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Comparison of Standard Calendar GA_{4+7} Plant Growth Regulator Programs to Applications Timed to Rainfall Events for Management of Scarf Skin, a Fruit Finish Disorder of Apple

David A. Strickland[1] | Jason P. Londo[2] | Kerik D. Cox[1,†]

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

[2] Section of Horticulture, School of Integrative Plant Science, Cornell University, Cornell AgriTech, Geneva, NY 14456

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† Corresponding author: K. D. Cox; kdc33@cornell.edu

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Abstract

Scarf skin is a fruit finish disorder of apple that leads to reduced grade quality and rejected crop loads. Although not established as a disorder specific to certain cultivars, the manifestation of the disorder is more apparent on red-skinned cultivars such as Gala and Stayman at harvest, where its whiteish cast is held in clear contrast with the redness of the mature fruit. The disorder afflicts fruit during the first 40 days after petal fall as the fruitlet is developing, although symptoms of the disorder may not be clearly visible until many months after. The exact causes of apple scarf skin are not well defined, although it is known that the presence of the disorder can be influenced by environment, fruit size, and some pesticides. Management currently relies on four applications of the plant hormones gibberellins A4 and A7 (GA_{4+7}) during the first 40 days after bloom. Here, we describe our attempts to use a commercialized GA_{4+7} product (ProVide 10SG) starting at petal fall, with applications made after or before rainfall events, to ease rainfall's putative influence on scarf skin development. We compared our programs to the standard program over 4 years in research orchards and a commercial orchard but observed no consistent reduction in scarf skin severity or incidence of out-of-grade fruit, in part due to the year-to-year variability in the manifestation of scarf skin. Rainfall, at the thresholds defined, does not appear to be a sufficiently significant factor influencing scarf skin development such that a GA_{4+7} management program can be designed.

Keywords: apple, plant growth regulator, ProVide, scarf skin

Apple scarf skin—also referred to as opalescence—is a fruit finish disorder manifesting as a whitish or clouded cast on the fruit peel, ranging in size from an infrequent trace to coverage of the entire fruit surface. The first recorded observations of apple scarf skin in the United States were in the early 1900s, noted on fruit from cultivars Sweet Winesap and Black Gilliflower in western New York and Ingram in Arkansas

(Beach et al. 1905; Truax 1914). Scarf skin is often reported on red apple cultivars such as Keepsake, Rome Beauty, Co-op 25 (Scarlet O'Hara), Stayman, and Turley due to the clear contrast between skin color and the disorder's effect, particularly near harvest, when matured fruit are in full color (Byers 1977; Dayton 1959; Ferree et al. 1984a; Janick et al. 2000; Merwin 2008). The disorder is not limited by geography and has been observed in Japan on the cultivar Kotaro (Soejima et al. 2012) and on Elstar and Redprince in Germany (Weber and Zabel 2011). Scarf skin is a solely cosmetic disorder, with no known influence on the fruit's nutritional value (Ferree et al. 1984a). In the United States, the presence of this disorder results in reduced fruit grade, as affected fruit with greater than 15% coverage were classified as having a "smooth russe" defect (Byers 1977). The opalescent sheen is undesirable, as it may be mistaken as pesticide residue when fruit are on display at market, leading to consumer rejection (Schupp et al. 2018). Several instances have been reported of packing houses rejecting apple loads with scarf skin severity beyond an aggregated area of 25% or more, which is the threshold used to delineate a grade of "U.S. No. 1" with respect to fruit russet (McArtney et al. 2006).

Although scarf skin and russet are both fruit finish disorders, these commercial ratings may be inadvertently misconstruing the two in such a way as to be misleading to researchers and growers alike. Although both scarf skin and russeting are in some respects visually similar, they differ in a critical element of their classification. Fruit afflicted with russeting produces a periderm to restore the damaged surface (Winkler et al. 2022). Russeting is the result of surface moisture-induced microcracks in the fruit cuticle, leading to the development of a tri-layered periderm, characterized visually by a cork cambium (Chen et al. 2020; Faust and Shear 1972; Khanal et al. 2021; Knoche and Grimm 2008). Scarf skin, however, lacks periderm formation and instead is the visual effect of light from pigmented hypodermal cells reflected into intercellular air spaces that have formed among cell layers below the fruit epidermis (Dayton 1959; Ferree et al. 1984a; McArtney et al. 2006; Weber and Zabel 2011).

Scarf skin develops during the 40 days after bloom, and its severity is dependent on orchard climate, fruit size, and the influence of some pesticides such as benomyl and petroleum-based horticultural oils (Agnello et al. 1994; Ferree and Ellis 1986; Ferree and Schmid 1986; Ferree et al. 1984a). Aspects of fruit microclimate, such as surface moisture, temperature, light, and relative humidity, may be primary contributing factors to scarf skin development, as prior research found that bagging fruit 10 days after petal fall significantly reduced scarf skin presence at harvest (Ferree and Schmid 1986; Ferree et al. 1984b). However, to date, a definitive cause of scarf skin has yet to be identified (Winkler et al. 2022).

The plant hormone gibberellin (GA) has many regulatory roles in plant development: tissue elongation and expansion by cell growth, seed germination, and promotion of seed, flower, and fruit development, among others (Davière and Achard 2013). Although over 130 gibberellins have been discovered, only a subset are used as plant growth regulators (PGRs) with commercial formulations (Binenbaum et al. 2018). Current recommendations for the management of apple scarf skin involve the regular application of the gibberellins A4 and A7 (GA_{4+7}) during the first 40 days after bloom (Ferree et al. 1984b). During this period, the fruit surface experiences considerable strain on the elements comprising the fruit cuticle as the fruit surface undergoes the highest rates of surface area expansion of its development, which may lead to microcracking (particularly if exacerbated by environmental or other external factors) (Khanal et al. 2014). Gibberellin applications promote smaller, more uniformly sized epidermal cells, characteristics helpful for the management of physical strain on the fruit as it develops (Curry 2012; Eccher 1975; Winkler et al. 2022).

