Infrequent Occurrence of Peach Skin Streaking and the Role of Rainwater Attributes on Symptom Development

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INFREQUENT OCCURRENCE OF PEACH SKIN STREAKING AND THE ROLE OF RAINWATER ATTRIBUTES ON SYMPTOM DEVELOPMENT

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Plant and Environmental Sciences

by
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Accepted by:
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ABSTRACT

Streaks lacking pigmentation in the skin of red blush cultivars of peaches have impacted many East Coast production areas. The underlying cause of streaking is unclear. Some evidence suggests that streaking may be caused by reactive agents in rainwater. Peach skin streaking was monitored over two consecutive years at a commercial farm with a history of streaking located near Ridge Spring, South Carolina. Six cultivars (two early season, two mid-season, and two late season cultivars) were evaluated each in two locations (LocA and LocB). Among those 12 experimental block cultivars, streaking occurred only in 2017 in cv. Scarletprince of LocA with an incidence of 6%. That same year two nearby non-experimental blocks with cv. Scarletprince revealed 11% and 25% streaking. Streaking was also monitored at the Musser Fruit Research Center (MFRC) in Seneca, SC. At that location, a high incidence of streaking was observed with 50% and 64% in cvs. Julyprince (2017) and Carored (2018), respectively. Rainwater pH taken from each of the 12 experimental blocks ranged from 3.03 to 7.4, ozone (O₃) levels ranged from <0.02 to 0.37 mg/l, and chlorine (Cl₂) and chlorine dioxide (ClO₂) levels were either just above or under the detection limit of 0.01 mg/l and 0.02 mg/l, respectively. Although the electrical conductivity (EC) was below 100 μS/cm on average, we measured EC values as high as 1500 μS/cm. For all samples, the oxidation-reduction potential (ORP) ranged from 90 to 302 mV, indicating oxidizing conditions. Fruit harvested one or two weeks prior to commercial maturity and treated with solutions of high (10) or low (3) pH, ozone >0.37 mg/l and EC values of up to 3000 μS/cm did not produce symptoms. However, streaking was reproduced with collected rainwater, but the
remaining sample volume did not allow further analyses. Using 0.05% ClO₂ to induce streaking, we show that fruit of different cultivars varied in susceptibility when treated one week prior to commercial maturity with cv. Juneflame being the most susceptible and cv. August Lady being the least susceptible. Our study shows that multiple factors determine the occurrence of streaking in peach orchards, including cultivar susceptibility, ripening stage, and the presence of rainwater with sufficient amounts of a yet unknown reactive agent or agent combination.
DEDICATION

To my grandfather who I hope would be proud to see where I am today.
ACKNOWLEDGMENTS

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I would also like to thank my committee members Dr. Juan Carlos Melgar and Dr. Sarah White for their valuable input and expertise over the past two years.

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CHAPTER ONE

LITERATURE REVIEW

Peach Production and Fruit Quality

Peaches [Prunus persica (L.) Batsch] are an important commodity and are among the top twelve of fruit produced worldwide (Statista 2016). In the United States the peach industry grosses close to $600 million annually, with peaches being produced in 23 states on more than 90,000 acres (USDA-NASS 2018a, 2018b). South Carolina is the second largest peach producing state after California, followed by Georgia and New Jersey (USDA-NASS 2017). High-quality fruit are considered for the fresh market, while fruit of lower quality are processed for canning or freezing. In 2017, 45% (310,480 tons) of the utilized U.S. production (690,100 tons) was marketed fresh, while the remaining 55% (379,620 tons) were processed (USDA-NASS 2018a).

The quality of peach fruit greatly influences consumer acceptance and market value and depends on characteristics such as appearance, flavor and texture (Abbott 1999). Yet peach fruit quality is a subjective concept as these traits differ in importance between parties along the retail chain. The three decisive properties seem to be ‘size’, which relates to yield, ‘color’ which translates into visual appeal, and ‘firmness’ which is associated with shelf-life (Layne and Bassi 2008). Therefore, the peach industry prefers to grow large and red fruit without defects or blemishes. Fruit of lesser quality, including smaller and misshapen fruit, will be marketed at a lower price or may even be rejected by the retailer. Fruit that are deemed unsuitable for fresh consumption may be processed. The USDA Agricultural Marketing Service has compiled a grading system for fresh
market and processed peaches which categorizes fruit according to maturity, color, shape and physical defects from pests or mechanical damage (USDA Agricultural Marketing Service 2004).

**Maturation and color development of peach.** A peach may be considered mature if its attributes are acceptable to the consumer (LaRue & Johnson 1989). Peaches are climacteric fruit for which ripening is accompanied by increased ethylene production and cellular respiration (Layne & Bassi 2008; Tonutti et. al. 1991). Biosynthesis of ethylene correlates to the expression of genes related to color development, sugar accumulation and flesh softening (Ruperti et. al. 2002). Red overcolor of peach is a result of chlorophyll reduction and accumulation anthocyanins and carotenoids (Erez & Flore 1986; Minas et al. 2018). Loss of fruit firmness is induced by solubilization of pectin and a decrease in cellulose (Lewallen & Marini 2003; Pressey & Avants 1973). Fruit that is firm when picked may bruise less during postharvest handling and may have a longer shelf life (Layne 2007). However, fruit harvested early may have lower organoleptic qualities. During fruit maturation internal properties including concentration of soluble solids and volatile compounds are also altered.

**Factors Influencing Crop Quality**

Agronomic and environmental factors throughout production determine final fruit quality (Crisosto et. al. 1995). Growing high quality peaches starts with selection of the cultivar since a genotype correlates to attributes including color and taste. Moreover, cultivars are selected based on their performance in a certain environment and need to be
suitable for the local soil and climate conditions (Frecon et. al. 2002; Layne and Bassi 2008). Rootstocks may confer reduced sensitivity to pathogens but may also influence yield, size and sensory attributes (Jiménez et al. 2004; Nyczepir et. al. 1999). Fruit quality generally declines after harvest (Minas et. al. 2018).

