Investigation of Potential Causes of Peach Skin Streaking

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Abstract

Peach skin streaking is a previously undescribed skin discoloration affecting red-blush peach cultivars in Georgia and South Carolina. Streaked peach fruit have been observed in the field close to harvest. The cause of streaking is still unknown but one hypothesis is that atmospheric pollutants may be involved. The goal of this study was to establish proof of concept that commonly found air pollutants can produce streaks on peach skin similar to those observed in commercial orchards and investigate the susceptibility of peach fruit during maturation. Common reactive byproducts of atmospheric pollutants, including sulfuric

acid (H₂SO₄), nitric acid (HNO₃), and hypochlorite acid (HCl), at concentrations up to 10 µg/ml did not produce streaking under field conditions when applied at week 3, 2, and 1 prior to commercial harvest. However, sodium hypochlorite (NaClO) in the form of Clorox solution and chlorine dioxide (ClO₂) at 100 µg/ml generated from the Aquamira water treatment solution produced streaking symptoms on detached peach fruit under controlled conditions and in the field. Peach fruit were most susceptible to streaking closest to harvest, suggesting that NaClO and ClO₂ interfere with pigment formation.

Peach skin discolorations can come in various shapes and colors and can severely affect marketable yield; for instance, black staining or inking (Cheng and Crisosto 1994; Crisosto et al. 1993), skin burning (Cantín et al. 2011), and suture red spot (Benson 1959; Drowley et al. 1963). Bright streaks on peach skin is a previously undescribed skin discoloration of red-blush cultivars that was first observed in 2003 at a research station near Byron, GA (P. Brannen, oral communication). Over the last few years, many red-blush cultivars in the southeastern United States were affected. Although symptoms in the form of occasional faint streaks are negligible from a consumer-acceptance point of view, multiple bright streaks on a fruit clearly suggest damage to the peach skin and will make the fruit unmarketable. During summer 2015 and 2016, commercial peach producers in South Carolina reported severely streaked fruit in multiple red-blush cultivars (Fig. 1A to C), including ‘Scarletprince’, ‘Julyprince’, ‘Summergold’, ‘Redglobe’, and ‘Contender’. Streaking was most commonly reported near or at commercial harvest but no damage to leaves was observed in any location.

In the field, streaks start on the top half of the fruit facing the sky and end on the bottom half, following gravity in direction. They lack red color on red-blush cultivars and vary in intensity, length, and width. The intensity of streaks tends to increase from top to bottom to reach maximum intensity and width (3 to 10 mm) near the bottom of the fruit. Streaks end in a club-shaped fashion. In severe cases, the skin turns brown and becomes sunken (Fig. 1C). Streaking is observed in cultivars of similar ripening dates and is observed inside and outside the canopy as well as on the top and bottom of the canopy as long as the fruit remains underneath the foliage. Streaking has been observed frequently in the upstate orchards near Trenton, SC but was also observed at low frequency upstate as well as in one county in Georgia. The cause of streaking is unknown. No fungi or bacteria were isolated from affected areas despite numerous attempts (more than three) by the authors and the Clemson University Plant

Problem Clinic. The current hypothesis is that streaks are caused by as-yet-unidentified chemicals interfering with pigment formation or destroying existing pigments. As small droplets containing the chemicals form by rain or dew on the top half of the fruit, they may increase in size as they run down the fruit. Drops would eventually come to a halt on the bottom half of the fruit, leaving the characteristic club-shaped symptoms after the water evaporates. Photographic evidence of dew droplets forming streaks in commercial orchards has been secured by the authors.

Other hypotheses include damage to peach skin due to atmospheric pollution or season-long accumulation of potential peach-skin-damaging pesticide residues in the canopy when concentrated in rain or dew. Certain pesticides have specifically been pointed out for their ability to cause phytotoxic symptoms, including copper-based fungicides (Lalancette and McFarland 2007), lime sulfur (Holb et al. 2003), diazinon, and captan formulation (Polavarapu 2000). Phytotoxicity on apple cultivars has also been described for single-mode-of-action fungicides, including azoxystrobin (Bazuin 1999; Lalancette et al. 2000) and the mixture of penthiopyrad plus captan (Villani et al. 2015). However, in South Carolina, streaking was observed in both conventional and organic orchards, thus excluding synthetic pesticides as culprits. Air pollution may also affect plant tissue health and several pollutants were shown to cause plant damage under certain circumstances, including ozone (Rich 1964), sulfur dioxide (Malhotra and Khan 1984), fluorine and fluorides (Fornasiero 2001), nitrogen oxides (Naemura et al. 1997), and radicals generated from nitrogen oxides (Kume et al. 2001). Atmospheric ozone, fluorine, and fluorides were reported to cause primarily leaf symptoms (Rich 1964, Fornasiero 2001) but nitrogen oxides and sulfur dioxide react with tiny droplets of water in clouds to form sulfuric and nitric acids, which have been associated with both foliar and fruit tissue damage (Neufeld et al. 1985; Proctor 1983; Rinallo and Mori 1996). Other potent air pollutants include chlorine dioxide (ClO₂) and chlorine ions, which are commonly released from factories such as textile plants (Tiwari and Babel 2013).

