Comparison of Trunk Wraps in their Ability to Protect Kiwifruit Vines from Freeze Injury

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A thesis submitted to the Graduate Faculty of
Auburn University in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 8, 2020

Keywords: *Actinidia chinensis*, *Actinidia deliciosa*, Golden Kiwifruit, Insulation

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Abstract

The golden kiwifruit is a new crop to the southeastern United States, with orchards being established across the region. Unfortunately, freeze injury is prevalent due to fluctuating winter temperatures that impact cold resistance of vines. Some vines become injured, developing cracks in their trunks or experiencing a softening of the vascular cambium, both of which reduce vigor and can result in die-back or mortality. Trunk wraps can be used to help regulate temperature fluctuations experienced by kiwifruit vines, so this experiment was designed to test the effectiveness of various materials on kiwifruit vines on an orchard in Reeltown, Alabama. Two studies were performed on one-year-old and two-year-old vines in the winter of 2018-2019, and two more studies were conducted in the same location over the winter of 2019-2020. A spun-bound polypropylene row cover (GG-51, Gro-Guard UV®, Atmore Industries, Atmore, AL), was wrapped around vine trunks six times to create the 6-wrap treatment, and twelve times to create the 12-wrap treatment. Polyethylene PVC pipe insulation 2 centimeters thick, fiberglass pipe insulation 2.2 centimeters thick, and white latex trunk paint were used to create the fourth, fifth, and sixth treatments. Data loggers were mounted on vines underneath wraps on vines where wraps were used. At the end of the season, vines were inspected for injury and temperature data were analyzed.

No treatments reduced the amount of damage received by the vines, but the polyethylene treatment increased damage during one study. There were pronounced differences in the temperature retention of some treatments, with the 12-wrap treatment and fiberglass wraps maintaining higher minimum temperatures and cooler maximum temperature than the control during most studies. This is in contrast to polyethylene treatments, which maintained higher

minimum temperatures than the control, but exceeded the control by as much as 7°C at maximum temperatures.

The effect of wraps was also compared by looking at the amount of time wraps were exposed to very low temperatures (-5°C and -3°C) and very high temperatures (25°C and 30°C). The 12-wrap and fiberglass treatments outperformed the control and the other treatments, with vines receiving these treatments spending less time at both low and high temperatures beneath wraps. Meanwhile, the polyethylene treatment maintained high temperatures under wraps for greater amounts of time than the control. The 6-wrap treatment maintained higher maximum temperatures around the vine trunk than the control, but did not remain as warm as the 12-wrap treatment.

These data imply that while spun-bound polyethylene has some valuable insulative properties, they are most useful when the wrap is applied at greater thickness. Trunk paint has negligible effects and is indistinguishable from the control when comparing temperature and damage. Polyethylene treatments used in this study had a similar insulative capacity to the 6-wrap application of trunk wrap, but the high temperatures it reaches in the daytime are not desirable, so it is less likely to be usable as a trunk wrap. The 12-wrap and fiberglass wraps were the most effective materials tested in the experiment, and have the greatest potential for use as trunk wraps.

Acknowledgements

I would like to thank Dr. James Spiers for his guidance throughout my time at Auburn. Thanks to his advice, I was able to design a more reliable experiment and write a more comprehensible thesis than I ever could have without his help. I am grateful for the time and effort he put into helping me with this project, as I certainly would not have been able to complete it without him. I also want to extend a hearty thanks to Dr. Raymond Kessler, who helped me with the statistics for my experiment, and to Dr. Edgar Vinson and Dr. Elina Coneva, members of my committee who helped me produce the best material I possibly could.

Thanks also to Clint Wall, who allowed me to use his orchard to test my treatments and showed me places in the orchard that would lend themselves well to the experiment.

Finally, I would like to thank my fellow graduate students, Claire Krofft and Jacob Kelley. Both were enormously helpful to me throughout my graduate program, helping set project up, take them down, and thinking about problems I encountered throughout my research. They were also of valuable emotional support, and their comradery cannot be understated in its role of getting me through the rough patches. This thesis is theirs as much as mine.

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CHAPTER 1

Introduction

The golden kiwifruit (*Actinidia chinensis* Planch.) has thrived in its relatively short time on the global market. Public interest in the fruit has increased over the past decade, and southeastern states may benefit from growing golden kiwifruit. Three cultivars of golden kiwifruit believed to have commercial potential have been studied at Auburn University since the 1990s. These three cultivars are 'AU Golden Sunshine' (Dozier et al 2010a) and 'AU Golden Dragon' (Dozier et al 2010b), and 'AU Gulf Coast Gold' (Dozier et al 2016). At the time of this writing, they are the main cultivars being grown in the southeast. 'AU Gulf Coast Gold' and 'AU' Golden Sunshine' are the major productive cultivars in the state of Alabama. Before golden kiwifruit can become an economical asset to the southeast, there are some issues that must be overcome. A major challenge facing the southeastern kiwifruit industry is freeze damage, which can cause severe trunk cracking and vine mortality. This project is designed to evaluate trunk wraps as a method of preventing freeze injury.

