Growth Manipulation of Slicer Carrots by Foliar-applied Gibberellic Acid in New York

Sarah J. Pethybridge[1], Sean P. Murphy[1], and Julie R. Kikkert[2]

KEYWORDS. **attainable yield, *Daucus carota* ssp. *sativus*, GA_3, gibberellins, plant growth regulators, vegetable root crops**

ABSTRACT. **New York, USA, is a regional hub for processing carrot (*Daucus carota* ssp. *sativus*) production and Nantes-type cultivars are preferred for slicing. Diameter is critical in carrots for slicing, with roots larger than 1 5/8 inch being rejected. The potential to manipulate carrot root diameter and hence suitability for slicing by foliar-applied gibberellic acid (GA_3) was tested in four small plot replicated field trials over 3 years (2020, 2021, and 2022). In the most efficacious treatments, GA_3 resulted in a 23.1% to 135.4% increase in foliar biomass at the expense of root weight and diameter. Increases in foliar biomass are beneficial to facilitate top-pulling harvest. Reductions in root diameter from GA_3 ranged from 9.5% to 19.6%, and in 2020 and 2022, increased the proportion of roots suitable for slicing. GA_3 did not significantly affect root length and number. In two 2021 trials, GA_3 increased color intensity quantified by a colorimeter, but this change was not noticeable to the naked eye. The optimal number of GA_3 applications was seasonally dependent, ranging from a single application at 107 to 108 days after planting (DAP) in 2021, to two applications at 74 + 92 DAP in 2022. Three GA_3 applications per season or late applications (up to 14 days prior to harvest) were not beneficial.**

New York, USA, is an important regional center of processing carrot (*Daucus carota* ssp. *sativus*) production on ~2223 acres annually (US Department of Agriculture 2017). The roots are a rich source of carotenoids, vitamins, and dietary fiber (Arscott and Tanumihardjo 2010). The main New York production occurs in localized areas across the Finger Lakes (Yates and Wayne counties) and Lake Plains (Genesee, Niagara, and Orleans counties) regions. Roots are then processed for dicing or slicing at either of two factories in western New York. Processing carrots are grown in light-textured soil with few rocks or well-drained histosol high in decomposed organic matter (muck soil) (Lag et al. 2008). In New York, carrots are planted by seed using precision planters in April and May and harvested in September and October. Harvesting uses self-propelled, multirow top-pulling machines that undercut and lift the roots by the foliage (Johnson J, personal communication). Foliar health is therefore critical to harvest in New York processing carrot production.

The yield components that influence slicer carrot profitability are the number of roots per unit area and the percent of roots that are suitable for slicing. The number of roots per unit area is influenced by planting populations that dictate attainable yield (Currah and Barnes 1979; Lana 2012; Shiberu and Tamiru 2016). For slicing, blunt-tipped Nantes cultivars are preferred because their diameter is consistent from the crown to the tip and hence a higher proportion of the root is useable (Que et al. 2019). However, root suitability for slicing is strictly defined as having a diameter less than 1 5/8 inch (Johnson J, personal communication). Roots larger than 1 5/8 inch represent a direct loss to the grower unless they can be used for other purposes such as dicing or the fresh market.

The growth and development of plants is influenced by environmental and metabolic processes, including hormones (Hooley 1994; Pimenta Lange and Lange 2006; Wolters and Jurgens 2009; Yamaguchi 2008). Gibberellins are a group of more than 100 diterpenoid compounds that play important roles in regulating many aspects of plant growth including seed germination (Tokuji and Kuriyama 2003), dormancy, parthenocarpy, and stem elongation (Claeys et al. 2014), flowering, fruit set and development (Nieuwhof 1984; Taylor and Geisler-Taylor 1998), and manipulation of senescence (Hooley 1994). They are also known to mitigate abiotic (Ghani et al. 2021; Ullah et al. 2018; Verma et al. 2016) and biotic (Santos et al. 2000) stress. These effects are predominantly through promoting cellular expansion and elongation (Wang et al. 2015; Yamaguchi 2008). On the basis of this knowledge, synthetic gibberellins can be exogenously applied for the manipulation of crop growth and favorable yield outcomes in agriculture (Claeys et al. 2014; Wang et al. 2015).

Units

To convert US to SI, multiply by	US unit	SI unit	To convert SI to US, multiply by
73.0778	fl oz/acre	$mL\cdot ha^{-1}$	0.0137
0.3048	ft	m	3.2808
9.3540	gal/acre	$L\cdot ha^{-1}$	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	$kg\cdot ha^{-1}$	0.8922
1.6093	mile(s)	km	0.6214
70.0532	oz/acre	$g\cdot ha^{-1}$	0.0143
93.0102	oz/ft	$g\cdot m^{-1}$	0.0108
1	ppm	$mg\cdot L^{-1}$	1
2.3385	qt/acre	$L\cdot ha^{-1}$	0.4276
(°F − 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Received for publication 6 Apr 2023. Accepted for publication 4 May 2023.

[1] Cornell AgriTech, School of Integrative Plant Science, Plant Pathology and Plant-Microbe Biology Section, Geneva, NY 14456, USA

[2] Cornell Cooperative Extension, Canandaigua, NY 14424, USA

This work was supported by the US Department of Agriculture, National Institute of Food and Agriculture Hatch project NYG-625424, managed by the New York State Agricultural Experiment Station and the New York State Vegetable Research Council and Association. We thank Paul Tomion (Tomion Farms) for advice and field access; and the summer field crews from the Pethybridge program (Cornell AgriTech) for technical assistance.

S.J.P. is the corresponding author. E-mail: sjp277@cornell.edu.

https://doi.org/10.21273/HORTTECH05231-23

Wang et al. (2016) documented the effects of exogenous gibberellic acid (GA$_3$) on the transcriptional regulatory networks of hormones that resulted in root growth inhibition. In carrot roots, GA$_3$ has also been found to promote the development of secondary xylem and decrease secondary phloem production (McKee and Morris 1986) and enhance lignification (Wang et al. 2016). For New York carrot production, an increase in shoot length and foliar biomass may be beneficial to enhance the efficiency of top-pulling harvest, assuming an absence of trade-offs in foliar disease severity or a tendency toward a more prostrate canopy architecture. Shifts in assimilate partitioning in carrot from foliar-applied GA$_3$ have been described but noted as seasonally dependent (Thomas et al. 1983). These changes in sink-source relationships were reflected as reductions in root weight (Currah and Thomas 1979; Morgan and Mees 1958), but no research has been reported on changes in root diameter. The objective of this study was to quantify the effect of foliar GA$_3$ applications on root diameter and other traits in carrots grown for slicing.