The objectives of this study were to (i) identify common atmospheric pollutants that may cause streaking, (ii) reproduce symptoms, and (iii) determine the susceptibility of peach skin to the identified chemicals during fruit maturation prior to harvest.

Materials and Methods

Reagents used to reproduce streaking. Atmospheric acids commonly found in acid rain and reactive, atmospheric molecules suspected to be released from industrial plants in South Carolina were used for this study. Water solutions of acids were prepared as follows: sulfuric acid (H₂SO₄; Fisher C, Hampton, NH) was diluted

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Technical Contribution Number 6561 of the Clemson University Experiment Station.

*The e-Xtra logo stands for “electronic extra” and indicates that one supplementary figure is published online.

Accepted for publication 15 May 2017.

to a final concentration of 0.1 µg/ml (1.02 µM), 1 µg/ml (10.2 µM), 10 µg/ml (102 µM), and 98 µg/ml (1 mM); hydrochloric acid (HCl; Fisher Scientific, Hampton, NH) was diluted to a final concentration of 0.1 µg/ml (2.74 µM), 1 µg/ml (27.4 µM), and 10 µg/ml (274 µM); and nitric acid (HNO₃; ACROS Organics, Geel, Belgium) was diluted to a final concentration of 0.1 µg/ml (1.59 µM), 1 µg/ml (15.9 µM), 10 µg/ml (159 µM), and 63 µg/ml (1 mM). The concentrations of acid solutions in this study were chosen to be below the common acid rain pH range of 4.1 to 5.5 in the United States (Singh and Agrawal 2008). The corresponding pH values of H₂SO₄ and HNO₃ solutions at a concentration of 1 mM were 2.75 and 3.01, respectively. ClO₂ was generated using the Aquamira Chlorine Dioxide Water Treatment kit (Aquamira Technologies, Inc., Logan, UT), according to instructions. Equal amounts of part A and part B solutions were mixed for 5 to 10 min to generate 1% active ClO₂ solution, which was further diluted to 0.1% (1,000 µg/ml), 0.05% (500 µg/ml), 0.01% (100 µg/ml), and 0.001% (10 µg/ml). Sodium hypochlorite (NaClO) solutions were obtained by diluting Clorox (Clorox, Oakland, CA) with water to a final concentration of NaClO of 0.1% (1,000 µg/ml), 0.05% (500 µg/ml), 0.01% (100 µg/ml), and 0.001% (10 µg/ml). The concentrations of ClO₂ and NaClO were chosen based on results of a preliminary detached-fruit assay, in which ClO₂ and NaClO at concentrations of 0.02% or higher produced streaks on peach skin.

Generation of streaking symptoms under field conditions. Two red-blush peach cultivars (Juneprince and Redglobe) were used for experiments. Juneprince ripens in mid-June and Redglobe ripens in mid-July. Chemical reagents, including H₂SO₄ at concentrations of 0.1 µg/ml (1.02 µM), 1 µg/ml (10.2 µM), and 10 µg/ml (102 µM); HCl at concentrations of 0.1 µg/ml (2.74 µM) and 10 µg/ml (274 µM); HNO₃ at concentrations of 0.1 µg/ml (1.59 µM), 1 µg/ml (15.9 µM), and 10 µg/ml (159 µM); ClO₂ solutions at concentrations of 0.1, 0.05, and 0.01%; NaClO solutions at concentrations of 0.1, 0.05, and 0.01%; and H₂SO₄ solutions at concentrations of 0.1, 0.05, and 0.01%, were used for each trial. Mixtures of 0.01% H₂SO₄ + 0.01% NaClO solutions and 0.01% H₂SO₄ + 0.01% NaClO + 10 µg/ml HNO₃ were also included in both field trials. Solutions (approximately 300 µl) of each treatment were pipetted slowly onto the top of peach skin using a 1-ml pipette until drops ran down the fruit along a single path and three to five of the same paths were made on one fruit. Five single-fruit replicates were used per treatment and concentration. For each time point, fruit similar in size