Growers may be doubtful of the efficacy of a scarf skin management program, concerned that the increased costs associated with additional GA_{4+7} applications are insufficient to offset the economic loss due to scarf skin incidence and severity at harvest, levels that may vary in some years and growing regions. Given the associated increased costs per hectare, improved management programs are needed to consistently provide control of this disorder while also reducing labor and material inputs. In New York State, a recent survey representing 41% of the state's apple acreage reported that cultivars known to manifest scarf skin, such as Gala and NY1 (SnapDragon), are among the most popular cultivars planned to be planted statewide in the next 3 years (Kahlke et al. 2022). Given the demand for high-quality fruit for the fresh market (which approximately 57% of New York's production is destined for, as of 2021) (NASS 2022), finding an implementable management program for scarf skin would be of economic value. Indeed, the downgrading of fresh market apples to "utility" grade can result in losses that may generate net profits lower than the cost of production (Cox 2015).

McArtney et al. (2006) reported that in their experimental trials with the cultivar sport Buckeye Gala, three applications of GA_{4+7} made during the postbloom period reduced severity as much as 14% compared with the untreated control. The PGR prohexadione-calcium (Ph-Ca), a gibberellin antagonist, has a synergistic effect when made in conjunction with GA_{4+7} applications during the early postbloom period; treatments with both compounds reduced scarf skin (Ferree et al. 1984b; McArtney et al. 2006). Another trial reported a 6 to 10% reduction in scarf skin symptoms from fruit treated with Ph-Ca alone (Cline 2017). Another trial reported that Ph-Ca applications alone had no impact on scarf skin reduction (Schupp et al. 2018). Applications of GA_{4+7} were also observed to reduce the incidence and severity of russeting as well, a beneficial side effect for simultaneous management of both disorders (Curry 2012; Knoche et al. 2011).

Given the uncertainties surrounding the definitive factor(s) contributing to the development of scarf skin, we focused our investigation on the putative influence of one factor on the disorder's management: rainfall. Here, we conducted a series of multi-year field trials with several GA_{4+7} programs consisting of applications made either prior to or shortly after specific rainfall thresholds were met. The programs' impact at harvest on scarf skin severity and the incidence of out-of-grade fruit due to scarf skin were assessed. These programs are compared with the currently recommended management program using four GA_{4+7} applications made in 10-day intervals starting at petal fall.

Materials and Methods

Evaluation of a GA_{4+7} program with applications timed after rainfall thresholds

A 4-year trial was conducted at Cornell AgriTech in Geneva, NY, during the 2019 to 2022 growing seasons to evaluate a GA_{4+7} program with applications timed just after rainfall events. The orchard used was a modern high-density (approximately 3,000 trees/ha) super spindle mixed cultivar planting including cultivar NY1 on G.935 rootstocks with a three-wire training system (planted in 2015), with treatments arranged in a randomized complete block design with eight single-tree replications. To prevent interplot interference, four-tree panels were spaced between treatment trees. Programs of ProVide 10SG (GA_{4+7}; Valent BioSciences, Libertyville, IL) were at the labeled high and low rates (247 and 148 g/ha, respectively) for use in 378 liters (100 gallons) of water, applied using a Solo 475-B gas-powered mist blower (Solo, Newport News, VA). Untreated control trees that received no PGR applications were also included. For the 'Calendar' high-rate program, four total GA_{4+7} applications were made starting at petal fall in 10-day intervals. For both the 'Rainfall' high- and low-rate program treatments, the application window was from petal fall until 40 days after petal fall (DAPF), but GA_{4+7} applications were only made within this period on the day after either a single rainfall event generated more than 2.5 cm of rain or more than 3.8 cumulative cm of rain were observed within the preceding 4 days. If a GA_{4+7} application was made due to an exceeded rainfall threshold, another GA_{4+7} application would not be applied until 10 days had passed, and no more than four total GA_{4+7} applications would be made in a year, as per label recommendations.

Evaluation of a GA_{4+7} program with applications timed preemptively to rainfall events

A 3-year trial was conducted at Cornell AgriTech in Geneva, NY, during the 2020 to 2022 growing seasons to evaluate GA_{4+7} programs with applications timed just prior to rainfall events. The orchard used was a mature vertical-axis planting of cultivar Gala on B.9 rootstocks (planted in 2001 at approximately 1,200 trees/ha), with treatments arranged in a randomized complete block design with four single-tree replications. The wide row and plot spacing (7 m between rows, 3 m between trees) of the vertical-axis orchard was sufficient to prevent interplot interference. Programs of ProVide 10SG (GA_{4+7}) were at the labeled high and low rates (247 and 148 g/ha, respectively), applied as described previously. Untreated controls were also included. For the 'Calendar' high- and low-rate programs, four total GA_{4+7} applications were made starting at petal fall in 10-day intervals. For both the 'Rainfall' high- and low-rate program treatments, the application window was from petal fall until 40 DAPF, but GA_{4+7} applications within this time period were only made within 1 to 3 days of a single rainfall event forecasted to generate more than 2.5 cm of rain, as indicated by the NEWA system (https://newa.cornell.edu/). If a GA_{4+7} application was made due to a forecasted rainfall event exceeding this threshold, another GA_{4+7} application would not be applied until 10 days had passed, and no more than four total GA_{4+7} applications would be made in a year, as per label recommendations.

Evaluation of a GA_{4+7} program with applications timed preemptively to rainfall events (commercial trial NY1s)

A 2-year trial was conducted at Two of Clubs Orchards in Appleton, NY, during the 2021 to 2022 growing seasons. The commercial orchard used was a mature high-density (1,320 trees/acre) planting of cultivar NY1 on NIC 29 rootstocks in a three-wire training system (planted in 2013), with treatments arranged in a randomized complete block design with eight single-tree replications. To prevent interplot interference, four-tree panels were spaced between treatment trees. As this was a commercial orchard in production, all trees received uniform applications of various PGRs during the growing season in addition to the experimental PGR treatments described below, consisting of Apogee (prohexadione calcium; 170 and 283 g/acre; 1 application each), Promalin (N-(phenylmethyl)-1H-purine 6-amine and gibberellins A_{4+7}; 118 ml/acre; 1 application), Fruitone L (NAA; 85 ml/acre; 1 application), MaxCel (6-benzyladenine; 1.8 liters/acre; 1 application), and Ethephon 2 SL ((2-chloroethyl)-phosphonic acid, 148 ml/acre; 2 applications).