Materials and methods

Small-plot replicated trials were conducted in each of 3 years (2020, 2021, and 2022) to evaluate the potential of 67 ppm GA$_3$ (FalGro® 2X LV; Fine Agrochemicals Ltd., Walnut Creek, CA, USA) for manipulating carrot growth. In each trial, plots were two 10-ft-long rows, separated by 5 ft. Blocks were also separated by two rows of carrots of the same cultivars. All cultivars were Nantes types that are preferred for slicing. Plant populations (density) were assessed within each plot to evaluate the uniformity of the crop stand as a potential covariate on the response variables by counting the number of plants in arbitrarily selected 1-m lengths in each of two rows after emergence (Table 1). GA$_3$ was applied using a carbon dioxide-pressurized backpack sprayer (17.5 gal/acre) with three flat fan nozzles (TJ 8002VS; TeeJet Technologies, Rockford, MI, USA) spaced 0.5 m apart along a 1-m boom.

2020. 'Sirocco' carrots were planted on 7 Apr into muck soil at Potter, NY, USA (lat. 42.76°N, long. 77.15°W; elevation 266 m) in single rows with a vacuum planter (Monosem Inc., Lenexa, KS, USA) at a population of 36 seeds/ft. Fertilizer (13N–0P–5K; Phelps Supply, Phelps, NY, USA) at 1 qt/acre was banded at planting. Linuron at 1 lb/acre (Lorox® DF; Novasource, Phoenix, AZ, USA) was applied at 43 d after planting (DAP). At 60 DAP, 2 oz/acre clethodim (Intensity One; Loveland Products, Loveland, CO, USA) and 14.2 fl oz/acre prometryn (Caparol® 4L; Syngenta Corp., Greensboro, NC, USA) were applied as a tank-mix for postemergent weed control. Linuron at 0.5 lb/acre and 14.2 fl oz/acre prometryn were also applied at 100 and 105 DAP, respectively. For fungal soilborne disease control, 1.6 oz/acre azoxystrobin (Quadris®, Syngenta Corp.) was applied in-furrow at planting. Foliar diseases were controlled by a fungicide program consisting of 2.5 fl oz/acre azoxystrobin + 1.6 fl oz/acre difenoconazole (Quadris Top®, Syngenta Corp.) at 100 DAP, 0.5 qt/acre chlorothalonil (Echo® 720; Sipcam Agro USA Inc., Durham, NC, USA) at 116 DAP, 1.9 oz/acre azoxystrobin + 1.6 oz/acre propiconazole (Cover XL®; Albaugh LLC, Ankeny, IA, USA) at 133 DAP, and 0.5 qt/acre chlorothalonil at 149 DAP. Aphids (*Myzus* sp. and *Macrosiphum* sp.) were controlled by imidacloprid at 0.5 oz/acre (Wrangler®, Loveland Products) at 78 and 133 DAP. The trial design was a completely randomized block with four replications of a single treatment: GA$_3$ applied at 69 + 83 DAP, compared with a nontreated control. Treatments were applied at 825 and 1132 growing degree days calculated by a base temperature of 0 °C [GDD$_0$ (DeGaetano et al. 1993)].

2021. Two small plot, replicated experiments were conducted in 'Sirocco' and 'Volcano' carrots in the same muck soil field at Gorham, NY, USA (lat. 42.77°N, long. 77.14°W; elevation 266 m), separated by 0.5 km. The trials were planted on 6 Apr ('Sirocco') and 7 Apr ('Volcano') using a vacuum planter (Monosem Inc.) with the same specifications and nutrition described for the 2020 trial. Azoxystrobin at 1.6 oz/acre was applied in-furrow at planting. Linuron at 0.5 lb/acre was applied at 36 and 42 DAP ('Sirocco') and 37 and 41 DAP ('Volcano'); followed by 14.2 fl oz/acre prometryn at 77 DAP ('Sirocco') and 76 DAP ('Volcano'). Foliar diseases were controlled by 2.5 fl oz/acre azoxystrobin + 1.6 fl oz/acre difenoconazole (Aquila XL™; Atticus LLC, Cary, NC, USA) at 104 DAP ('Sirocco') and 103 DAP ('Volcano'); 0.9 lb/acre copper sulfate (Cuprofix® Ultra 40 Disperss; United Phosphorus Inc.,

Table 1. Date and days after planting (DAP) of measurements to evaluate the effect of foliar-applied gibberellic acid (GA$_3$) on slicing carrot ('Sirocco', 'Volcano', and 'Bergen') production in New York, USA.

	2020 Sirocco	2021 Sirocco	2021 Volcano	2022 Bergen
Variable[i]	Date (DAP)			
Plant density (plants/m)	11 Jun (65)	27 May (51)	31 May (55)	6 Jun (35)
Leaf length (cm)	23 Jul (107)	27 May (51)	31 May (55)	8 Jul (67)
	10 Aug (125)	7 Jul (92)	7 Jul (91)	28 Jul (87)
		5 Sep (152)	5 Sep (151)	14 Sep (135)
Foliar disease severity (%)[ii]	4 Aug (119)	5 Sep (152)	5 Sep (151)	14 Sep (135)
Normalized difference vegetative index	25 Aug (140)	27 May (51)	31 May (55)	8 Jul (67)
		5 Sep (152)	5 Sep (151)	14 Sep (135)
Harvest (yield components)[iii]	26 Aug (141)	9 Sep (156)	9 Sep (155)	16 Sep (137)

[i] 1 plant/m = 0.3048 plant/ft, 1 cm = 0.3937 inch.

[ii] Alternaria and Cercospora leaf blights.