and maturity (visually assessed based on background color) were used. Three experiments were conducted at 1, 2, and 3 weeks prior to commercial harvest. A nonionic surfactant (TN INDUCE; DuPont, Wilmington, DE) at 0.125% was added to all solutions, including the water control, to achieve a slow run-down on the peach skin. All reagents containing chlorine were made fresh in the field immediately prior to application.

Data collection and analysis. Pictures of experimental fruit in the field were taken 1, 3, and 7 days after treatments. For the second trial (Redglobe block), streaking intensity of experimental fruit was evaluated the day of harvest. Peach fruit were assessed visually on a scale from 0 to 5, where 0 = no streaks, 1 = barely visible streaks, 2 = light streaks, 3 = clearly visible streaks, 4 = pronounced streaks but no necrosis, and 5 = pronounced streaks with necrosis in the form of browning and sunken tissue. Fisher's extract test was used to determine whether concentrations or timing of treatments had significant effects on streaking. Analysis of variance and significant difference procedures were conducted using JMP Pro 10.0.0 software (SAS Institute Inc., Cary, NC) and all tests were performed with $\alpha = 0.05$.

Results

Ability of selected air pollutants to cause streaking under field conditions. The chemical reagents used for the field trials were initially tested on detached peach fruit under laboratory conditions. ClO₂ or NaClO at concentrations of 0.02% or higher produced streaks on the skin similar in form and intensity to streaks observed in commercial orchards. Acids including H₂SO₄, HNO₃, or citric acid solutions at concentrations up to 1 mM did not cause visible symptoms on the skin (data not shown). In this study, the same treatments and concentrations were applied on peach skin under field conditions to confirm the results of the detached-fruit assays.

Largely identical results were observed in the Redglobe block. None of the acids, including H₂SO₄, HCl, or HNO₃, at any of the concentrations tested produced streaking (data not shown). Streaking symptoms on peach fruit produced by NaClO and ClO₂ at concentrations of 0.01, 0.05, and 0.1% under field conditions are shown in Figure 2A to F, respectively. The presence and intensity of streaking on peach fruit treated with different concentrations of ClO₂, NaClO, and mixtures of ClO₂, NaClO, and HNO₃ was determined at week 3, 2, and 1 before harvest. Significant differences ($P \leq 0.05$) in intensity of streaking were found between treatments. ClO₂ at 0.1% consistently produced streaking at all three application times and with

Fig. 1. Peach skin streaking with different levels of severity. **A**, Peach skin with light streaks; **B**, peach skin with pronounced streaks; and **C**, peach skin with pronounced streaks plus necrosis (sunken).

increasing intensity as treatments were applied closer to harvest (Table 1). The same trend was observed at the lower dose of 0.05% but streaking intensity was lower. At the lowest dose of 0.01%, streaking was primarily observed when applied closest to harvest (Table 1). NaClO solutions only produced streaks reliably when applied at week 2 and 1 prior to harvest but with less intensity compared with ClO₂ (Table 1). No significant difference ($P \geq 0.05$) was found in streaking occurrence or intensity when 0.01% ClO₂ was applied with or without 0.01% NaClO. Similarly, no significant difference ($P \geq 0.05$) was found when 0.01% NaClO plus 0.01% ClO₂ was applied with or without HNO₃ at 10 µg/ml at all three application times (Table 1). The experiment was repeated on Juneprince with similar results (data not shown).

Preharvest susceptibility of peach fruit to streaking. Significant differences ($P \leq 0.05$) were found in susceptibility of peach fruit to streaking between different applications. Peach fruit exposed to the ClO₂ and NaClO 1 week prior to harvest were most susceptible, and peach fruit exposed to the streaking agent 3 weeks prior to

harvest were least susceptible. At 3 weeks prior to harvest, 62.5, 30, 7.5, and 0% of fruit had no streaking (0 on the visual scale), light streaking (1 to 2 on the visual scale), pronounced streaking (3 to 4 on the visual scale), or pronounced streaking with necrosis (5 on the visual scale), respectively. At 2 weeks before harvest, 42.5, 32.5, 20, and 5% of the fruit, and at 1 week before harvest, 17.5, 47.5, 22.5 and 12.5% of the fruit were rated in those streaking severity categories, respectively (Fig. 3).