Programs of ProVide 10SG (GA_{4+7}) were at the labeled high and low rates (247 and 148 g/ha, respectively), applied as described previously. Untreated controls were also included. For the 'Calendar' high- and low-rate programs, four total GA_{4+7} applications were made starting at petal fall in 10-day intervals. For both the 'Rainfall' high- and low-rate program treatments, the application window was from petal fall until 40 DAPF, but GA_{4+7} applications within this time period were only made within 1 to 3 days of a single rainfall event forecasted to generate more than 2.5 cm of rain, as indicated by the NEWA system (https://newa.cornell.edu/). If a GA_{4+7} application was made due to a forecasted rainfall event exceeding this threshold, another GA_{4+7} application would not be applied until 10 days had passed, and no more than four total GA_{4+7} applications would be made in a year, as per label recommendations.

Data analysis

In all trials in all years, at harvest, all fruit from each tree replication were collected. Scarf skin incidence of out-of-grade apples was determined as the number of apples with aggregated area of the scarf skin disorder greater than 25%. Overall scarf skin severity (percentage of fruit surface area affected) was assessed by a visual quantification by the same individual rater for all treatments. Additionally, several horticultural parameters were assessed to confirm the GA_{4+7} treatments did not generate adverse effects. The total weight of the crop yield was collected, and mean fruit weight was determined. Fifteen fruit were arbitrarily selected from the total harvest of each replicate tree to measure fruit length and diameter with digital calipers. The trunk cross sectional area of each replicate tree was also calculated from measurements of the trunk diameter. The effect of each treatment on the out-of-grade scarf skin incidence, scarf skin severity, fruit metrics (size, length, diameter), mean fruit produced, and total tree crop yield (kg) was determined using analysis of variance for a randomized block design using accepted statistical procedures and software (i.e., Generalized Linear Mixed Models [GLIMMIX] procedure of SAS [version 9.4; SAS Institute, Cary, NC]) whereby the treatments were fixed effects, and the replicate trees or fruits were random effects.

Results

Evaluation of a GA_{4+7} program with applications timed after rainfall thresholds

On untreated replicates of NY1 during the 2019 growing season, the observed mean scarf skin severity on fruit was 31.32% (Fig. 1; Table 1). Trees receiving four GA_{4+7} applications timed to a calendar program in regular 10-day intervals starting at petal fall (four applications at 0, 10, 20, and 30 DAPF) had a recorded 15.54% mean scarf skin severity at harvest, which was significantly reduced compared with the untreated control ($P < 0.05$) (Fig. 1; Table 1). Trees receiving either the low- or high-rate GA_{4+7} applications made after rainfall thresholds (two applications at 24 and 41 DAPF) also had significantly reduced scarf skin severity on fruit (15.90 and 15.62%, respectively) at harvest compared with the untreated control ($P < 0.05$), and only two total PGR applications were made (Fig. 1; Table 1). The mean percentage incidence of fruit considered "out-of-grade" (having >25% of the fruit surface affected by the disorder) was significantly reduced for the two programs using the high-rate GA_{4+7} applications (calendar program: 24.48%, rainfall program: 27.62%), compared with the untreated control (65.15%) (Table 1).

In 2020, the observed mean scarf skin severity on fruit from any treatment was 1% or less and not suitable for meaningful analysis (Fig. 1; Table 1).

In 2021, the severity of scarf skin on untreated fruit was 12.74%. The scarf skin severity observed on any treatment was not significantly different than the untreated control ($P > 0.05$).

The severity of scarf skin was 10.17% for the calendar program, 10.13% for the low-rate rainfall program, and 12.97% for the high-rate rainfall program (Fig. 1; Table 1). The precipitation events during the early growing season of 2020 triggered only one GA_{4+7} application for the rainfall programs at 26 DAPF, whereas the calendar program received the typical four GA_{4+7} applications at 0, 10, 20, and 30 DAPF (Table 1). The programs receiving any GA_{4+7} applications also had no difference in out-of-grade fruit compared with the untreated control, which was 27.18% (Table 1).

In 2022, orchard-wide damage due to fire blight dramatically reduced fruit set and survival to maturity. The data were not statistically useful for analysis and could not provide insight for effects of each of the programs on scarf incidence and severity and thus are not included (data not shown).

In all years (2019 to 2021) for this trial, recorded observations of most horticultural parameters (mean number of fruit, tree yield, fruit weight, fruit length) that might have been influenced by GA_{4+7} applications were not significantly different from the untreated control trees and fruit (Table 1). Note that in 2020, the