**Environmental factors.** Moreover, crop status and quality are impacted by the respective growing environment. Abiotic factors including light, temperature, water availability, and particularly extremes of such, may negatively affect plant performance. Stress inducing conditions such as drought, heat or soil salinity may alter physiological processes that determine yield, nutritional value and appearance (Wang and Frei 2011). Excess absorption of light may trigger photooxidative reactions and damage plant tissues (Demmig-Adams and Adams 1992). Color development in ripening fruit, i.e. synthesis of anthocyanins, is related to light availability (Arakawa 1988; Minas et. al. 2018). In apples, altered pigmentation may be a result of light stress (Merzlyak and Chivkunova 2000). In addition to ripening, light exposure also impacts fruit size and shelf life. Peach fruit grown under a high light environment maybe less prone to internal break down during storage compared to fruit grown under a low light environment (Layne and Bassi 2008).

Morphological, physiological and biochemical processes in plant tissues are a function of temperature (Moretti et. al. 2010). Extreme temperatures can significantly impact crop quality by imposing changes on photosynthesis and respiration but also plant hormone and metabolite levels (Moretti et. al. 2010). Fruit development strongly depends on temperature (Corelli-Grappadelli and Lakso 2004). During dormancy, low
temperatures are necessary for accumulation of chill hours. Temperatures below 0°C close to bud break may severely damage peach trees (Carbone and Schwartz 1993). In 2007 and 2017, South Carolina growers experienced substantial crop losses of up to 90% due to spring frost (Southeast Farm Press 2017). High temperatures following bloom are essential for fruit development of apples (Warrington et. al. 1999); however, one study on peaches suggests that high temperatures immediately after bloom may limit translocation of nutrients during fruit development resulting in smaller fruit (Lopez and DeJong 2007). Prolonged heat may injure fruit crops and fruiting vegetables directly by causing sunburn (Ernest 2016). Sunburn impacts apples quality in the form of necrosis and browning (Schrader et. al. 2003).

**Atmospheric pollutants.** Injury in the form of foliar discoloration, and reduced growth may be induced by air pollution. Such damage may lower the quality, productivity and economic value of field grown and ornamental crops (Ormrod 1978). For symptoms to occur, a susceptible plant must be exposed to the pollutant at a harmful concentration over a certain period of time (Ormrod 1978). Therefore, symptom severity and reduction in marketability are highly variable and difficult to quantify. Acute symptoms are the result of short-term exposure to high pollutant concentration, while chronic injury may appear after prolonged exposure to low concentrations (Mackenzie and El-Ashry 1989). Pollutants are taken up via gas exchange during stomatal opening under light conditions (Guderian 1977). Common atmospheric pollutants include sulfur dioxide (SO₂), nitrogen oxides (NOₓ), ozone (O₃) and fluorides (F) with vegetative injury often occurring on a localized scale (Emberson et. al. 2003). Atmospheric pollutants are
generated from combustion of fossil fuels, smelters, and power plants amongst others (Mackenzie and El-Ashry 1989).

Sulfur dioxide adversely affects various types of plants including conifers, ornamentals and vegetable crops (Adepipe et. al. 1972; Costonis 1970; Tingey et. al. 1971). Exposure of susceptible plants to 0.25 ppm SO₂ for more than eight hours can induce chlorosis of the leaf margins and interveinal necrosis (Sikora and Chappelka 2004). Uptake of SO₂ and degree of injury were greater at 70% RH compared to 40% RH high humidity (Norby and Kozlowski 1982). Conifers such as eastern white wine (Pinus strobus) are especially sensitive to SO₂ and can serve as indicators of forest decline due to SO₂ pollution (Costonis 1970; Linzon 1971). While fruit quality of tomato (Solanum lycopersicum) is not directly affected by SO₂, yield may be reduced by as much as 18% (Heggestad et. al. 1986). The fresh and dry weight of radish (Raphanus sativus L.) decreased when exposed to 5 pphm SO₂ for 40 h per week for 5 weeks (Tingey et al. 1971). In floriculture crops such as begonia (Begonia L.) and petunia (Petunia Juss.), SO₂ may cause stunting and reduce flower number, lowering marketability (Adepipe et. al. 1972).

Nitrogen oxides including nitric oxide (NO) and nitrogen dioxide (NO₂) may negatively impact plant health at high concentrations but normally do not cause visible injury (Emberson et al. 2003; Rowland et. al. 1985). Crop productivity may be lessened if plants exposed to NOₓ and other pollutants like SO₂ and O₃ simultaneously (Amundson & Maclean 1982). However, several studies promote the benefits of NO treatment at 5 – 40 µl l⁻¹ for 2 h to improve the shelf life of various fruits including peach, strawberries
and mango (Siti and Singh 2011; Wills et. al. 2000; Zhu et. al. 2006). Nitric oxide retards postharvest fruit ripening by suppressing the biosynthesis of ethylene (Manjunatha et. al. 2012).

Exposure to O$_3$ may significantly reduce yields of important agricultural crops like soybean, maize and wheat (Avnery et. al. 2011). Ozone is formed by the reaction of NO$_x$ with volatile organic compounds (Moretti et al. 2010; Saitanis et. al. 2015). The symptoms of O$_3$ damage include chlorosis, mottling and impaired bud formation; but sensitivity varies among plants (Sikora and Chappelka 2004). For sensitive potato varieties, O$_3$ exposure can reduce yields by 50% (Heggestad 1973). On peach seedlings, O$_3$ concentrations as low as 60 ppb may impair photosynthesis and cause a substantially reduction of leaf epidermal thickness (Dai et al. 2017).

Occurrence of vegetative damage as a result of chlorine (Cl$_2$) or hydrogen chloride (HCl) pollution is limited to the proximity of the emission source (Hindaw 1968). Pollutant sources include facilities associated with water-purification and sewage disposal but also manufacturing processes where HCl is formed as a byproduct (Endreess et. al. 1978; Heck et al. 1980; Lerman et. al. 1976a; Sikora and Chappelka 2004). One study reports injury of various crops including radish, soybean [Glycine max (L.) Merr.], tomato and corn (Zea mays) from exposure to less than 10 ppm for 60 minutes (Heck et al. 1980). Plants with extensive epicuticular waxes show decreased susceptibility to HCl exposure (Swiecki et. al. 1982). Symptoms of chlorine pollution like interveinal necrosis or foliar bleaching may be mistaken for injury due to SO$_2$ (Sikora and Chappelka 2004).
On peaches, chlorination may improve postharvest quality and storability (Wells and Bennett 1976).