[iii] Dry weight of foliage, root weight, root number, average root diameter, root length, color (red, blue, and green reflectance used to calculate lightness, hue, and saturation), and core separation.

King of Prussia, PA, USA) at 115 DAP (‘Sirocco’) and 116 DAP (‘Volcano’); 2.5 fl oz/acre azoxystrobin + 1.6 fl oz/acre difenoconazole (Quadris Top®) at 136 DAP (‘Sirocco’) and 135 DAP (‘Volcano’); and 0.5 qt/acre chlorothalonil (Echo® 720) at 149 DAP (‘Sirocco’) and 148 DAP (‘Volcano’). Aphids were controlled by 0.5 oz/acre imidacloprid (Wrangler®) at 77 DAP (‘Sirocco’) and 76 DAP (‘Volcano’). In ‘Sirocco’, GA_3 was applied once (108, 129, or 142 DAP), twice (108 + 129 or 129 + 142 DAP), or three times (108 + 129 + 142 DAP). Treatments applied at 108, 129, or 142 DAP corresponded to 1789, 2243, and 2544 GDD_0.

In ‘Volcano’, GA_3 was applied once (107, 128, or 141 DAP), twice (107 + 128 or 128 + 141 DAP), or three times (107 + 128 + 141 DAP). Treatments at 107, 128, or 141 DAP corresponded to 1780, 2234, and 2535 GDD_0. In both cultivars, the trial design was a completely randomized block with five replications. A nontreated control was also included in each trial.

2022. ‘Bergen’ carrots were planted on 2 May into muck soil at Potter, NY, USA (lat. 42.77°N, long. 77.15°W; elevation 266 m) with a vacuum planter (Monosem Inc.) and the same specifications and nutrition described for the earlier trials, including 1.6 oz/acre azoxystrobin in-furrow. Pendimethalin at 0.4 qt/acre (Prowl® H2O; BASF, Research Triangle Park, NC, USA) was applied 2 d before the crop was planted for preemergent weed control. Additional weed control was achieved using 0.5 lb/acre linuron at 23 and 37 DAP, 14.2 fl oz/acre prometryn at 49 DAP, and a tank mix of 0.5 lb/acre linuron + 14.2 fl oz/acre prometryn at 100 DAP. Foliar diseases were controlled by 2.5 fl oz/acre azoxystrobin + 1.6 fl oz/acre difenoconazole (Quadris Top®) at 100 DAP, 0.5 qt/acre chlorothalonil at 114 DAP, and 3.2 oz/acre azoxystrobin (Aframe™, Syngenta Corp.) at 131 DAP. Aphids were controlled by 0.6 oz/acre imidacloprid (Acronyx™ 4F, Atticus LLC) at 100 DAP. The trial design was a completely randomized block with five replications of GA_3 applied once (74, 92, or 129 DAP), twice (74 + 92 or 92 + 129 DAP), or three (74 + 92 + 129 DAP) times, compared with the nontreated control. Treatments at 74, 92, or 129 DAP corresponded to 1366, 1781, and 2581 GDD_0.

Yield and other horticultural characteristics. Leaf length was evaluated by measuring 20 arbitrarily selected leaves within each plot (10 per row) from the crown to tip on two occasions representing mid and late season in each trial (Table 1). Foliar disease severity was quantified by estimating the percent area affected by Alternaria leaf blight caused by *Alternaria dauci* and Cercospora leaf blight caused by *Cercospora carotae* (Gugino et al. 2007a, 2007b) on each of 20 leaves within each plot at the end of the season (Table 1). In each year, 30 arbitrarily selected carrot leaves were also collected across each trial. Leaves were rinsed with sterile distilled water and placed in glass petri plates in humid boxes to induce sporulation. Conidiophores were observed using a dissecting microscope and identified as either *A. dauci* (Farrar et al. 2004) or *C. carotae* (Thomas 1942; van Delden and Carisse 1993). The frequency of each fungus associated with foliar disease symptoms was recorded. Foliar biomass was also evaluated using a handheld crop sensor (GreenSeeker; Trimble, Sunnyvale, CA, USA) to measure the normalized difference vegetative index [NDVI (Sellers 1985)]. The sensor was held 1 m above the crop canopy and used to scan the entire length of both rows to obtain the average NDVI per plot (Table 1).

Plots were harvested by manual removal of plants within a 1 m section of each plot at 137 to 156 DAP (Table 1). Foliage was removed from the roots and weighed separately before a $\sim$20% sub-sample was dried at 60 °C for 48 h to calculate dry weight. Roots were counted and fresh weight recorded. The diameter of all roots from each plot was measured using digital callipers (Mitutoyo, Aurora, IL, USA) 2 inches below the crown. Thirty roots were arbitrarily selected from each plot and individually measured from the crown to the distal point at which the root tapered. The percent of roots suitable for slicing (<1 5/8 inch diameter) was also calculated. In trials conducted in 2021 and 2022, the color of the inner root was measured on the cut surface of five arbitrarily selected, bisected roots per plot using a hand-held tristimulus colorimeter with a single 8-mm aperture (PCE-XXM 20 Model; PCE Instruments, Jupiter, FL, USA). The reflectance in the red, green, and blue regions were recorded and averaged on a per-plot basis to calculate saturation, hue, and lightness. First, red (R'), green (G'), and blue (B') reflectance values were standardized by dividing by 255, and the $C\max$ [maximum (R', G', B')] and $C\min$ [minimum (R', G', B')] values calculated. Lightness (L) was calculated by the equation: $[(C\max - C\min)/2]$. Saturation was calculated by the equation: $(C\max - C\min)/(1 - |2 \times L - 1|)$. Hue was calculated by the equation: $60° \times [(G' - B')]/(C\max - C\min)]$; $C\max = R'$ (Kender 1976). Core separation was also evaluated on 10 randomly selected roots per plot in the 2021 and 2022 trials. Core separation was defined as a fracture in the phloem parenchyma leading to separation of the core from the remainder of the root. Core separation would make the root unsuitable for slicing. Each root was cut horizontally into three approximately equal sections and evaluated in situ.