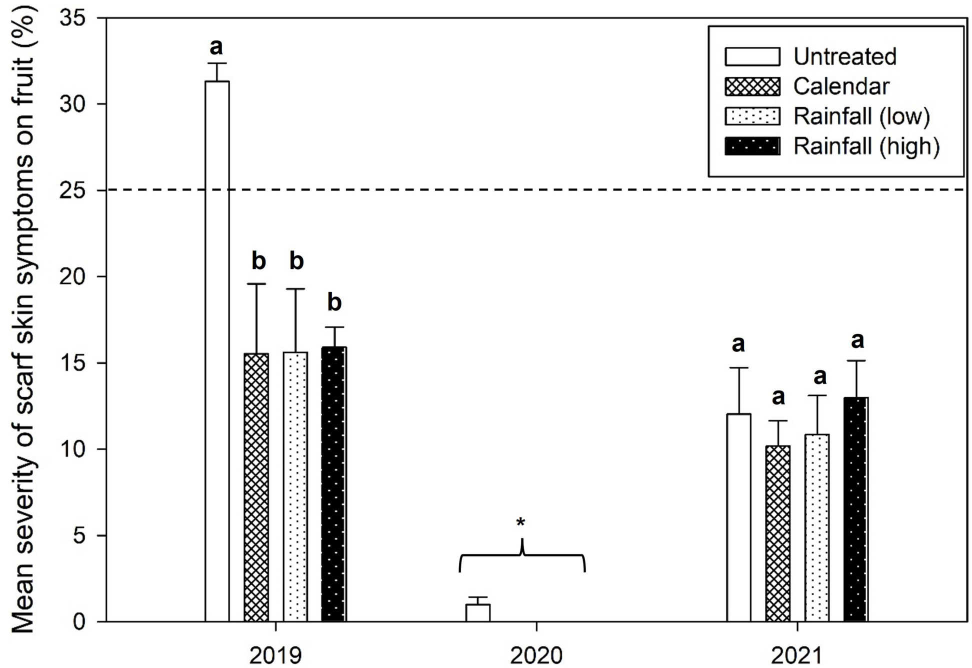

FIGURE 1

Mean severity of scarf skin symptoms on fruit of cultivar NY1 (SnapDragon) for trials conducted in 2019 to 2021 with experimental ProVide 10SG high- and low-rate programs. GA_{4+7} applications started at petal fall and were made after rainfall events of suitable magnitude. Also included was a high-rate 'Calendar' standard program following label recommendations and an untreated control. The dashed line indicates an aggregated 25% scarf skin severity, the threshold used for a grade of "U.S. No. 1" with respect to fruit russet (McArtney et al. 2006). Within each year, different letters above bars indicate significant differences between means based on a Tukey honestly significant difference test ($P < 0.05$). (*) The mean scarf severity on fruit and mean number of out-of-grade fruit due to the disorder was 1% or less among all treatments for the 2020 trial year, which was not suitable for meaningful statistical analysis.

TABLE 1

Mean severity of apple scarf skin symptoms, mean incidence of out-of-grade fruit, and horticultural data recorded from the cultivar NY1 trial at Cornell AgriTech, Geneva, NY, in 2019 to 2021

Program (rate)	Cumulative number of GA_{4+7} applications	Mean severity (%)	Mean incidence of out-of-grade fruit (%)[y]	Mean number of fruit	Mean tree yield (kg)	Mean fruit weight (g)	Mean fruit length (mm)	Mean fruit diameter (mm)
2019								
Untreated	0	31.32 ± 1.04 a	65.15 ± 1.52 a	14.5 a	2.98 ± 0.72 a	205.50 ± 0.05 a	64.29 ± 0.49 a	71.96 ± 0.52 a
Calendar (high; 247 g/ha)	4	15.54 ± 4.03 b	24.48 ± 4.79 b	15.7 a	3.20 ± 0.56 a	204.04 ± 6.09 a	68.36 ± 1.01 a	74.74 ± 0.85 a
Rainfall (low; 148 g/ha)	2	15.62 ± 3.66 b	30.73 ± 7.70 ab	17 a	3.05 ± 0.29 a	180.82 ± 8.04 a	66.49 ± 0.64 a	73.14 ± 0.13 a
Rainfall (high; 247 g/ha)	2	15.90 ± 1.15 b	27.62 ± 1.51 b	16.8 a	3.18 ± 0.60 a	193.43 ± 5.67 a	68.46 ± 0.58 a	74.55 ± 0.47 a
2020[z]								
Untreated	0	1.00 ± 1.00	0 ± 0	14.20 ± 6.59 a	2.70 ± 1.14 a	207.73 ± 20.50 a	68.78 ± 2.68 a	75.02 ± 2.06 a
Calendar (high; 247 g/ha)	4	0 ± 0	0 ± 0	19.70 ± 3.02 a	3.40 ± 0.49 a	184.8 ± 11.40 a	68.52 ± 1.40 a	73.70 ± 1.15 a
Rainfall (low; 148 g/ha)	1	0 ± 0	0 ± 0	22.66 ± 3.78 a	3.77 ± 0.61 a	166.38 ± 9.16 a	65.04 ± 0.45 a	70.38 ± 0.60 b
Rainfall (high; 247 g/ha)	1	0 ± 0	0 ± 0	17.0 ± 3.60 a	3.06 ± 0.55 a	190.72 ± 10.15 a	67.03 ± 0.86 a	72.07 ± 0.92 ab
2021								
Untreated	0	12.74 ± 2.03 a	27.18 ± 6.30 a	23 a	5.52 ± 0.91 a	241.56 ± 3.06 a	61.75 ± 0.82 a	66.48 ± 1.01 a
Calendar (high; 247 g/ha)	4	10.17 ± 0.99 a	22.82 ± 5.51 a	21.7 a	4.91 ± 1.01 a	215.49 ± 2.70 a	63.54 ± 0.63 a	67.02 ± 0.44 a
Rainfall (low; 148 g/ha)	1	10.13 ± 2.22 a	17.27 ± 6.21 a	15.7 a	2.78 ± 0.54 a	179.84 ± 7.40 a	63.71 ± 1.02 a	67.22 ± 0.81 a
Rainfall (high; 247 g/ha)	1	12.97 ± 2.41 a	27.02 ± 4.57 a	21 a	4.79 ± 1.16 a	217.7 ± 3.03 a	63.91 ± 1.05 a	68.04 ± 0.97 a

[y] Out-of-grade fruit is defined as fruit having > 25% coverage of the scarf skin disorder. Values within columns for a given year followed by a different letter are significantly different ($P < 0.05$) according to the LSMEANS procedure in SAS 9.4 with an adjustment for Tukey's HSD to control for family-wise error.

[z] The mean scarf severity on fruit and mean number of out-of-grade fruit due to the disorder was 1% or less among all treatments for the 2020 trial year, which were not suitable for meaningful statistical analysis.

mean fruit diameter of the PGR programs was significantly different from that of the untreated fruit, but the reduction in size was not biologically impactful ($P < 0.05$) (Table 1).

Evaluation of a GA_{4+7} program with applications timed preemptively to rainfall events

In 2020, the observed mean scarf skin severity on Gala fruit was 12.67%. Trees receiving four GA_{4+7} low- or high-rate applications timed to a calendar program (applied at 0, 10, 20, and 30 DAPF) had a recorded 7.54 and 9.92% mean scarf skin severity at harvest, which was not significantly different than the untreated control ($P > 0.05$) (Fig. 2; Table 2). Trees receiving either the low- or high-rate GA_{4+7} applications made after rainfall thresholds also did not have significantly lower severity of scarf skin on fruit (13.72 and 9.05%, respectively) compared with the untreated control ($P > 0.05$), and only one total PGR application was made at 26 DAPF (Fig. 2; Table 2). The mean percentage incidence of out-of-grade fruit was not significantly different for any program receiving GA_{4+7} applications from that of the untreated control (Table 2).