In addition to gaseous uptake, air pollutants may also be deposited on vegetation via rainwater in the form of soluble derivatives such as sulfuric acid (H₂SO₄) and nitric acid (HNO₃) (Likens et al. 1979). Acid rain is characterized by a pH below 5.6 and has the potential to affect marketability by reducing yield and causing visual defects on several crops (Lee et al. 1981). In one study, yield of five crops including radish, beet (Beta vulgaris), carrot [Daucus carota L. var. sativus Hoffm.], mustard greens (Brassica juncea) and broccoli (Brassica oleracea) was reduced by exposure to deionized water that had been adjusted to pH 3.0 using sulfuric acid (H₂SO₄) (Lee et al. 1981). Another study also reports a significant decrease in yield of beet after treatment with simulated rain of pH 4 (Evans 1982). Bean plants subjected to treatment with water of pH 3 exhibited foliar necrosis and reduced growth (Ferenbaugh 1976). Acid rain may also have a negative effect on pome fruit. On apples leaf spots and reduced fruit quality due to necrotic lesions have been reported (Forsline et al. 1983; Proctor 1983; Rinallo and Mori 1996).

**Pesticide phytotoxicity.** Foliar injury and reduced marketability of fruit crops may also be the result of pesticide phytotoxicity. Rates of copper-based bactericides exceeding 30 g metallic copper per hectare may damage leaves and causes defoliation on peach (Lalancette and McFarland 2007). Phytotoxic effects on apple as a result of exposure to Azoxystrobin at concentrations as low as 10 ppb have been described (Lange
Fruit skin defects on citrus may be caused by treatment with methyl iodide or sodium o-phenyl-phenate (Aung et al. 2001; Hopkins and Loucks 1950).

**Peach Skin Disorders and Discolorations**

Visual appearance is a primary criterium for marketability of peaches in the U.S., any fruit that exhibit defects or discolorations will have reduced value or might not be accepted for retail (USDA Agricultural Marketing Service 2004). Defects that impact consumer acceptability may occur before picking or during post-harvest handling. Inking of peach and nectarine has been identified as a result of abrasion damage in combination with heavy-metal contamination (Crisosto et. al. 1999). Exposure of fruit to alkaline conditions during retail preparations can damage phenolic compounds in the peach, and may inducing “skin burning” (Cantín et. al. 2011). Peaches infected with pathogens may cause discoloration of the fruit skin without causing rot. For example, *Fusicladosporium carpophilum* will exhibit dark-green, scab like spots that reduce economic value (Scherm & Savelle 2001). Water-soaked, necrotic lesions on peach fruit are characteristic of bacterial spot caused by *Xanthomonas arboricola* pv. *pruni* (Ritchie 1995). Plum pox potyvirus will induce discolored halo-shaped spots not only on peach but also on other stone fruit including plum and apricot (Badenes et. al. 1996; Levy et. al. 2000). Bronzing is a peach skin disorder characterized by tan, irregular shaped patches on the fruit (Melgar and Schnabel n.d.). Exposure to hydrogen fluoride has been identified to cause premature ripening of the suture of peach fruit, termed suture red spot (MacLean et. al. 1984).
CHAPTER TWO

INFREQUENT OCCURRENCE OF PEACH SKIN STREAKING AND THE ROLE OF RAINWATER ATTRIBUTES ON SYMPTOM DEVELOPMENT

Introduction

Peach fruit appearance aka “finish” greatly influences consumer acceptance and marketability. Final fruit quality is affected by all decisions and practices throughout production from site and cultivar selection to postharvest handling (Crisosto et. al. 1995). Because of consumer preference, the peach industry prefers to grow large, red fruit. To make fruit suitable for postharvest handling and to avoid blemishes during transportation, the fruit must be firm when picked (Layne 2007). Fruit of poor quality, including smaller and misshapen fruit is likely to get a reduced price or may even get rejected by the retailer. Peach skin discolorations, such as inking (Crisosto et. al. 1999), skin burning (Cantín et. al. 2011), and suture red spot (MacLean et. al. 1984) impair fruit finish and lower marketability.

Peach skin streaking is another form of skin discoloration and was only recently described in the scientific literature (Hu et. al. 2017). It was first observed in 2003 at a fruit research station near Byron, Georgia (P. Brannen, UGA, personal communication). Since then, streaking has become more prevalent and in some years has become a major issue for South Carolina growers. Substantial damage in multiple cultivars was reported in 2015 and 2016; depending on location and cultivar, streaking severity varied from barely visible to necrotic streaks (Unpublished data). Peach fruit with streaking was also
reported in Pennsylvania and Maryland peach orchards as recently as 2018 (M. Shannon, personal communication).

Streaking affects red-blush cultivars in both conventional and organic production, essentially eliminating synthetic pesticides as possible contributors (Hu et al. 2017). Streaks can be faint yellow, solid yellow, or even necrotic brown in color extending in general from the stem of the fruit to the tip end following the flow of liquid over the fruit surface. Fruit with solid yellow or necrotic brown stripes are unmarketable. Symptoms on fruit have not been associated with foliar damage and underlying causes of peach skin streaking are still unknown. Based on field observations, the occurrence of preharvest streaking was associated with light rain one to two weeks prior to harvest preceding a period of drought of about 10 days (Hu et al. 2017). Rainwater may therefore concentrate atmospheric pollutants at high enough doses to damage peach skin.

Multiple attributes of rainwater have shown to cause harm to plant tissue. The pH of rainwater may cause epidermal defects, reductions in crop yield (Proctor 1983; Rinallo and Modi 1995), and discoloration of peach skin in association with ionic contaminants (Cheng and Crisosto 1994). The stability of anthocyanins, which are increasingly synthesized during peach fruit maturation, is also highly dependent on pH (Torskangerpoll and Andersen 2005). Chlorine in irrigation water has also been reported to induce stunting and foliar damage on several nursery crops (Cayanan et al. 2008). Ozone (O₃) causes leaf injury and impaired growth of several crops, including tomato and rice (*Oryza sativa*) (Sawada and Kohno 2009; Wohlgemuth et al. 2002). Finally, there is
a possibility that leaf exudates concentrated in rainwater may be responsible for streaking symptoms.