Data analysis. The effect of GA_3 treatment on leaf length, NDVI, foliar disease severity, and yield components [dry weight of foliage, fresh weight of roots, root number, root diameter and length, and color features (lightness, saturation, and hue)] were assessed using one-way analysis of variance. Data from each trial were analyzed separately due to differences in GA_3 timings between years and trials. Multiple comparisons were conducted using the Fisher’s protected least significant difference test ($P = 0.05$). All analyses were conducted within statistical software (Genstat ver. 17.2; VSN International, Hemel Hempstead, Hertfordshire, UK).

Results and discussion

This study quantified significant and reproducible changes in the growth and suitability of slicer carrots from foliar-applied GA_3 in New York, USA. These changes did not result from significant differences in carrot populations before treatments

($P > 0.05$), also reflected in homogeneity of leaf length ($P > 0.05$) and NDVI ($P > 0.05$) in the 2021 and 2022 trials (data not shown). In all trials, there was evidence of a GA_3-induced shift in source–sink relationships likely resulting from changes in hormone directed transport (Barnes 1979a, 1979b; Patrick and Woolley 1973) and assimilate sink competition (Barnes 1979a; Hooley 1994). This finding is congruent with previous studies that documented changes in root weight (Currah and Thomas 1979; Thomas et al. 1983). Similar results have also been found with other growth-retardant plant growth regulators, chlormequat chloride and aminozide (Thomas et al. 1973). The response to GA_3 in carrot has been reported to be rate and seasonally dependent. For example, GA_3 at 100 ppm increased the shoot-to-root ratio and reduce root yield (weight) by 35% (Currah and Thomas 1979), but this study did not clarify whether this resulted from changes in root dimensions of length, diameter, or both. Moreover, Thomas et al. (1973) documented similar changes at GA_3 concentrations from 100 to 500 ppm and attributed them to repartitioning of carbohydrates. Santos et al. (2000) also detected a strong GA_3 dose response with low rates (20 to 40 ppm) increasing foliar biomass but not affecting carrot root weight, but at high rates (250 ppm), foliar growth was enhanced sufficiently to be at the expense of root biomass.

In this study, we used a concentration (67 ppm) at the lower end of the labeled range for carrots in New York to enable evaluation of multiple applications. Even at this relatively low concentration, foliar biomass was significantly increased at the expense of root weight and diameter in all years and three slicer carrot cultivars. For example, in 2020, GA_3 application (69 + 83 DAP) significantly increased leaf length by 10.3% and 19.9%, respectively, compared with the nontreated plots (Table 2). The increase in leaf length was also reflected in the NDVI, with GA_3 applications resulting in an increase of 17.6%, compared with nontreated plots. Moreover, the dry weight of foliage at harvest was increased by 77.8%, compared with nontreated plots (Table 2). In the 2021 'Sirocco' trial, GA_3 treatments significantly increased leaf length at 152 DAP [$P < 0.001$ (Table 3)]. Three GA_3 applications significantly increased leaf length compared with other treatments, and by 46.2% compared with the nontreated plots. Two GA_3 applications (129 + 142 DAP) also increased leaf length compared with all single applications (108, 129, or 142 DAP) and by 27.1% compared with the nontreated plots. Of the single application treatments, GA_3 at 129 or 142 DAP significantly increased leaf length compared with 108 DAP and were not significantly different from each other (Table 3). Increases in leaf length from GA_3 were also reflected in NDVI at 152 DAP. Of the single GA_3 applications, 129 DAP resulted in a significant increase in NDVI compared with 108 or 142 DAP (Table 3). Similar treatment effects were also observed in the 2021 'Volcano' trial. For example, three GA_3 applications (107 + 128 + 141 DAP) produced significantly longer leaves than all other treatments, and leaves were 49% longer than in nontreated plots (Table 3). The significant effects of GA_3 on leaf length were also reflected in NDVI. In the 2022 trial, at 135 DAP, GA_3-treated plots, irrespective of timing and frequency, had leaves that were 61.5% longer than the nontreated plots. NDVI was also significantly increased by GA_3 compared with the nontreated plots, and treated plots were not significantly different from each other (Table 4).

Increases in NDVI were usually also reflected on the dry weight of foliage. For example, in the 2021 'Sirocco' trial, the dry weight of foliage compared with the nontreated plot was increased by GA_3 at 108 + 129 DAP (by 54.1%). In the 2021 'Volcano' trial, the dry weight of foliage was significantly increased in plots receiving GA_3 at 107 DAP, 107 + 128 DAP, and 107 + 128 + 141 DAP, compared with nontreated plots, and treated plots were not significantly different from each other (Table 3). The dry weight of foliage was also significantly increased in the 2022 trial, in all GA_3 treatments except for applications made at 129 DAP, and 92 + 129 DAP (Table 5).

The increase in foliar biomass is likely to be favorable for mechanical harvest by top-pulling machinery and did not exacerbate foliar disease severity in the 2021 and 2022 trials. The low foliar disease severity in the 2021 [0% to 0.12% in 'Sirocco' and 0.8% to 2.1% in 'Volcano' (Table 3)] and 2022 [1.4% to 2.9% (Table 4)] trials was likely due to control by fungicides and not significantly affected by treatments. In these trials, Cercospora leaf blight was also dominant in the foliar

Table 2. Effect of foliar-applied gibberellic acid (GA_3) at 69 + 83 d after planting (DAP) on leaf length, foliar disease severity (Alternaria and Cercospora leaf blights), normalized difference vegetative index (NDVI), dry weight of foliage, and root attributes (weight, number, length, and diameter) of 'Sirocco' carrots in a small plot replicated trial at Potter, NY, USA in 2020.