In 2021, the observed mean scarf skin severity on untreated fruit was 29.89%. For both treatment programs timing GA_{4+7}

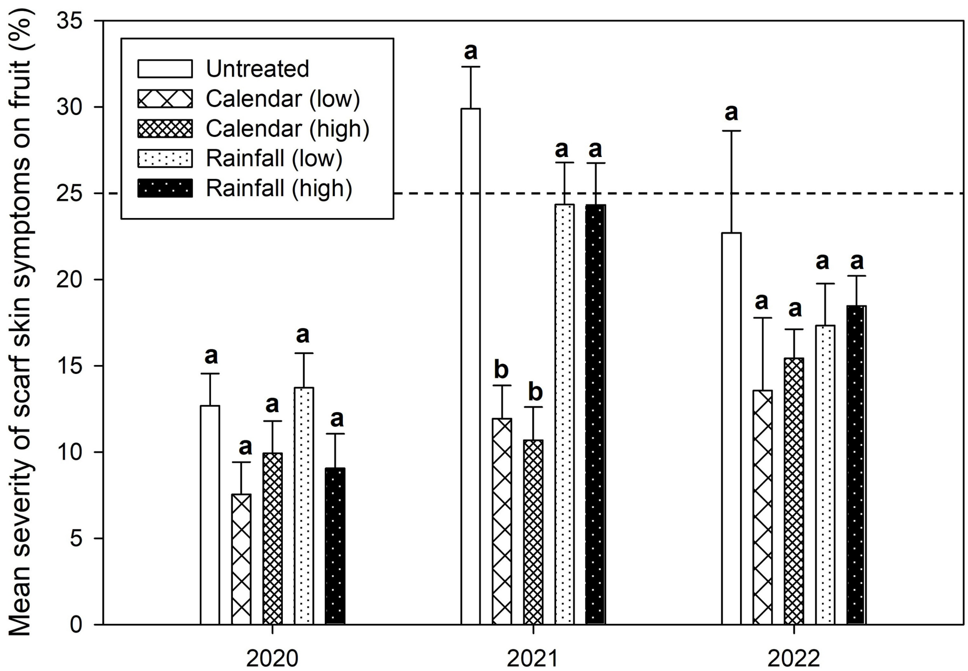

FIGURE 2

Mean severity of scarf skin symptoms on fruit of cultivar Gala for trials conducted in 2020 to 2022 with experimental ProVide 10SG high- and low-rate programs. GA_{4+7} applications started at petal fall and were made prior to rainfall events of suitable magnitude. Also included were low- and high-rate 'Calendar' standard programs following label recommendations and an untreated control. The dashed line indicates an aggregated 25% scarf skin severity, the threshold used for a grade of "U.S. No. 1" with respect to fruit russet (McArtney et al. 2006). Within each year, different letters above bars indicate significant differences between means based on a Tukey honestly significant difference test ($P < 0.05$).

TABLE 2

Mean severity of apple scarf skin symptoms, mean incidence of out-of-grade fruit, and horticultural data recorded from the cultivar Gala trial in 2020 to 2022

Program (rate)	Cumulative number of GA_{4+7} applications	Mean severity (%)	Mean incidence of out-of-grade fruit (%)[z]	Mean number of fruit	Mean tree yield (kg)	Mean fruit weight (g)	Mean fruit length (mm)	Mean fruit diameter (mm)
2020								
Untreated	0	12.67 ± 2.34 a	19.21 ± 6.59 a	55 a	8.98 ± 2.09 a	172.07 ± 13.30 a	66.18 ± 1.23 a	70.51 ± 0.89 a
Calendar (low; 148 g/ha)	4	7.54 ± 1.94 a	11.11 ± 2.73 a	68.25 a	11.31 ± 4.31 a	169.67 ± 6.62 a	68.26 ± 0.97 a	71.64 ± 0.67 a
Calendar (high; 247 g/ha)	4	9.92 ± 1.13 a	13.66 ± 1.49 a	30.75 a	5.76 ± 2.02 a	195.48 ± 13.76 a	70.72 ± 1.46 a	74.22 ± 0.77 a
Rainfall (low; 148 g/ha)	1	13.72 ± 0.59 a	23.54 ± 3.06 a	53.5 a	9.54 ± 1.56 a	179.45 ± 4.14 a	68.08 ± 0.54 a	73.76 ± 0.68 a
Rainfall (high; 247 g/ha)	1	9.05 ± 2.49 a	11.91 ± 4.27 a	52.75 a	8.91 ± 1.47 a	175.55 ± 10.30 a	67.49 ± 1.30 a	72.23 ± 0.76 a
2021								
Untreated	0	29.89 ± 1.82 a	62.74 ± 6.03 a	69.5 a	11.93 ± 2.74 a	170.14 ± 3.16 b	69.22 ± 0.57 ab	72.09 ± 0.92 a
Calendar (low; 148 g/ha)	4	11.93 ± 2.67 b	19.41 ± 4.76 b	72 a	14.83 ± 1.95 a	211.78 ± 13.14 a	73.99 ± 1.95 ab	74.73 ± 1.09 a
Calendar (high; 247 g/ha)	4	10.68 ± 0.77 b	19.99 ± 2.25 b	90 a	19.34 ± 3.63 a	220.82 ± 8.68 a	75.69 ± 1.39 a	76.27 ± 1.40 a
Rainfall (low; 148 g/ha)	1	24.33 ± 1.84 a	50.84 ± 1.26 a	102.5 a	20.27 ± 1.81 a	198.64 ± 3.07 ab	72.96 ± 0.88 ab	74.77 ± 0.40 a
Rainfall (high; 247 g/ha)	1	24.31 ± 3.32 a	45.31 ± 7.63 a	92.75 a	17.88 ± 3.09 a	195.8 ± 5.90 ab	73.00 ± 1.34 ab	74.97 ± 1.54 a
2022								
Untreated	0	22.69 ± 5.92 a	53.18 ± 16.72 a	16.25 a	3.08 ± 1.07 a	185.8 ± 7.13 a	69.34 ± 1.70 a	68.71 ± 1.20 a
Calendar (low; 148 g/ha)	4	13.56 ± 4.21 a	25.27 ± 10.66 a	21 a	4.14 ± 0.50 a	198.2 ± 1.15 a	71.37 ± 0.65 a	69.72 ± 0.51 a
Calendar (high; 247 g/ha)	4	15.43 ± 1.68 a	18.69 ± 9.83 a	9 a	1.82 ± 1.39 a	187.0 ± 12.0 a	70.53 ± 1.32 a	67.35 ± 0.37 a
Rainfall (low; 148 g/ha)	2	17.33 ± 2.42 a	29.67 ± 8.21 a	23.75 a	4.57 ± 1.68 a	197.8 ± 12.0 a	71.61 ± 1.49 a	69.43 ± 0.96 a
Rainfall (high; 247 g/ha)	2	18.46 ± 1.73 a	15.79 ± 15.79 a	7.33 a	1.51 ± 1.25 a	194.1 ± 22.0 a	72.62 ± 3.45 a	69.22 ± 3.16 a