The objectives of this study were to (i) monitor the occurrence of peach skin streaking over two consecutive seasons in multiple cultivars at a commercial farm in South Carolina; (ii) determine the distribution of streaking within a canopy; (iii) monitor chemical attributes in rainwater suspected to be streaking agents over the course of the peach fruit ripening season and assess their ability to produce streaking on peach fruit; and to (iv) assess the influence of ripening stage on the susceptibility of peach fruit to streaking.

Materials and Methods

Experimental locations. Six peach cultivars, including cvs. Blazeprince (ripening late June), Scarletprince (ripening early July), Redskin (ripening mid-July), O’Henry (ripening late July), August Lady (ripening early August) and September Sun (ripening mid-August) were monitored for streaking in two different locations (LocA and LocB) at a commercial farm in South Carolina. LocA was near Trenton (33°45’36.4” N, 81°49’08.0” W) and LocB was near Ridge Spring (33°51’09.1” N, 81°40’30.9” W). The orchards (referred to as experimental blocks) in LocA and LocB were clustered within a 10- and 16-km diameter circle (referred to as cluster), respectively, and the two clusters were separated by at least 6 km. According to the farm operator, some experimental block cultivars near Trenton (LocA) exhibited streaking symptoms in previous years that rendered many fruit unmarketable. Both experimental blocks received the same pesticide
treatments in both years for pest and disease management starting with oil sprays at dormancy and ending with preharvest applications for brown rot management. In addition, peach cultivars at the Musser Fruit Research Center (MFRC) in Seneca, SC (34°36'11" N, 82°52'43" W) were monitored for streaking occurrence. This research station is located 160 km northwest of the commercial farm. All locations were monitored throughout the growing seasons of 2017 and 2018. The trees used for this study were all 6 to 8 years old and in full production.

**Assessment of streaking occurrence.** Fruit were examined weekly for streaking symptoms starting four weeks prior to harvest. For each experimental block cultivar, streaking incidence was determined on 50 arbitrarily selected fruit per tree for 5 single trees with at least 2 buffer trees between each experimental tree. To assess distribution of streaking within the tree canopy, incidence was recorded for fruit at the top, bottom, inside, and the sides of the canopy. For each position, 25 fruit were arbitrarily selected and evaluated.

**Rainwater analysis.** Rainwater was collected from each experimental block and attributes, including, pH, electrical conductivity (EC), oxidation-reduction potential (ORP), chlorine species (Cl₂, ClO₂) and ozone (O₃), were assessed for their ability to cause streaking symptoms. AcuRite rain gauges (12.5 cm; Chaney Instrument Co., Lake Geneva, WI) as well as polyethylene bins (7.5 L, 24 cm; Lowe´s Companies, Inc., Mooresville, NC) were set up in each experimental block to measure precipitation and collect rainwater for analysis. Collection bins were examined for rain twice a week or when forecasts predicted a 30% or greater chance of rain starting four weeks prior to
harvest. The frequent collection schedule was implemented to minimize potential impacts of temperature and light on the rainwater chemistry. At each inspection the bins were cleaned with DI water. Rainwater was transferred into 500 ml polyethylene bottles (SKS Bottle and Packaging, Inc., Watervliet, NY) and placed on ice for transportation. Samples were analyzed at room temperature within 24 h of sampling. Oxidation reduction potential (ORP), electrical conductivity (EC), and pH were determined in a 100 ml aliquot. ORP was measured using the RE300 ExStik ORP meter (Extech Instruments, Nashua, NH). EC and pH were measured using the pH/conductivity tester PHH-7200 (Omega Engineering, Surrey, United Kingdom). Rain samples and leaf rinsate exhibiting low ionic strength (less than 100 µS/cm) were treated with pHisa ionic strength adjustor (Thermo Scientific, Waltham, MA) for improved accuracy and stability. The EC electrode was calibrated according to manual instructions and pH electrode was calibrated using Orion pure water pH buffers (Thermo Scientific, Waltham, MA). Instruments were calibrated weekly. Chlorine species (Cl₂, ClO₂) and ozone (O₃) in rainwater were quantified with the AQUAfast AQ3700 colorimetry meter (Thermo Scientific, Waltham, MA) and respective test reagents AC2070 for Cl₂, AC2099 for ClO₂ and AC3048 for O₃ (Thermo Scientific Orion, Waltham, MA).

**Preparation of leaf rinsate.** Leaf samples were collected from experimental block cultivars after at least 10 days of no rain to investigate the potential for leaf rinsate to cause streaking symptoms. Ten leaves closest to the fruit were collected from five trees, totaling 50 leaves per block. Leaf samples from the 6 experimental block cultivars within LocA were pooled and so were leaf samples within LocB to yield 300 leaves for
each of the two locations. Each leaf collection was rinsed by adding 50 leaves at a time to 250 ml of distilled water in a 500 ml flask with screw cap. Then the flask was inverted several times for 30 sec. Rinsed leaves were removed from the rinsate and a fresh set of 50 leaves was added to the same liquid until 300 leaves were processed. The LocA and LocB rinsate was examined separately for the ability to cause streaking symptoms on detached, immature fruit.