	Leaf length (cm)[i]		Foliar disease severity (%)	NDVI	Foliage dry wt ($g \cdot m^{-1}$)[i]	Root fresh wt (kg)[i]	Roots (no./m)[i]	Root length (cm)	Root diam (mm)[i]
Treatment	107 DAP	125 DAP	119 DAP	119 DAP	141 DAP	141 DAP	141 DAP	141 DAP	141 DAP
GA_3	45.2 a[ii]	54.2 a	8.5 b	0.954 a	447.4 a	2.14 b	82.0	13.6	19.7 b
Nontreated	41.9 b	45.2 b	19.2 a	0.811 b	251.6 b	3.66 a	71.8	14.4	24.5 a
F	7.2	9.5	6.5	8.5	10.4	9.7	2.01	1.95	10.2
LSD[ii]	3.9	3.1	2.7	0.103	44.5	0.45	—	—	1.6
P	0.006	<0.001	<0.001	<0.001	<0.001	<0.001	0.187 NS[iv]	0.547 NS	<0.001
CV (%)[iii]	10.3	9.1	12.1	6.2	8.8	12.5	18.2	39.6	15.1

[i] 1 cm = 0.3937 inch, 1 $g \cdot m^{-1}$ = 0.0108 oz/ft, 1 kg = 2.2046 lb, 1 root/m = 0.3048 root/ft, 1 mm = 0.0394 inch.

[ii] Means followed by the same letter within a column are not significantly different by a least significant difference (LSD) test at $P = 0.05$.

[iii] Coefficient of variation.

[iv] Not significant ($P > 0.05$).

Table 3. Effect of foliar-applied gibberellic acid (GA$_3$) on leaf length, normalized difference vegetative index (NDVI), foliar disease severity (Alternaria and Cercospora leaf blights), dry weight of foliage, and fresh weight of roots in 'Sirocco' and 'Volcano' carrots in a small plot replicated trial at Gorham, NY, USA, in 2021.

GA$_3$ application (DAP)[i]	Leaf length (cm)[ii]		NDVI		Foliar disease severity (%)	Foliage dry wt (g·m^{-1})[ii]	Root fresh wt (kg)[ii]
Sirocco	**92 DAP**	**152 DAP**	**105 DAP**	**152 DAP**	**92 DAP**	**156 DAP**	
108	49.9	59.5 d[iii]	0.832	0.889 e	0.06	476 b	3.40 b
129	49.6	63.8 c	0.828	0.912 c	0.08	431 b	4.53 a
142	50.1	62.5 c	0.830	0.899 d	0	455 b	4.74 a
108 + 129	49.8	64.7 c	0.826	0.920 b	0.08	601 a	3.47 b
129 + 142	49.8	71.2 b	0.830	0.921 b	0.02	440 b	4.74 a
108 + 129 + 142	49.8	74.4 a	0.828	0.929 a	0.12	493 b	3.45 b
Nontreated	49.9	50.9 e	0.826	0.796 f	0.1	390 b	4.85 a
F	1.9	10.2	2.1	9.9	2.3	13.2	12.5
LSD[ii]	—	2.4	—	0.007	—	117.3	0.42
P	0.982 NS	<0.001	0.671 NS	<0.001	0.493 NS	0.035	<0.001
CV (%)[iii]	1.6	2.9	0.7	0.6	24.8	11.3	4.0
Volcano	**91 DAP**	**151 DAP**	**104 DAP**	**151 DAP**	**91 DAP**	**155 DAP**	
107	48.5	60.77 d	0.834	0.930 b	1.2	519 ab	1.77 b
128	49.2	63.77 c	0.828	0.912 c	0.6	457 bcd	2.79 a
141	48.9	64.60 c	0.826	0.946 a	0.9	382 d	2.94 a
107 + 128	48.6	63.93 c	0.836	0.922 bc	0.8	557 a	1.80 b
128 + 141	48.7	72.30 b	0.822	0.922 bc	1.1	477 abcd	2.93 a
107 + 128 + 141	49.3	78.36 a	0.826	0.950 a	0.8	512 abc	1.43 b
Nontreated	48.8	52.61 e	0.828	0.882 d	0.8	422 cd	3.13 a
F	1.7	8.5	1.9	6.6	1.5	11.5	12.4
LSD[ii]	—	2.41	—	0.015	—	95.8	0.53
P	0.793 NS[iv]	<0.001	0.236 NS	<0.001	0.372 NS	0.014	<0.001
CV (%)[iii]	1.8	2.8	1.1	1.2	22.5	7.7	10.7

[i] DAP = days after planting.

[ii] 1 cm = 0.3937 inch, 1 g·m^{-1} = 0.0108 oz/ft, 1 kg = 2.2046 lb.

[ii] Means followed by the same letter within a column are not significantly different by a least significant difference (LSD) test at $P = 0.05$.

[iii] Coefficient of variation.

[iv] Not significant ($P > 0.05$).

disease complex, with 87% to 97% of symptoms associated with *C. carotae* and *A. dauci* observed in less than 3% of lesions. In contrast, in 2020, foliar disease severity was higher across the trial (19.5% in the nontreated plots), and foliar disease severity was decreased by 55.7% in plots receiving GA$_3$ compared with nontreated plots (Table 2). In that year, the foliar disease symptoms were predominantly associated with *A. dauci* (93%), but

Table 4. Effect of foliar-applied gibberellic acid (GA$_3$) on leaf length, normalized difference vegetative index (NDVI), and foliar disease severity (Alternaria and Cercospora leaf blights) at 87 and 135 d after planting (DAP) in 'Bergen' carrots in a small plot, replicated trial at Potter, NY, USA, in 2022.

	Leaf length (cm)[i]		NDVI		Foliar disease severity (%)	
GA$_3$ (DAP)	**87 DAP**	**135 DAP**	**87 DAP**	**135 DAP**	**87 DAP**	**135 DAP**
74	39.4 a	57.9 a	0.83 c	0.89 ab	0	2.8
92	38.0 ab	57.7 a	0.84 b	0.91 a	0	2.4
129	29.6 c	60.7 a	0.79 e	0.89 ab	0	2.9
74 + 92	39.9 a	60.3 a	0.86 a	0.91 a	0	2.2
92 + 129	35.7 b	58.4 a	0.83 c	0.90 a	0	2.3
74 + 92 + 129	39.1 a	58.6 a	0.84 b	0.90 a	0	2.1
Nontreated	29.5 c	36.2 b	0.80 d	0.80 b	0	2.2
F	10.4	9.8	11.4	11.2	—	1.4
LSD[ii]	2.5	3.9	0.001	0.03	—	—
P	<0.001	<0.001	<0.001	<0.001	NA[iv]	0.291 NS[v]
CV (%)[iii]	5.4	3.2	0.5	1.3	—	20.7

[i] 1 cm = 0.3937 inch.