[z] Out-of-grade fruit is defined as fruit having >25% coverage of the scarf skin disorder. Values within columns for a given year followed by a different letter are significantly different ($P < 0.05$) according to the LSMEANS procedure in SAS 9.4 with an adjustment for Tukey's honestly significant difference to control for family-wise error.

applications to rainfall—for which only one PGR application was made during the early season at 26 DAPF—the observed mean scarf skin severity at harvest was 24.33% for the low-rate program and 24.31% for the high-rate program and not significantly different from the untreated control ($P > 0.05$) (Fig. 2; Table 2). Trees receiving four GA_{4+7} applications under either the low- or high-rate calendar programs (applied at 0, 10, 20, and 30 DAPF) had a recorded 11.93 and 10.68% mean scarf skin severity, respectively. These mean scarf skin severities were significantly lower than those of the untreated control and rainfall programs ($P < 0.05$) (Fig. 2; Table 2). The mean percentage incidence of out-of-grade fruit was 62.74% for the untreated control and 50.84 and 45.31% for the respective low- and high-rate rainfall programs. Only the calendar-based programs had significantly different incidence of out-of-grade fruit, 19.41% for the low rate and 19.99% for the high rate ($P < 0.05$) (Table 2).

In 2022, the severity of scarf skin on untreated fruit was 22.69%. The scarf skin severity observed on any treatment was not significantly different from that of the untreated control ($P > 0.05$). The severity observed was 13.56% for the low-rate calendar program, 15.53% for the high-rate calendar program, 17.33% for the low-rate rainfall program, and 18.46% for the high-rate rainfall program (Fig. 2; Table 2). The precipitation events during the early growing season of 2020 triggered only two GA_{4+7} applications for the rainfall programs at 20 and 30 DAPF, whereas the calendar program received the typical four GA_{4+7} applications at 0, 10, 20, and 30 DAPF (Table 2). The programs receiving any GA_{4+7} applications also had no difference in out-of-grade fruit compared with the untreated control, which was 53.18% (Table 2). The additional analysis conducted also showed there was a significant interaction between season (year) and the GA_{4+7} programs for application timing ($F_{4,8} = 14.36$, $P < 0.0001$) (Supplementary Table S1).

In all years (2020 to 2022) for this trial, recorded observations of most horticultural parameters (mean number of fruit, tree yield, fruit weight, fruit length) that might have been influenced by GA_{4+7} applications were not significantly different from those of the untreated control trees and fruit (Table 2). Note that in 2021, the mean fruit diameter of the PGR programs was significantly different from that of the untreated fruit, but the reduction in size was not biologically impactful ($P < 0.05$) (Table 2).

Evaluation of a GA_{4+7} program with applications timed preemptively to rainfall events (commercial trial NY1s)

In 2021, the observed mean scarf skin severity on NY1 fruit was 5.22% (Fig. 3; Table 3). Trees receiving four GA_{4+7} low- or high-rate applications timed to a calendar program (applied at 0, 10, 20, and 30 DAPF) had a recorded 4.43 and 3.91% mean scarf skin severity at harvest, which was not significantly lower compared with the untreated control ($P > 0.05$) (Fig. 3; Table 3). Trees receiving either the low- or high-rate GA_{4+7} applications made after rainfall thresholds also did not have significantly lower scarf skin severity on fruit (4.72 and 4.14%, respectively) compared with the untreated control ($P > 0.05$), but note that no GA_{4+7} applications were ever made (as precipitation thresholds never called for any) (Fig. 3; Table 3).

In 2022, the observed mean scarf skin severity on untreated fruit was 18.34% (Fig. 3; Table 3). For both treatment programs timing GA_{4+7} applications to rainfall—for which only one GA_{4+7} application was made during the early season at 0 DAPF—the observed mean scarf skin severity at harvest was 12.2% for the low-rate program and 9.13% for the high-rate program, the latter which was not significantly different from the untreated control (Fig. 3; Table 3). Trees receiving four GA_{4+7} applications under either the low- or high-rate calendar programs (applied at 0, 10, 20, and 30 DAPF) had 4.69 and 14.9% mean scarf skin severity, respectively. The severity observations from the low-rate calendar program and the high-rate rainfall programs were significantly lower compared with those of the untreated control ($P < 0.05$) (Fig. 3; Table 3).

In both 2021 and 2022, recorded observations of horticultural parameters (mean fruit length, mean fruit diameter) that might have been influenced by GA_{4+7} applications were not significantly different from the fruit of the untreated control ($P > 0.05$) (Table 3).