**Generation of streaking symptoms on immature fruit.** Fruit were harvested one and two weeks prior to commercial maturity for detached fruit experiments in the laboratory. The ripening status was estimated based on visual assessments during fruit maturation. Fruit used for experiments were collected from the commercial farm and included fruit from cvs. August Lady, Blazeprince, Fireprince, Gloria, Julyprince, Juneflame, O’Henry, Redglobe, Redskin, Scarletprince and September Sun. Sodium chloride (NaCl; Fisher Scientific, Hampton, NH) was evaluated at concentrations of 700 µg/ml and 1500 µg/ml. These were chosen based on EC value extremes detected in rainwater samples. Chlorine dioxide solutions were generated according to (Hu et. al 2017) using the Aquamira Chlorine Dioxide Water Treatment kit (Aquamira Technologies, Inc., Logan, UT). Equal amounts of solutions part A and part B were mixed for 5 min to generate 1% active ClO₂ which was further diluted to 0.05% (500 µg/ml). The concentration of ClO₂ was chosen based on Hu et. al. (2017) who reported ClO₂ at concentrations of 0.02% induced streaking symptoms on immature peach fruit. Water solutions were adjusted to pH 3 and pH 10 using sulfuric acid (H₂SO₄; VWR, Radnor, PA) and sodium hydroxide (NaOH; Fisher Scientific, Hampton, NH),
respectively. To examine possible combination effects, mixtures of 700 µg/ml NaCl + pH 3 solution, 700 µg/ml NaCl + pH 10 solution, 500 µg/ml ClO₂ + pH 10 solution, 1500 µg/ml NaCl + 500 µg/ml ClO₂ and 1500 µg/ml NaCl + 500 µg/ml ClO₂ + pH 10 were also applied. Additional treatments consisted of leaf rinsate. Treatments were applied to three equally distant spots on the fruit starting from the shoulder of the stem end using a 1000 µl pipette (Eppendorf, Hamburg, Germany). A total of 300 µl of treatment solution was pipetted onto the fruit surface as droplets in a single drip line. To ensure slow droplet run-off, a nonionic surfactant (INDUCE; BASF, Ludwigshafen, Germany) was added at 0.125% to all solutions, including the water control. The addition of a surfactant to the individual treatments increased retention and made the drops stick to the fruit simulating slow run-off in the field. The surfactant did not cause symptoms by itself. Three single fruit replicates were used per treatment and each experiment was repeated at least once. All treatment solutions were prepared immediately prior to application. Pictures of experimental fruit were taken every 24 h after treatment for 7 days.

The ability of ozone (O₃) to generate streaking was evaluated in a separate study. The trials were conducted in the early morning hours from 5 am to 6 am to ensure slow drying conditions. Immature fruit, one and two weeks shy of commercial maturity, of cv. Cresthaven were subjected to ozone treatments at a concentration of 0.3 µg/ml. A leaf was mounted on each experimental fruit vertically and tip pointing to the fruit using a metal mesh wire contraption. That allowed treatment solutions to persistently run over the fruit surface. The mounted leaves were misted with a hand-held sprayer to run-off and re-wetted every 10 to 15 min for 60 min to ensure a constant supply of spray solution.
drip. Ozone treatments were generated in 250 ml distilled water using the Aqua-6 Ozone Generator (A2Z Ozone Inc., Louisville, KY). Ozonation was conducted for 2 min within 10 min of the first application. Each treatment was conducted on five trees with three single fruit replicates per fruit for each maturity stage. The experiment was repeated.

**Statistical analysis.** Using JMP® Pro version 14.1.0 (SAS Institute Inc., Cary, NC) we tested for relationships between precipitation and rainwater attributes. Simple linear regressions were evaluated between (i) precipitation and pH, (ii) precipitation and electrical conductivity, (iii) precipitation and oxidation/reduction potential, (iv) precipitation and chlorine, (v) precipitation and chlorine dioxide, and (vi) precipitation and ozone at $P < 0.05$. To confirm significant relationships, correlation analysis was estimated by Row-wise method for precipitation and O$_3$, and REML method for precipitation and ORP. ANOVA analysis was used to determine a relationship between reproduction of streaking and ripening status of peach fruit. Where relationships were significant ($P < 0.05$), we compared means between cultivars using Fisher’s LSD student´s $t$ test.

**Results**

**Streaking occurrence and incidence in 2017 and 2018 growing season.**

Streaking was only observed in the experimental block cv. Scarletprince of LocA in 2017 with 6% incidence. None of the other experimental block cultivars in LocB exhibited streaking. However, streaking with incidences of 11 and 25% was observed in two non-experimental blocks with cv. Scarletprince situated within LocA that same year.
Streaking was not observed in either block in 2018; however, a non-experimental block with cv. Harvester located within LocB exhibited 23% streaking. At the MFRC in Clemson, SC mild streaking occurred on multiple cultivars, including Scarletprince, August Prince and O’Henry (J. C. Melgar, Clemson, personal communication), but the highest incidence was observed in mid-season cv. Julyprince in 2017 (50% incidence) and in early-season cv. Carored in 2018 (64% incidence).

**Distribution of streaking within single tree canopies.** Distribution of streaking within single tree canopies differed between locations. In the commercial orchards, fruit from the top and canopy sides were predominantly affected, while symptomatic fruit were distributed uniformly within the canopy at the MFRC (Fig. 2.1). Cultivars Scarletprince and Harvester, which were in non-experimental blocks near LocA and LocB, revealed streaking distribution patterns within single tree canopies similar to cv. Scarletprince (data not shown). Locations with uniform streaking distribution within single tree canopies received more precipitation during the week prior to symptom development compared to the locations where fruit at the top and canopy sides were predominantly affected (Fig. 2.1).

**Analysis of rainwater from peach orchards.** A total of 205 rainwater samples were taken from twelve experimental blocks in 2017, and 2018 between mid-May and mid-August and examined for pH, Cl\textsubscript{2} and ClO\textsubscript{2} content. Average seasonal pH values ranged from 5.18 to 6.38 between locations in 2017 and from 4.90 to 6.55 in 2018 (Table 2.1). In both years the median pH of all samples compiled was greater than 5.85. The minimum pH value recorded was 4.1 in 2017 and 3.03 in 2018, while the maximum pH
value was 7.4 in 2017 and 7.01 in 2018 (Table 2.1). In both years, levels of chlorine (Cl₂) and chlorine dioxide (ClO₂) were either below or just above the detection limit of 0.01 mg/l and 0.02 mg/l, respectively (Table 2.1). Additionally, EC, ORP and O₃ were determined for samples collected in 2018. Average seasonal EC values ranged from 0 to 60 µS/cm between locations. However, we observed individual EC values as high as 1,505 µS/cm (Table 2.2). The ORP of all rainwater samples was positive, indicating oxidizing conditions, but did not exceed 300 mV (Table 2.2). Simple linear regression revealed a significant effect of precipitation on ORP ($P < 0.05$). Further statistical analysis showed that precipitation and ORP were negatively correlated with a correlation coefficient of -0.212 based on REML method.