[ii] Means followed by the same letter within a column are not significantly different by a least significant difference (LSD) test at $P \leq 0.05$.

[iii] Coefficient of variation.

[iv] Not applicable.

[v] Not significant ($P > 0.05$).

Table 5. Effect of foliar-applied gibberellic acid (GA_3) on above and below ground yield components at 137 d after planting (DAP) in 'Bergen' carrots in a small plot replicated trial at Potter, NY, USA, in 2022.

GA_3 application (DAP)	Foliage dry wt (g·m^{-1})[i]	Roots (no./m)[i]	Root fresh wt (kg)[i]	Root diam (mm)[i]	Roots suitable for slicing (%)[ii]	Root length (cm)[i]
74	344.1 b	74.2	3.94 a	22.5 cd	100 a	16.5
92	353.3 b	64.4	2.96 bc	24.7 abc	98.7 a	14.9
129	228.8 c	72.2	4.01 a	24.6 abc	85.7 b	15.8
74 + 92	441.7 a	60.6	2.66 c	24.2 bc	99.7 a	15.6
92 + 129	225.8 c	69.8	3.82 a	25.9 ab	99.4 a	15.1
74 + 92 + 129	446.3 a	69.6	2.37 c	21.6 d	98.7 a	13.6
Nontreated	188.6 c	65.6	3.70 ab	27.1 a	82.1 b	15.2
F	11.5	2.1	15.1	13.2	14.1	2.4
LSD[iii]	65.6	—	7.86	2.7	4.6	—
P	<0.001	0.382 NS[v]	<0.001	0.006	<0.001	0.284 NS
CV (%)[iv]	15.8	23	18.0	8.6	3.7	11.4

[i] 1 g·m^{-1} = 0.0108 oz/ft, 1 root/m = 0.3048 root/ft, 1 kg = 2.2046 lb, 1 mm = 0.0394 inch, 1 cm = 0.3937 inch.

[ii] Roots with a diameter < 1 5/8 inch (41.3 mm) are suitable for slicing.

[iii] Means followed by the same letter within a column are not significantly different by a least significant difference (LSD) test at $P = 0.05$.

[iv] Coefficient of variation.

[v] Not significant ($P > 0.05$).

C. carotae was also found in 16.7% of leaves. Santos et al. (2000) found that two GA_3 applications provided equivalent control of Alternaria leaf blight to four applications of the fungicide, iprodione. This finding was hypothesized to be from a more upright habit that enhanced air movement through the canopy and hence disease development. No information is available on the effect of GA_3 on Cercospora leaf blight of carrot. Although the

Table 6. Effect of foliar-applied gibberellic acid (GA_3) on root number, diameter and length, percentage of roots suitable for slicing, and color properties (hue, lightness, and saturation) in 'Sirocco' [156 d after planting (DAP)] and 'Volcano' (157 DAP) carrots, in small plot replicated trials at Gorham, NY, USA, in 2021.

GA_3 application (DAP)	Roots (no./m)[i]	Root diam (mm)[i]	Roots suitable for slicing (%)[ii]	Root length (cm)[i]	Hue (°)	Lightness (%)	Saturation (%)
			Sirocco				
108	90.8	22.72 c	100	21.7	342	55.1 a	73.5
129	92	25.32 ab	100	20.5	352	43.2 b	71.6
142	91	25.73 a	95.5	20.9	361	56.3 a	71.0
108 + 129	84.4	24.04 bc	98.8	23.9	377	42.2 b	74.6
129 + 142	90.4	26.55 a	98.2	20.6	359	46.3 b	74.9
108 + 129 + 142	85.6	23.56 c	100	22.4	350	56.1 a	75.2
Nontreated	90.8	25.91 a	99.5	22.2	369	45.8 b	72.2
F	1.6	5.6	1.8	2.0	2.2	6.1	2.3
LSD[iii]	—	1.36	—	2.38	—	5.35	—
P	0.627 NS[v]	<0.001	0.200 NS	0.065 NS	0.410 NS	<0.001	0.566 NS
CV (%)[iv]	9.3	4.2	99.2	3.9	3.4	4.1	9.5
			Volcano				
107	83.0	20.38 b	100	20.1	379	59.1 a	78.5
128	90.4	22.56 a	100	19.8	368	60.2 a	79.6
141	92.2	23.47 a	100	18.9	365	60.4 a	77.4
107 + 128	85.0	20.40 b	100	21.1	397	59.7 a	77.3
128 + 141	85.6	23.90 a	100	19.5	382	60.0 a	80.1
107 + 128 + 141	82.6	18.91 b	100	19.8	369	63.2 a	76.5
Nontreated	89.4	22.80 a	100	19.7	374	55.2 b	72.2
F	2.3	8.5	—	1.5	1.7	6.8	2.0
LSD	—	1.68	—	—	—	3.9	—
P	0.716 NS	<0.001	—	0.447 NS	0.776 NS	0.022	0.666 NS
CV (%)	6.3	5.4	—	5.6	3.0	3.5	8.5

[i] 1 root/m = 0.3048 root/ft, 1 mm = 0.0394 inch, 1 cm = 0.3937 inch.

[ii] Roots with a diameter <1 5/8 inch (41.3 mm) are suitable for slicing.

[iii] Means followed by the same letter within a column are not significantly different by a least significant difference (LSD) test at $P = 0.05$.

[iv] Coefficient of variation.

[v] Not significant ($P > 0.05$).

significant increases in leaf length led to visibly taller canopies in GA_3-treated plots, we did not observe changes in canopy architecture, which may have influenced disease development through variation in microclimate.