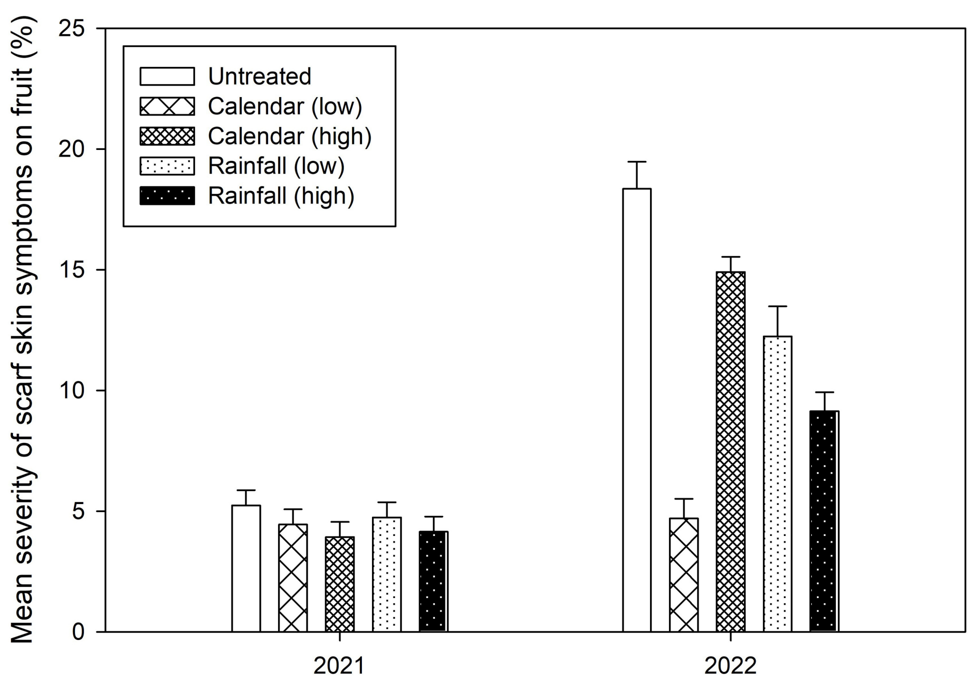

FIGURE 3 Mean severity of scarf skin symptoms on fruit of cultivar NY1 (SnapDragon) from a commercial orchard for trials conducted in 2021 and 2022 with experimental ProVide 10SG high- and low-rate programs. GA_{4+7} applications started at petal fall and were made prior to rainfall events of suitable magnitude. Also included were low- and high-rate 'Calendar' standard programs following label recommendations and an untreated control. Within each year, different letters above bars indicate significant differences between means based on a Tukey honestly significant difference test ($P < 0.05$).

Discussion

The results of our three multi-year GA_{4+7} trials did not provide sufficient evidence that the rainfall-based management program designs described here would reliably reduce scarf skin severity and the incidence of out-of-grade fruit. With respect to GA_{4+7} applications timed after threshold-breaking rainfall events, the initial 2019 trial on NY1 did generate promising data, indicating that 'Rainfall' programs (with either a high- or low-rate application of GA_{4+7}) managed scarf skin severity as well as the high-rate 'Calendar' program yet used two fewer GA_{4+7} applications. These 'Rainfall' programs resulted in fruit with an approximate 15% mean severity of scarf skin, below the 25% threshold indicated to delineate a grade of "U.S. No. 1" (McArtney et al. 2006). However, repeated trials in 2020 and 2021 did not reproduce these results. In 2020, scarf skin never manifested in any appreciable amount (<1%), and in 2021, the amount of disorder observed on the fruit of the untreated control was well below (approximately 10 to 12%) the 25% threshold known to lead to economic losses at harvest, so no meaningful comparisons could be drawn.

With respect to GA_{4+7} applications timed prior to forecasted threshold-breaking rainfall events, the trial conducted in our Gala orchard had variable results as well. In 2020 and 2022, there was no significant difference in mean scarf skin severity or in the incidence of out-of-grade fruit between any of the PGR programs and the untreated control treatment. In addition, the mean severity observed for any treatment program using GA_{4+7} was well below (approximately 7.5 to 18%) the 25% target. However, in 2021, both the low- and high-rate 'Calendar' programs adequately managed the disorder, whereas the 'Rainfall' programs had little effect, with a mean severity at approximately 25%. For the trial conducted in a commercial orchard of NY1, there was also no significant difference in scarf skin severity between any of the PGR programs and the untreated control in 2021. In 2022, the low-rate 'Calendar' program and both low- and high-rate 'Rainfall' programs reduced scarf skin severity compared with the untreated. However, in both years, mean severity never exceeded 15% among all GA_{4+7} treatment programs.

The results of our multi-year trials may indicate that either (i) rainfall does not have as impactful a role in scarf skin development compared with other external environmental factors or (ii) that the rainfall thresholds we defined for use in the experimental 'Rainfall' programs to trigger GA_{4+7} applications (either before or after the rain event) were not the best thresholds for timing applications to manage scarf skin. Considering the variable success observed even within the commercial standard low- and high-rate 'Calendar' programs for all (e.g., sometimes they worked, sometimes they did not), as well as the vast variation in scarf skin that appeared on untreated fruit from year to year, we can conclude that the factors influencing scarf skin development are myriad and complex. Indeed, in our 2020 to 2022 Gala trials, we observed a significant interaction between season (year) and the GA_{4+7} programs for application timing.

In general, it appears that making the recommended four GA_{4+7} applications is better than doing nothing to manage scarf skin. In years where scarf skin is not going to develop to be an economically impactful problem at harvest (i.e., <25% severity), the use of GA_{4+7} applications is indeed a loss. However, in years when scarf skin develops and GA_{4+7} applications are absent, the impact on fruit quality may be severe. Given the uncertainties of the disorder's manifestation tendencies year-to-year, making GA_{4+7} applications as a prophylactic approach would ensure the best possible returns on investment for a grower's apple crop and also manage other finish disorders, such as russet or cracking.