Similar to chlorine species, O₃ levels were either below or just above the detection limit of 0.02 mg/l on average per location (Table 2.2), but there was a significant ($P < 0.05$) relationship between precipitation and O₃. A positive correlation was estimated to be 0.3643 by Row-wise method. There were no relationships between precipitation and pH, EC, Cl₂ or ClO₂, respectively ($P < 0.05$). Analysis of leaf rinsate after periods of drought revealed an average pH of 5.01 and 5.22, average EC of 13 and 23 µS/cm, and average ORP of 173 and 163 mV for locations A and B, respectively (data not shown). For both locations (A and B) average values of Cl₂, ClO₂ and O₃ were under the respective detection limits 0.01, 0.02 and 0.02 µg/ml, respectively (data not shown).

**Development of streaking symptoms and relationship to ripening status of peach fruit.** Rainwater attributes including pH and EC extremes as well as leaf rinsate did not cause symptoms on detached fruit picked one and two weeks prior to harvest.
Likewise, neither NaCl at concentrations of 700 µg/ml, solutions of pH 3 or 10, or mixtures of 700 µg/ml NaCl and pH 3 or 10 produced streaking symptoms (Table 2.3). ClO₂ at 500 µg/ml generated streaking symptoms on ripening fruit (Table 2.3). Susceptibility to streaking was dependent on fruit maturity and cultivar. Among fruit that was collected 7 days prior to commercial harvest, cvs. Juneflame, Blazeprince, Redglobe, September Sun, and Julyprince were most susceptible. Cultivar Juneflame was significantly more susceptible than cvs. O’Henry, Redskin, and August Lady (Figs. 2.2 and 2.3). Among fruit harvested two weeks before harvest, cv. Gloria was significantly more susceptible than cvs. September Sun and Scarletprince (Fig. 2.4). Ozone at 0.3 µg/ml did not produce symptoms on hanging, treated fruit one or two weeks prior to commercial harvest (data not shown).

**Discussion**

Monitoring of streaking in 6 cultivars over two consecutive growing seasons suggested that peach skin streaking is an infrequent, non-cultivar-specific and localized phenomenon. In one year streaking appeared in one cultivar of a specific location, and in another, it showed up at a different location and cultivar on the same farm. Likewise, streaking appeared in the same year in one cultivar but not in another nearby. This impeded predictability considerably; however, this also indicated that the occurrence of streaking does not predict continuation of the problem that same year in other cultivars or in the same cultivar the next year. However, streaking did cause significant damage. We recorded incidences of up to 64%. While streaked peaches may be acceptable for local
markets, such fruit will experience significant downgrades at the retail level. At best they may qualify for U.S. Grade No. 2, the lowest of four USDA Peach Grades and Standards (USDA Agricultural Marketing Service 2004). Due to the nature of symptom development close to commercial harvest, streaking often goes unnoticed during the production season until harvest.

Our data suggested that the distribution of streaking in single tree canopies appeared to be influenced by the amount of rainfall associated with the streaking incidence. During heavy rainfall (i.e. more than 25 mm per day) it is more likely that the entire canopy will be wetted evenly resulting in similar streaking incidence among canopy positions. For light rain events however, it is reasonable to assume that fruit at the top and sides of the canopy are wetted predominantly, which may lead to localized incidence within single tree canopies. However, more data is needed to conclusively determine the true nature of the relationship between rainfall and streaking occurrence in single tree canopies. There are also alternative explanations that may be considered. The susceptibility to streaking increases as fruit matures and generates more anthocyanins close to harvest (Hu et al. 2017). Photosynthetic photon flux (PPF) is greater in the upper canopy compared to the lower canopy and may lead to differences in pigment formation (Bible and Singha 1993). Hence, differences in streaking incidence with regard to canopy position may also be explained by differing ripening stages of peach fruit within single tree canopies. Lastly, pruning can impose changes on microclimates of fruit tree canopies by altering relative humidity and evaporative potential (Cooley et. al. 1997). Such changes could affect exposure of the peach skin to pollutants in rainwater. Therefore,
differences in canopy microclimates as a result of pruning may affect distribution of streaking within single tree canopies. However, all trees used in our experiments were open center and pruning had been conducted to the same standards and by the same pruning crew at the commercial farm and MFRC.

The quality of rainwater varied depending on location, time and amount of precipitation; however, none of the attributes could be associated with streaking development. Although samples were collected in regular intervals, we acknowledge the potential impact of light and temperature on water chemistry between rain events and sample collection. Rainwater attributes examined in this study included pH value extremes pH 3 and 10, as well as EC value extremes 1500 and 3000 µS/cm. Neither of those extremes caused streaking by themselves in our detached fruit tests. Streaking symptoms were produced recently using Cl\textsubscript{2} or ClO\textsubscript{2} solutions with concentrations greater than 100 µg/ml (Hu et al. 2017). However, levels of Cl\textsubscript{2} or ClO\textsubscript{2} in rainwater were significantly lower than concentrations used to induce streaking symptoms on detached fruit in the laboratory. In 2017, streaking was observed on cv. Scarletprince (LocA) at the commercial farm. This experimental block received 25 mm precipitation in the week prior to symptom development. Rainwater analysis revealed a pH of 6, chlorine content of 0.02 µg/ml while chlorine dioxide was under the detection limit of 0.02 µg/ml. These findings were not significantly different from rainwater collected from unaffected experimental blocks. It is still possible, however, that combinations of these attribute extremes in rainwater have the ability to damage peach skin. In one instance we were lucky to have directly associated the occurrence of streaking on cv. Carored (2018;
MFRC) after a 50 mm rainfall on May 16 and to have collected sufficient rainwater for follow up experiments. The rainwater was stored at 4°C for 7 days before it was used for experiments. The stored water produced streaking symptoms on detached cv. Rubyprince fruit (pictures not shown). To the best of our knowledge this batch of rainwater was free of pesticide residues and had never touched peach tree tissue. Unfortunately, the remaining sample volume did not allow for follow up studies. This finding combined with our inability to reproduce symptoms with concentrated leaf rinsate further strengthens our hypothesis that rainwater alone can induce streaking.

