yield, marketable root yield, and average storage root number were all greater when sweetpotatoes were grown with plastic mulch than no-mulch. Furthermore, no jumbo or U.S. No. 1 grade sweetpotatoes were produced in the no-mulch reference bed. These results indicate that at this location, sweetpotato plants become established and grow more quickly with mulch than with no-mulch, likely because of the increased soil temperature. Although mulch type (PE, BDM) did not significantly affect total yield (18.5 $t \cdot ha^{-1}$ on average) or marketable yield (13.9 $t \cdot ha^{-1}$ on average), growers need to consider that yield was 7 $t \cdot ha^{-1}$ more with PE mulch than with BDM. Further, there were almost seven times more jumbo sweetpotatoes produced with PE mulch than with BDM, likely because of the 1 °C greater soil temperature throughout the season with PE mulch than with BDM, as there were no differences in plant growth. Although BDM deterioration reached 11% by the end of the season, no differences were observed in weed suppression between PE mulch and BDM. A disadvantage of PE mulch is that it must be removed before harvest. In contrast, BDM does not need to be removed or disposed at the end of the season, and in this study, the BDM posed no issues with mechanical harvest. Most of the BDM remained in the plots when the harvester lifted the sweetpotatoes, and the BDM pieces that were lifted onto the harvester conveyer belt were returned to the field along with soil as the harvester belt rotated. These results indicate that BDM is a suitable alternative to PE mulch for fresh market sweetpotato production, although jumbo-grade sweetpotatoes for processing may be reduced with BDMs.

Plant spacing had minimal impact on plant growth measured by the length of the longest vine. Although plants grown with closer spacing had greater percent canopy cover later in the season, this was likely because of intermingling of vines from adjacent plants. In contrast, the intermediate canopy cover of plants grown with 38-cm in-row spacing was likely because of an increase in the number of secondary vines formed per plant (Somda and Kays, 1990). Plant spacing did have an impact on storage root size and number, which are important production considerations. The 20-cm plant spacing produced the greatest total storage root yield per hectare but lowest number of storage roots per plant, whereas 38-cm plant spacing produced the lowest total storage root yield per hectare but the greatest number of storage roots per plant. Mortley et al. (1991) also found that increasing in-row spacing from 13 to 38 cm increased the number of storage roots per plant, and similarly, Wees et al. (2016) found increased yield per plant of 'Beauregard' sweetpotato with wider spacing when grown with BDM. Other studies reported that total yield of sweetpotatoes generally increased as in-row plant spacing decreased (Anderson et al., 1945; Peterson, 1961; Schultheis et al., 1999). In contrast, Guertal and Kemble (1997) and Arancibia et al. (2014) reported little or no effect of in-row spacing on marketable yield of 'Beauregard' and 'Evangeline' sweetpotatoes.

The size of sweetpotato storage roots is an important consideration for marketing. In our study, the yield of U.S. No. 1 grade sweetpotatoes did not differ due to spacing, whereas the yield of jumbo sweetpotatoes was greatest with a 30-cm spacing (3 $t \cdot ha^{-1}$) and yield of U.S. No. 2 grade sweetpotatoes was greatest with a 20-cm plant spacing (10.2 $t \cdot ha^{-1}$). Wider plant spacing generally produces a greater number of larger storage roots, whereas narrower plant spacing produces more smaller storage roots (Swiader et al., 1992). In other studies, it has been shown that it can take longer for storage roots to increase in size with smaller in-row spacing. For example, in North Carolina, 'Beauregard' sweetpotato planted at 38-cm in-row spacing reached optimal yield of U.S. No. 1 grade in ≈90 d, 110 d at a 25-cm in-row spacing, and 130 d at 15-cm in-row spacing (K.V. Pecota, personal communication). No. 1–grade storage roots are the most desired for fresh market with the greatest monetary return, whereas jumbo-grade storage roots are marketable for processing such as sweetpotato puree, but they have an increased risk of chilling injury, which can shorten storage life (Schultheis et al., 1999; Wees et al., 2016). Results from our study and others demonstrate there is a tradeoff and a balance between total yield and plant density such that overall yields can be greater at higher plant density, whereas individual yield per plant is reduced. Thus, the target market must be considered when selecting in-row spacing; and in regions with shorter growing seasons, wider in-row spacing may be needed to ensure higher yield.

In this study, the overall average total yield of 'Covington' sweetpotato in 2019 was 18.5 $t \cdot ha^{-1}$ and marketable yield was 13.9 $t \cdot ha^{-1}$, a loss of ≈25% because of off-shaped, cracked, and undersized roots. This total yield was less than the national average of 11 tons/acre (24.7 $t{\cdot}ha^{-1}$) and was likely a result of the unhealthy slips that were planted in 2019 and that took a few months to become well established. In 2020, total yield of the highest-yielding accessions was 32.5 to 58.5 $t{\cdot}ha^{-1}$, likely because of healthy transplants that were propagated on-site, but may also have been due to a cultivar effect. In New Hampshire, ‘Covington’ sweetpotato produced 405 to 747 50-lb bushels/acre (22.7 to 41.9 $t{\cdot}ha^{-1}$) when grown with BDM and 24,000 plants/ha with 9-inch (22.9 cm) in-row spacing (Sideman, 2015). In contrast, in Quebec, Canada, Wees et al. (2015) found poor total and marketable yields for ‘Covington’ sweetpotato (14 and 9 $t{\cdot}ha^{-1}$, respectively), whereas marketable yield of other cultivars ranged between 18 and 25 $t{\cdot}ha^{-1}$. Although ‘Covington’ sweetpotato is currently the most common cultivar grown in North Carolina, it may not be the best cultivar for northern regions of the United States.

Sweetpotato yields have the potential to be high in northern latitude regions because of the longer photoperiod during the growing season that increases growth of the storage roots (Lebot, 2009). In growth chamber experiments, sweetpotato root number was greater with photoperiods of 15 to 21 h per day compared with 12 h, and storage root yield almost doubled when daylength was increased from 9 to 18 h (Mortley et al., 1996). The establishment stage of sweetpotato is the first 4 weeks after planting, and is considered the most critical phase in the growing cycle because plant development during this time largely determines later plant growth and yield (Pardales and Esquibel, 1996). Thus, at high latitudes, such as Mount Vernon, where daylength is 16 h on average in June and July, rapid growth during establishment of healthy transplants likely contributes to higher yields.

In conclusion, marketable sweetpotato yield that is similar to the southern United States can be produced in northwest Washington with PE mulch and BDM. Although the yield in this study in 2019 was lower than the national average, this was likely a result of unhealthy slips and highlights the importance of healthy slips for successful sweetpotato production. Wireworm can be a major pest affecting sweetpotatoes grown in this region, and the greater-than-national-average yield of wireworm-resistant accessions in 2020 opens the door for further research focusing on wireworm-resistant sweetpotato cultivars suitable for northwest Washington. The three plant spacings tested in this study (20, 30, and 38 cm) produced equal yield of U.S. No. 1 storage roots; however, the greatest total yield with more U.S. No. 2 grade storage roots was produced at 20-cm spacing and more jumbo storage roots were produced at a 30-cm spacing. These results indicate a 20-cm in-row spacing is suitable for the greatest production of roots for fresh market and for sweetpotato fries, whereas a 30-cm in-row spacing is suitable for the processing puree market. Overall, sweetpotatoes appear to be suitable for production in northwest Washington, and future research should evaluate cultivars with maximum adaptation to the region, techniques to reduce wireworm damage including genetic resistance, and the economics of producing sweetpotatoes in our region.

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