Considering the continued lack of a clear understanding of the factor(s) influencing scarf skin development in the literature (Winkler et al. 2022), more research is needed to better understand and manage this disorder. Future work may consider management programs using GA_{4+7} applications timed to other environmental thresholds deemed impactful. Indeed, canopy and fruit microclimate humidity and/or surface moisture may be a more critical variable influencing scarf skin development, as evidenced by prior work showing that bagging fruit just after petal fall reduced surface moisture and produced fruit with reduced scarf skin at harvest (Ferree and Schmid 1986; Ferree et al. 1984b). Byers (1977) reported that the disorder was more severe on fruit positioned lower and closer to the trunk within the canopy than elsewhere. Experimentation is needed, but GA_{4+7} applications directed into these sections of the orchard canopy may better manage scarf skin. Alternatively, direct measures of leaf wetness duration (LWD)—or the simpler LWD models predicted from readily available relative humidity data as more recently advocated by Rowlandson et al. (2015)—may also be worth consideration from which to investigate scarf skin and to design management programs. This has been successful for management of fruit surface pathogens such as sooty blotch and flyspeck, and the

TABLE 3

Mean severity of apple scarf skin symptoms and horticultural data recorded from the cultivar NY1 trial at a commercial orchard in Appleton, NY, in 2021 and 2022[z]

Program (rate)	Cumulative number of GA_{4+7} applications	Mean severity (%)	Mean fruit length (mm)	Mean fruit diameter (mm)
2021				
Untreated	0	5.22 ± 0.75 a	63.16 ± 0.51 a	66.32 ± 0.57 a
Calendar (low; 148 g/ha)	4	4.43 ± 0.63 a	65.50 ± 0.21 a	67.11 ± 0.47 a
Calendar (high; 247 g/ha)	4	3.91 ± 0.43 a	60.82 ± 2.62 a	64.63 ± 2.41 a
Rainfall (low; 148 g/ha)	0	4.72 ± 0.76 a	61.97 ± 0.28 a	67.45 ± 0.66 a
Rainfall (high; 247 g/ha)	0	4.14 ± 0.49 a	62.90 ± 0.43 a	66.13 ± 0.51 a
2022				
Untreated	0	18.34 ± 1.12 a	72.34 ± 0.65 a	67.30 ± 0.43 a
Calendar (low; 148 g/ha)	4	4.69 ± 0.82 d	70.01 ± 0.73 a	64.86 ± 0.79 a
Calendar (high; 247 g/ha)	4	14.9 ± 1.33 ab	73.94 ± 0.94 a	67.31 ± 0.74 a
Rainfall (low; 148 g/ha)	1	12.2 ± 1.25 bc	70.42 ± 0.85 a	65.65 ± 0.35 a
Rainfall (high; 247 g/ha)	1	9.13 ± 0.79 c	70.36 ± 0.70 a	65.44 ± 0.42 a

[z] Values within columns for a given year followed by a different letter are significantly different ($P < 0.05$) according to the LSMEANS procedure in SAS 9.4 with an adjustment for Tukey's honestly significant difference to control for family-wise error.

model—helpfully—starts at petal fall (Batzer et al. 2008). Also, another apple skin disorder, "skin spot," is induced by surface wetness occurring during later stages of fruit development and may be useful for future investigation (Winkler et al. 2014).

Rootstock choice may also be a factor influencing the development of apple scarf skin. Apple rootstocks are selected for several factors that they bestow upon their grafted scion, including influence on tree vigor and water uptake (Marini and Fazio 2018). Byers (1977) reported that the fruit of low-vigor trees had less scarf skin than those from high-vigor trees. This tendency was also observed among fruit from young, high-vigor trees (<10 years old) in Germany (Weber and Zabel 2011). Cultivars whose economic marketability is dramatically impacted by the presence of a fruit finish disorder such as scarf skin (e.g., fruit destined for the fresh market) may be better paired with rootstocks that do not promote too-high vigor, providing that the selection for slightly reduced vigor does not have an undue influence on the other marketable traits that make that particular cultivar-rootstock pairing economically valuable. Alternatively, if rainfall influx to the tree is indeed a contributing factor to scarf skin, it could be that rootstocks with increased water flow capacity to the tree leads to a rapid swelling of fruitlets and subsequent strain that promotes scarf skin development—particularly on fruit lower in the canopy closer to the trunk and thus the first to experience water influx.

Another possibility is that fruit skin thickness may be associated with scarf skin susceptibility and could be a factor for consideration of its management. Adjacent work in apple russet has established that cultivars vary in their tendency to develop the disorder (Winkler et al. 2022). In early fruit development, increased numbers of epidermal and hypodermal cells (per unit area) of more uniform sizes are observed in the skin of russet non-susceptible cultivars (Khanal et al. 2020). Indeed, increasing epidermal cell density in fruit with use of GA_{4+7} applications led to a concomitant reduction in russet (Curry 2012). Susceptibility to russet is instead linked to cultivars with apple skin composed of cells that are larger and of variable sizes (Khanal et al. 2020). If these concepts also hold true for scarf skin, it may be that "thin-skinned" cultivars with skin comprising fewer layers of larger, more irregularly sized epidermal and hypodermal cells will manifest scarf skin more readily. The reflection of light from pigmented hypodermal cells into intercellular air spaces below the fruit epidermis is more apparent to the naked eye as gaps in these layers appear as the disorder manifests. Microscopy advances may better support continued scarf skin research. For example, transillumination microscopy becomes unreliable for observation of epidermal cells beyond 6 to 8 weeks of fruit development as cuticle becomes thicker (Curry 2012). Improved techniques leveraged for russet studies to visualize fruit surface topology and disorder effects may provide better insight into the biomechanics and timing of scarf skin manifestation: Pigmentation analysis with the paired digital photography and scanning methodology developed by Grimm et al. (2022) may be one such method, or optical coherence tomography as a useful non-destructive means of observation (Verboven et al. 2013).

The use of regular gibberellin applications in the weeks after petal fall remains the best option for the reduction of scarf skin, as our attempts with GA_{4+7} applications timed to pre- and post-rainfall events were variable. Future work is needed to explore other factors that may have more of an impact on scarf skin development, such as fruit surface moisture or fruit skin thickness. Additionally, a clearer understanding of the mechanical stresses that lead to scarf skin, and how they may be better alleviated, is worth investigation. The considerable body of research on apple russet is useful to draw inspiration, but the differences in the biomechanical origins of these disorders will require specific focus on scarf skin physiology for optimal management. For now, scarf skin will remain a fruit finish disorder that—barring a shift in consumer demand away from the idealized perfect, red apple—will continue to incur economic losses in apple crops produced for the fresh market.

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