Detached peach fruit was susceptible to streaking two weeks and one week prior to harvest, and we noticed differential responses depending on cultivar. Earlier reports confirmed that fruit skin susceptibility to streaking increases as ripening progresses, with fruit one week away from harvest being the most susceptible (Hu et al. 2017). In this study we show that at the same maturity stage there are cultivar differences as well. This may explain anecdotal observations from peach growers who noted that streaking occurred on one cultivar, but adjacent cultivars of a similar ripening stage may be affected to a lesser extent or not be affected at all (M. Shannon, personal communication).

In conclusion, streaking may develop only when multiple factors coincide, including the presence of a susceptible cultivar, susceptible fruit of the susceptible cultivar at the time of rainfall, and rainwater containing one or more streaking-causing agents. The concentration of the streaking agent in rainwater is likely dependent on the amount of rainfall. Our monitoring efforts revealed very different precipitation totals in
locations that were less than 2 km apart. For example, one field received 38 mm of rainfall, while another nearby field received 76 mm that same day (data not shown). Such differences in precipitation would greatly influence the concentration of the streaking agent in rainwater assuming that little precipitation concentrates atmospheric pollutants more than larger precipitation.
Table 2.1 Precipitation, pH, chlorine (Cl$_2$), and chlorine dioxide (ClO$_2$) in rainwater collected over two years from 12 experimental blocks of a commercial farm in South Carolina.

<table>
<thead>
<tr>
<th>Location within Commercial Farm</th>
<th>Cultivar</th>
<th>Weekly precipitation (mm)</th>
<th>Total precipitation (mm)</th>
<th>pH</th>
<th>pH range$^b$</th>
<th>Cl$_2$ (µg/ml)</th>
<th>ClO$_2$ (µg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location A</td>
<td>Blazeprince</td>
<td>29.97 / 25.91</td>
<td>298 / 311</td>
<td>6.07</td>
<td>4.7-6.9 / 3.0-6.5</td>
<td>0.02 / 0.03</td>
<td>&lt;0.02 / 0.03</td>
</tr>
<tr>
<td></td>
<td>Scarletprince</td>
<td>14.48 / 32.77</td>
<td>145 / 394</td>
<td>5.34</td>
<td>5.1-7.4 / 3.7-7.0</td>
<td>0.03 / &lt;0.01</td>
<td>&lt;0.02 / &lt;0.02</td>
</tr>
<tr>
<td></td>
<td>Scarletprince</td>
<td>42.67 / 29.21</td>
<td>425 / 349</td>
<td>5.89</td>
<td>4.7-6.6 / 3.9-5.9</td>
<td>0.02 / &lt;0.01</td>
<td>&lt;0.02 / &lt;0.02</td>
</tr>
<tr>
<td></td>
<td>O’Henry</td>
<td>14.99 / 23.88</td>
<td>149 / 286</td>
<td>6.38</td>
<td>5.9-6.9 / 4.0-6.7</td>
<td>0.02 / 0.02</td>
<td>&lt;0.02 / 0.02</td>
</tr>
<tr>
<td></td>
<td>August Lady</td>
<td>21.08 / 37.59</td>
<td>210 / 451</td>
<td>6.1</td>
<td>5.6-6.3 / 3.9-6.3</td>
<td>0.02 / 0.01</td>
<td>&lt;0.02 / 0.02</td>
</tr>
<tr>
<td></td>
<td>September Sun</td>
<td>31.75 / 24.38</td>
<td>318 / 368</td>
<td>6.19</td>
<td>5.3-7.0 / 6.0-7.0</td>
<td>0.03 / 0.01</td>
<td>0.02 / 0.04</td>
</tr>
<tr>
<td>Location B</td>
<td>Blazeprince</td>
<td>19.56 / 35.56</td>
<td>196 / 425</td>
<td>5.85</td>
<td>4.5-6.5 / 5.5-6.4</td>
<td>0.01 / 0.01</td>
<td>&lt;0.02 / 0.09</td>
</tr>
<tr>
<td></td>
<td>Scarletprince</td>
<td>17.53 / 14.22</td>
<td>174 / 127</td>
<td>6.34</td>
<td>5.5-6.9 / 5.8-7.0</td>
<td>0.02 / 0.02</td>
<td>&lt;0.02 / 0.02</td>
</tr>
<tr>
<td></td>
<td>Redskin</td>
<td>27.43 / 20.57</td>
<td>273 / 248</td>
<td>5.76</td>
<td>4.6-6.6 / 4.7-5.9</td>
<td>0.02 / 0.02</td>
<td>&lt;0.02 / &lt;0.02</td>
</tr>
<tr>
<td></td>
<td>O’Henry</td>
<td>25.15 / 34.04</td>
<td>250 / 375</td>
<td>5.3</td>
<td>4.2-6.2 / 5.1-6.2</td>
<td>0.02 / 0.01</td>
<td>&lt;0.02 / &lt;0.02</td>
</tr>
<tr>
<td></td>
<td>August Lady</td>
<td>21.84 / 24.89</td>
<td>218 / 298</td>
<td>6.4</td>
<td>5.1-7.3 / 6.0-6.7</td>
<td>0.02 / 0.01</td>
<td>&lt;0.02 / 0.03</td>
</tr>
<tr>
<td></td>
<td>September Sun</td>
<td>24.13 / 20.32</td>
<td>241 / 222</td>
<td>5.18</td>
<td>4.1-6.1 / 4.2-6.4</td>
<td>0.01 / 0.01</td>
<td>0.07 / 0.03</td>
</tr>
</tbody>
</table>

$^a$ Numbers separated by ‘/’ indicate values from experimental years 2017 (left) and 2018 (right).