Discussion

In this study, neither H₂SO₄ nor HNO₃ solutions at concentrations of 1 mM produced streaking on skin of detached fruit; their corresponding pH values were 2.75 and 3.01, respectively. The highest concentrations of H₂SO₄, HNO₃, or HCl used in the field trials of the present study were at least 100-fold higher than expected atmospheric concentrations. Potential hydrogen (pH) value less than 5.6 is considered acidic (Evans 1984), and Galloway et al. (1982) proposed a pH of 5.0 as a limit of natural contribution. For the United

Fig. 2. Streaking produced by **A to C**, sodium hypochlorite and **D to F**, chlorine dioxide on Redglobe peach fruit under field conditions. **A to C**, Concentrations of sodium hypochlorite applied were 0.1, 0.05, and 0.01%, respectively. **D to F**, Concentrations of chlorine dioxide applied were 0.1, 0.05, and 0.01%, respectively.

Table 1. Severity of streaking on peach fruit Redglobe^a

Week ^c	ClO ₂ concentration (%)			NaClO concentration (%)			Combination ^b	
	0.01*	0.05*	0.10*	0.01	0.05	0.10	NaClO + ClO ₂	NaClO + ClO ₂ + HNO ₃
3	0	0.6	2.8	0	1	0.2	0.2	0.4
2	0.2	2.4	4.2	0.4	0.6	2.2	0.4	0.2
1	1.8	3.8	4.8	0.8	0.6	2	1.8	1

^a An asterisk (*) indicates that a significant difference was detected among the values within the same column based on Fisher's extract test at $\alpha = 0.05$. Numbers indicate mean of severity rating of streaking, where 0 = no streaks, 1 = barely visible streaks, 2 = light streaks, 3 = clearly visible streaks, 4 = pronounced streaks but no necrosis, and 5 = pronounced streaks with necrosis in the form of browning and sunken tissue.

^b Concentrations of NaClO, ClO₂, and HNO₃ used in the combinations were 0.01, 0.01, and 10 µg/ml, respectively.

^c Week before harvest.

States, acid rain pH usually ranges from 4.1 to 5.5 (Singh and Agrawal 2008). Another source of acids may be the spray water. Analysis of the pH of well water used for spray applications on the affected farms revealed pH values between 4.5 and 5.5 (data not shown). It is unlikely, however, that spray water is responsible for the symptoms observed for several reasons. First, air blast applications conducted at commercial farms spray a fine mist of spray solution that typically dries within minutes and does not allow for congregation of large droplets, perhaps with the exception when nozzles get blocked by foliage, which may locally generate some runoff. We would then expect a pattern effect, where streaking would primarily show up at the periphery of the tree canopy. Second, affected farms have since adjusted the pH of spray tank water following our recommendations but streaking symptoms still appeared at similar severity and frequency (G. Schnabel, personal communication). Third, on 10 May 2017, widespread streaking was observed at a farm near Ridge Spring, SC in the early-season 'Carored' peach that had not been sprayed since the first week of March due to low crop load. Although this provides evidence that atmospheric acids or spray water may not contribute to the streaking problem, duration of exposure and peach skin physiology during dew formation may be different from those encountered in our experiments. Thus, we cannot rule out acidic dew as playing a role in streaking formation.

Instead, the atmospheric pollutants ClO_2 and NaClO (majority component in Clorox) at a concentration of 100 $\mu\text{g}/\text{ml}$ produced streaking under field conditions. This provides proof of concept that atmospheric pollutants at relatively low concentrations can cause skin damage on peach. Also, it is possible that lower concentrations may cause streaking when exposure is extended. For example, during morning dew in summer months, temperature is relatively low, humidity is high, and the peach skin may be exposed to these chemicals for many minutes or even hours. In our field assays, the treatment drops were applied during warm and dry conditions and drops typically had disappeared within 15 min. Neither ClO_2 nor NaClO at the tested concentrations caused discoloration on peach leaves (data not shown), which is consistent with our observations in symptomatic commercial blocks. ClO_2 and chlorine are frequently released from textile factory plants and other plants that use them in bleaching processes (Tiwari and Babel 2013). Chlorine is highly active and reacts with water to produce HCl and HClO . Both ClO_2 and Cl_2 atmospheric concentrations are not routinely monitored by the Environmental Protection Agency but total chlorine discharge from existing lightweight aggregate kilns and solid fuel-fired boilers can be as high as 600 and 440 $\mu\text{g}/\text{mlv}^2$, respectively (<http://www1.deq.louisiana.gov/portal/Portals/0/technology/HWC/Final%20Standards.pdf>)