The reductions in root weight from GA_3 were also consistent across trials. In 2020, in GA_3-treated plots, root weight and diameter were decreased by 41.5% and 19.6%, compared with nontreated plots, respectively. GA_3 had no significant effect on root number ($P = 0.187$) and root length [$P = 0.547$ (Table 2)], respectively. The root-to-shoot biomass ratio was 14.5 to 5.4 in nontreated and GA_3-treated carrots. The percent of roots suitable for slicing in GA_3-treated plots was 65% compared with 11.3% in nontreated plots. Therefore, applications of GA_3 at 69 + 83 DAP were sufficient to significantly decrease root weight and diameter and increase the percentage of roots suitable for slicing. In the 2021 'Sirocco' trial, the treatments that significantly reduced root weight (Table 3) and diameter were 108 DAP, 129 + 142 DAP, and 108 + 129 + 142 DAP (Table 6). In the 2021 'Volcano' trial, advantageous effects on root weight and diameter also occurred in plots receiving GA_3 at 107 DAP, 107 + 128 DAP, and 107 + 128 + 141 DAP (Tables 3 and 6). Therefore, the changes in magnitudes of root weight and diameter, and foliar biomass were analogous across cultivars in 2021. However, in both trials, although there was a significant reduction in average root diameter, all roots were already of a diameter suitable for slicing so GA_3 had no significant effect on the frequency of suitable roots [$P > 0.05$ (Table 6)]. In 2022, there was no significant benefit from multiple applications of GA_3, but significant reductions in root diameter were obtained by GA_3 at 74 or 92 DAP (Table 5).

The optimal number of GA_3 applications to achieve favorable outcomes on root weight and diameter were seasonally dependent. On the basis of GDD_0 thermal accumulation in the 2021 growing season was 13.1% and 6.7% less than in the 2020 and 2022 seasons, respectively (DeGaetano et al. 1993). The variation in GA_3 application timings between years was dictated by seasonal changes in carrot growth and predictions of harvest time depending on factory availability. Additional research is needed to standardize the reproducibility of responses in slicer carrot growth from GA_3 to determine the point after which application is not beneficial. In the 2021 and 2022 trials, the latest GA_3 single applications, which occurred when at least 2500 GDD_0 had accumulated, did not significantly affect foliar biomass or root yield components. This may be related to the relative proximity to harvest in 2022 (8 d). However, the final application was made 14 to 16 d before harvest in the 2021 trials, a duration likely to be sufficient to elicit a response based on results from this study when applied earlier in the season. Therefore, carrots may be less responsive to GA_3 close to maturity due to senescence and abiotic or biotic stresses, or changes in environmental conditions, making late harvest manipulation with GA_3 challenging.

Changes in root quality have also been associated with GA_3. Santos et al. (2000) found that inner root color was significantly altered by GA_3, but the color of the outer root was unaffected. In both 2021 trials, color lightness was significantly increased in plots receiving GA_3 at 107 ('Volcano') or 108 ('Sirocco') DAP or 108 + 129 + 142 DAP ('Sirocco'). Moreover, in 'Volcano', color lightness was significantly increased in all GA_3-treated plots except for 128 + 141 DAP (Table 6). These effects were not observed by the naked eye. Changes in color lightness from GA_3 were not detected in 2022. Moreover, changes in color hue and saturation were also not observed from GA_3. An increase in the incidence of core separation has also been noted in GA_3-treated carrots with a concentration 40 ppm at 4 and 6 weeks after emergence (Santos et al. 2000). Core separation was not observed in these trials.

Conclusions

Foliar-applied GA_3 was beneficial for the manipulation of slicer carrot growth. The optimal frequency of applications was seasonally dependent and varied between a single application at 107 to 108 DAP to two applications (74 + 92 DAP). GA_3 resulted in significant increases in foliar biomass reflected in leaf length, NDVI, and the dry weight of foliage at harvest. These effects are favorable to facilitate mechanical, top-pulling harvest, which is standard practice in New York, USA. GA_3 also decreased carrot root weight and diameter but did not affect number and length. The effect of slowing root growth may provide plasticity in harvest time. The decreases in root diameter were consistent across years and resulted in increases in the percentage of roots suitable for slicing in 2020 and 2022. Two GA_3 applications were associated with a decrease in Alternaria leaf blight severity but no significant effects were observed on foliar disease severity when Cercospora leaf blight was dominant in 2021 and 2022.

References cited

Arscott SA, Tanumihardjo SA. 2010. Carrots of many colors provide basic nutrition and bioavailable phytochemicals acting as a functional food. Compr Rev Food Sci Food Saf. 9:223–239. https://doi.org/10.1111/j.1541-4337.2009.00103.x.

Barnes A. 1979a. Vegetable plant part relationships. II. A quantitative hypothesis for shoot/storage root development. Ann Bot. 43:487–499.

Barnes A. 1979b. Vegetable plant part relationships. IV. An interpretation of growth regulator experiments with root crops. Ann Bot. 43:513–522.

Claeys H, De Bodt S, Inzé D. 2014. Gibberellins and DELLAs: Central nodes in growth regulatory networks. Trends Plant Sci. 19:231–239. https://doi.org/10.1016/j.tplants.2013.10.001.

Currah IE, Barnes A. 1979. Vegetable plant part relationships. I. Effects of time and population density on the shoot and storage root weights of carrot (*Daucus carota* L.). Ann Bot. 43:475–486.

Currah IE, Thomas TH. 1979. Vegetable plant part relationships. III. Modification of carrot (*Daucus carota* L.) root and shoot weights by gibberellic acid and daminozide. Ann Bot. 43:501–511.

DeGaetano AT, Knapp WW, Eggleston KL. 1993. Standardizing growing degree day totals for differences in temperature observing schedules. Northeast Regional Climate Center (NRCC) Res Pub RR 93-3.

Farrar JJ, Pryor BM, Davis RM. 2004. Alternaria diseases of carrot. Plant Dis. 88:776–784. https://doi.org/10.1094/PDIS.2004.88.8.776.

Ghani MA, Abbas MM, Ali B, Aziz R, Qadri RWK, Noor A, Azam M, Bahzad S, Saleem MH, Abualreesh MH, Alatawi A, Ali S. 2021. Alleviating role of gibberellic acid in enhancing plant growth and stimulating phenolic compounds in carrot (*Daucus carota* L.) under lead stress. Sustainability. 13:12329. https://doi.org/10.3390/su132112329.