$^b$ Minimum and maximum value recorded for cultivar in respective location and experimental year.
Table 2.2 Electrical conductivity (EC), oxidation-reduction potential (ORP) and ozone (O₃) content mean values of rainwater collected in 2018 from 12 experimental blocks of a commercial farm in South Carolina.

<table>
<thead>
<tr>
<th>Commercial Farm</th>
<th>Cultivar</th>
<th>EC (µS/cm)</th>
<th>EC range</th>
<th>ORP (mV)</th>
<th>ORP range</th>
<th>O₃ (µg/ml)</th>
<th>O₃ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location A</td>
<td>Blazeprince</td>
<td>11</td>
<td>0-56</td>
<td>197</td>
<td>129-252</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>Scarletprince</td>
<td>69</td>
<td>0-1505</td>
<td>206</td>
<td>149-263</td>
<td>0.06</td>
<td>&lt; 0.02 - 0.37</td>
</tr>
<tr>
<td></td>
<td>Redskin</td>
<td>8</td>
<td>0-72</td>
<td>242</td>
<td>151-302</td>
<td>0.04</td>
<td>&lt; 0.02 - 0.30</td>
</tr>
<tr>
<td></td>
<td>O’Henry</td>
<td>24</td>
<td>0-214</td>
<td>186</td>
<td>129-279</td>
<td>0.05</td>
<td>&lt; 0.02 - 0.29</td>
</tr>
<tr>
<td></td>
<td>August Lady</td>
<td>18</td>
<td>0-173</td>
<td>202</td>
<td>148-273</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>Sept. Sun</td>
<td>34</td>
<td>0-188</td>
<td>174</td>
<td>127-225</td>
<td>0.02</td>
<td>&lt; 0.02 - 0.13</td>
</tr>
<tr>
<td>Location B</td>
<td>Blazeprince</td>
<td>4</td>
<td>0-42</td>
<td>158</td>
<td>98-227</td>
<td>0.05</td>
<td>&lt; 0.02 - 0.31</td>
</tr>
<tr>
<td></td>
<td>Scarletprince</td>
<td>15</td>
<td>0-71</td>
<td>154</td>
<td>87-203</td>
<td>0.05</td>
<td>&lt; 0.02 - 0.27</td>
</tr>
<tr>
<td></td>
<td>Redskin</td>
<td>11</td>
<td>0-66</td>
<td>218</td>
<td>143-269</td>
<td>0.06</td>
<td>&lt; 0.02 - 0.31</td>
</tr>
<tr>
<td></td>
<td>O’Henry</td>
<td>0</td>
<td>0</td>
<td>177</td>
<td>90-231</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02 - 0.35</td>
</tr>
<tr>
<td></td>
<td>August Lady</td>
<td>11</td>
<td>0-62</td>
<td>167</td>
<td>101-208</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>Sept. Sun</td>
<td>9</td>
<td>0-62</td>
<td>223</td>
<td>151-255</td>
<td>&lt; 0.02</td>
<td>&lt; 0.02</td>
</tr>
</tbody>
</table>
Table 2.3 Streaking symptoms induced on detached peach fruit by experimental dose.

<table>
<thead>
<tr>
<th>Rainwater Attributes</th>
<th>Detected Range</th>
<th>Experimental Dose</th>
<th>Streaking Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>3.03 to 7.4</td>
<td>H$_2$SO$_4$; pH3</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NaOH; pH10</td>
<td>No</td>
</tr>
<tr>
<td>Electrical conductivity (EC)</td>
<td>0 to 1,505 µS/cm</td>
<td>NaCl 700 µg/ml; 1500 µS/cm</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NaCl 1500 µg/ml; 3000 µS/cm</td>
<td>No</td>
</tr>
<tr>
<td>Oxidation reduction potential (ORP)</td>
<td>90 to 302 mV</td>
<td>N/A$^a$</td>
<td>N/A</td>
</tr>
<tr>
<td>Chlorine (Cl$_2$)</td>
<td>&lt; 0.01 µg/ml</td>
<td>NaClO &gt; 100 µg/ml$^b$</td>
<td>Yes</td>
</tr>
<tr>
<td>Chlorine dioxide (ClO$_2$)</td>
<td>&lt; 0.02 µg/ml</td>
<td>ClO$_2$ &gt; 100 µg/ml$^b$</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ClO$_2$ 500 µg/ml + NaCl 1,500 µg/ml</td>
<td>Yes</td>
</tr>
<tr>
<td>Ozone (O$_3$)</td>
<td>&lt; 0.02 – 0.37 µg/ml</td>
<td>O$_3$ &gt; 0.3 µg/ml</td>
<td>No</td>
</tr>
</tbody>
</table>

$^a$ N/A = not applicable. There was no treatment that specifically tested the influence of ORP on streaking development.

$^b$ Based on previous data published by Hu et al. 2017.
Figure 2.1 Distribution of streaking within single tree canopies (bars) and cumulated precipitation (open circle) 7 days prior to symptom development in cultivars Julyprince and Carored at Musser Fruit Research Center (MFRC) and cv. Scarletprince at a commercial farm near Ridge Spring, South Carolina.
Figure 2.2 Streaking incidence on fruit picked one week prior to commercial harvest and treated with 500 µg/ml chlorine dioxide (ClO₂) solution. LSD test (alpha = 0.05), error bars represent ± 11 SE. Different letters represent significantly different responses between cultivars.
Figure 2.3 Streaking on detached fruit generated using chlorine dioxide (ClO$_2$) at 500 µg/ml on cv. Juneflame (left) and cv. August Lady (right). The point of drip treatment is indicated with a red arrow but symptoms on cv. August Lady were evident at lower frequencies.
Figure 2.4 Streaking incidence on fruit picked two weeks prior to commercial harvest and treated with 500 µg/ml chlorine dioxide (ClO₂) solution. LSD test (alpha = 0.05), error bars represent ± 13 SE. Different letters represent significantly different responses between cultivars.
REFERENCES


Rinallo, C., and Mori, B. 1996. Damage in apple (Malus domestica Borkh) fruit exposed to different levels of rain acidity. J. Hort Sci. 71: 17–23.


https://doi.org/10.1016/j.ejmech.2015.10.017