In addition to Cl_2 and ClO_2 , other reactive substances may also be able to cause streaking. Kume et al. (2001) found that OH and NO radicals in polluted dew water may have harmful effects on the photosynthesis of Japanese Red Pine (*Pinus densiflora*). Arakaki et al. (1998, 1999) observed that OH and NO radicals were formed from

the photolysis of nitrite ions (NO_2^-); they suggested that the photolysis of aqueous-phase N (III) (HNO_2 and NO_2^-) plays a significant role in initiating oxidation reactions in dew water. Arakaki et al. (1999) also reported that the average rate of OH radical formation in dew collected on a Teflon sheet was 3.6 times greater than that in the rainwater during the period 1997 to 1998 at Higashi-Hiroshima, Japan. It is possible that light rain accumulates atmospheric or secondary pollutants from the air and deposits them on the leaves or fruit, but it is also possible that dew forming during subsequent cooler temperatures concentrates atmospheric pollutants, leading to fruit skin damage. Analysis of dew collected from orchards with streaked fruit may shed some light on the cause of streaking.

Peach fruit were found to be most susceptible to streaking 7 to 14 days before harvest. At this time, red pigments had not yet fully developed. In contrast, fruit still mostly green in background color and red-pigmented, mature fruit (data not shown) were less susceptible. The data suggest that ClO_2 and NaClO interfere with the pigment formation responsible for red color. Symptom severity and expression were dependent on the dose. At high concentrations, severe symptoms developed on peach skin only hours after exposure whereas, at low concentrations, less severe symptoms appeared after about 3 days. Chlorine is a powerful antimicrobial substance due to its potential oxidizing capacity. In addition to drinking water disinfection (Sisti et al. 1998), there are a number of other commercial uses for chlorine in the food industry, including reduction of microbial populations on the surfaces of raw foods, such as fruit and vegetables, and sanitation of surfaces in food-processing environments (Kotula et al. 1997; Roberts and Reymond 1994; Trinetta et al. 2013). Venkobachar et al. (1977) showed that treatment with chlorine induced the leakage of macromolecules from the cells of *Escherichia coli*, indicating permeability changes of the membrane.

Circumstantial evidence suggests that streaking may be associated with certain weather patterns. Streaking was consistently associated with periods of dry weather followed by a single, light rain event (up to 8.1 mm) close to harvest. For example, heavy streaking was observed in Byron, GA in 2003 after 8.1 mm of rain followed 10 days of no precipitation (Supplementary Fig. S1). In 2015, in the experimental Scarletprince block, 16 days of dry weather was followed by 3.3 mm of rain on 29 June, about 4 days before the first streaked peach fruit were observed in the field. Similar to the 2015 data, streaking occurred in the same area after 10 days of dry weather followed by 5.6 mm of rain in 2016. Moreover, except for the years when streaking was observed, such weather patterns only occurred once in the past 13 years (2003 to 2016; no historical data available before 2003) in the same area where severe streaking was observed in 2015 and 2016. Therefore, it is possible that atmospheric pollutants, pesticides, or leaf exudates were concentrated in the rain or following morning dew and deposited on peach leaves and fruit skin.

In conclusion, we show that some atmospheric pollutants can cause skin damage and our data suggest that streaking may only develop close to harvest, when the fruit skin is most vulnerable. That is consistent with field observations indicating that streaking has only been observed close to harvest during pigment formation. Further studies such as high-performance liquid chromatography analysis of dew or rain water and monitoring of atmospheric total chlorines might shed more light on what molecules cause streaking in southeastern peach orchards.

Acknowledgments

This material is based upon work supported by the United States Department of Agriculture National Institute of Food and Agriculture under project numbers 2014-51181-22377 and SC-1700501. We thank K. Bryson and B. Cox for technical assistance.

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Fig. 3. Severity of streaking on 'Redglobe' peach in relation to exposure timing. Visual ratings are provided in parentheses.

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