Gugino BK, Carroll JE, Widmer TL, Chen P, Abawi GS. 2007a. An IPM program for managing fungal leaf blight diseases of carrot in New York. Plant Dis. 91:59–65. https://doi.org/10.1094/PD-91-0059.

Gugino BK, Carroll JE, Widmer TL, Chen P, Abawi GS. 2007b. Field evaluation of carrot cultivars for susceptibility to fungal leaf blight diseases in New York. Crop Prot. 26:704–714. https://doi.org/10.1016/j.cropro.2006.06.009.

Hooley R. 1994. Gibberellins: Perception, transduction, and responses. Plant Mol Biol. 26:1529–1555.

Kender JR. 1976. Saturation, hue, and normalized color: Calculation, digitization effects, and use. Carnegie-Mellon Univ, Pittsburgh, PA, USA.

Lag J, Hadas A, Fairbridge RW, Muñoz JN, Pombal XP, Cortizas AM. 2008. Histosols. In: Chesworth W (ed). Encyclopedia of soil science. Springer, Dordrecht, the Netherlands.

Lana MM. 2012. The effects of line spacing and harvest time on processing yield and root size of carrot for Cenourete® production. Hortic Bras. 30:304–311. https://doi.org/10.1590/S0102-05362012000200020.

McKee JMT, Morris GEL. 1986. Effects of gibberellic acid and chlormequat chloride on the proportion of phloem and xylem parenchyma in the storage root of carrot (*Daucus carota* L.). Plant Growth Regulat. 4:203–211.

Morgan DG, Mees GC. 1958. Gibberellic acid and the growth of crop plants. J Agric Sci. 50:49–59.

Nieuwhof M. 1984. Effect of gibberellic acid on bolting and flowering of carrot (*Daucus carota* L.). Scientia Hortic. 24:211–219. https://doi.org/10.1016/0304-4238(84)90104-3.

Patrick JW, Woolley DJ. 1973. Auxin physiology of decapitated stems of *Phaseolus vulgaris* L. treated with indol-3yl-acetic acid. J Expt Bot. 24:949–957.

Pimenta Lange MJ, Lange T. 2006. Gibberellin biosynthesis and the regulation of plant development. Plant Biol. 8:281–290. https://doi.org/10.1055/s-2006-923882.

Que F, Hou XL, Wang GL, Xu ZS, Tan GF, Li T, Wang YH, Khadr A, Xiong AS. 2019. Advances in research on the carrot, an important root vegetable in the Apiaceae family. Hortic Res. 6:69. https://doi.org/10.1038/s41438-019-0150-6.

Santos P, Nunez JJ, Davis RM. 2000. Influence of gibberellic acid on carrot growth and severity of Alternaria leaf blight. Plant Dis. 84:555–558. https://doi.org/10.1094/PDIS.2000.84.5.555.

Sellers PJ. 1985. Canopy reflectance, photosynthesis, and transpiration. Int J Remote Sens. 6:1335–1372.

Shiberu T, Tamiru S. 2016. Effect of intra spacing on yield and yield components of carrot (*Daucus carota* L. sub sp. *sativus*). Curr. Res. Agric. Sci. 3:1–6. https://doi.org/10.18488/journal.68/2016.3.1/68.1.1.6.

Taylor BH, Geisler-Taylor D. 1998. Flower bud thinning and winter survival of 'Redhaven' and 'Cresthaven' peach in response to GA_3 sprays. J Am Soc Hortic Sci. 123:500–508. https://doi.org/10.21273/JASHS.123.4.500.

Thomas HR. 1942. Cercospora blight of carrot. Phytopathology. 33:114–125.

Thomas TH, Currah IE, Salter PJ. 1973. Effects on carrot root yield and size distribution of the growth-retardants chlormequat chloride and aminozide. Ann Appl Biol. 75:63–70. https://doi.org/10.1111/j.1744-7348.1973.tb01338.x.

Thomas TH, Barnes A, Rankin WEF, Hole CC. 1983. Dry matter distribution between the shoot and storage root of carrot (*Daucus carota* L.): II. Effect of foliar application of gibberellic acid. Ann Bot. 51:189–199.

Tokuji Y, Kuriyama K. 2003. Involvement of gibberellin and cytokinin in the formation of embryogenic cell clumps in carrot (*Daucus carota*). J Plant Physiol. 160: 133–141. https://doi.org/10.1078/0176-1617-00892.

Wang G, Que F, Xu Z, Wang F, Xiong A. 2015. Exogenous gibberellin altered morphology, anatomic and transcriptional regulatory networks of hormones in carrot root and shoot. BMC Plant Biol. 15:290. https://doi.org/10.1186/s12870-01500679-y.

Wang G, Que F, Xu Z, Wang F, Xiong A. 2016. Exogenous gibberellin enhances secondary xylem development and lignification in carrot taproot. Protoplasma. 254:1–10. https://doi.org/10.1007/s00709-016-0995-6.

Wolters H, Jurgens G. 2009. Survival of the flexible: Hormonal growth control and adaptation in plant development. Nat Rev Genet. 10:305–317. https://doi.org/10.1038/nrg2558.

Ullah A, Manghwar H, Shaban M, Khan AH, Akbar A, Ali U, Ali E, Fahad S. 2018. Phytohormones enhanced drought tolerance in plants: A coping strategy. Environ Sci Pollut Res Int. 25:33103–33118. https://doi.org/10.1007/s11356-018-3364-5.

US Department of Agriculture. 2017. Agricultural statistics for 2015. https://www.nass.usda.gov/Quick-Stats/. [accessed 28 Dec 2022].

van Delden A, Carisse O. 1993. Effect of plant age, leaf age and leaf position on infection of carrot leaves by *Cercospora carotae*. Phytoprotection. 74:75–87. https://doi.org/10.7202/706038ar.

Verma V, Ravindran P, Kumar PP. 2016. Plant hormone-mediated regulation of stress responses. BMC Plant Biol. 16:1–10. https://doi.org/10.1186/s12870-016-0771-y.

Yamaguchi S. 2008. Gibberellin metabolism and its regulation. Annu Rev Plant Biol. 59:225–251. https://doi.org/10.1146/annurev.arplant.59.032607.092804.