In most kiwifruit production areas, kiwifruit orchards frequently experience radiation freezes. These freezes can kill buds, limiting fruit set for the season (Lu and Reiger, 1990). Injured vines will eventually form new buds, but this delays production and may reduce yield. Radiation freezes occur when warm air stratifies above the ground on cool nights, allowing air near the ground to cool below levels plants can tolerate. They commonly occur during calm, clear nights when temperatures are near freezing. Radiation freeze injury can be minimized by disrupting the temperature zones that occur as the atmosphere stratifies. For example, wind

machines may be used in the orchard to disrupt the inversion layer, bringing warm air from higher in the atmosphere and mixing it with lower atmospheric layers. In places where wind machines are not installed, helicopters may fly over the field for the same effect (Perry, 1998). Overhead microsprinkler irrigation can also be used to protect tender crops from radiation freezes.

The southeastern region of the United States frequently experiences advection freezes, which are caused by cold fronts from northern latitudes moving across the south. These freezes behave very differently from radiative freezes, and are capable of quickly lowering ambient temperature. Because these freezes can occur suddenly after periods of relatively warm weather, they may shock plants that have begun to break dormancy. Sudden temperature fluctuations that advection freezes thrust upon vernalizing plants can cause freeze injury (Hewett and Young, 1981). In the case of kiwifruit, this injury can manifest as gaping wounds where the vascular cambium freezes and splits, stunting or killing the vines. Even if a vine is not completely killed during a freeze, it becomes vulnerable to refreezing and may experience reduced vigor during the growing season. Advection freezes are more injurious to younger vines. As vines mature, they become more resistant to damage by advection freezes.

Kiwifruit vines are very vigorous and will usually send out new shoots from the root crown after the trunk experiences freeze injury, but these shoots need two to three seasons of growth before they set fruit. If vines were grafted and the graft union was killed, vines will need to be grafted again. An average of 38 days per year have minimum temperatures below 0 °C in central Alabama, where this study is located, so there are many opportunities for freeze injury to occur (Southern Region Climate Center, 2015). This impedes the establishment of a kiwifruit industry in the southeastern United States. Because advection freezes are associated with

different conditions than radiation freezes, protection methods that work with radiation freezes become less effective or useless under advection conditions (Perry, 1998). Therefore, other protective methods must be devised.

Advection freezes are best counteracted passively, by only planting species resistant to the temperatures that are common in the region. In some cases, freezes will bring colder temperatures than an orchard can withstand, and action must be taken to prevent injury. In such cases, protection against advection freezes involves direct heating of a target plant, an insulative component, or both. The energy and materials involved in direct heat production are prohibitive, so direct application of heat is uncommon (Perry, 1998). Instead, protection against advection freezes usually relies on some form of heat retention, in the form of insulation.

For low-growing herbaceous crops, row covers may be used to trap heat radiating from the ground. For fruit trees and other crops with greater height, row covers become impractical. Instead, orchard managers may try to protect the trunk of the tree from injury. They may opt to protect their trees by banking soil against the trunks. This process is labor-intensive and subjects tree trunks to damage associated with being buried under soil over the winter season, but it is capable of preventing cold damage (Jackson and Parsons, 1994). Trunk wraps are a promising alternative to soil banks. They work by holding atmospheric heat captured during warm periods against the trunk and slowing its diffusion into the atmosphere. Some materials, especially those with small air pockets like polystyrene or fiberglass, can provide some insulation during freeze events, which can be the difference between survival or not. Trunk wraps have been used to good effect on green kiwifruit in the past (Dozier et al., 1992; Pyke et al., 1988), so there is reason to believe that they may be able to protect the golden kiwifruit from freeze damage as well.

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CHAPTER 2

Literature Review

Kiwifruit vines are dioecious vines native to the temperate woodlands and ravines of southeastern China, where they have been used by the Chinese people since the early 1700s (Huang, 2016). Cultivation was uncommon during this era, so almost all fruits were harvested from wild vines. European botanists collected the green kiwifruit (*Actinidia deliciosa* C.F. Liang and A.R. Ferguson) for study and first recorded captive fruiting in the early 1900s (Ferguson, 1983). The kiwifruit vine caught on quickly as an ornamental in New Zealand, but struggled to move beyond ornamental usage until the 1930's, when commercial production of the fruit began in earnest (Huang, 2016). Early fruit quality was wildly variable, and it was not until the advent of 'Hayward' in the late 1940s that fruit quality became consistent. Shortly thereafter, New Zealand began exporting kiwifruit to other countries. The high demand for green kiwifruit lead to an explosion of interest in kiwifruit farming in the 1970s, and kiwifruit production has since spread across the world.

The Economy of Kiwifruit

According to 2017 data by the Food and Agriculture Organization of the United Nations, China was the world's largest producer in at 1,986,368 metric tons, followed by Italy (541,150 metric tons) and New Zealand (410,772 metric tons).

Even though China produces more kiwifruit than any other country, it only exported around 19,000 metric tons in 2017, leaving the lion's share of export to New Zealand (456,202 metric tons exported in 2017), Italy (321,507 metric tons in 2017), and Chile (176,050 metric

tons in 2017) (FAOSTAT, 2017). Most of New Zealand's production has historically been green kiwifruit, but golden kiwifruit, which has only been on the kiwifruit market since the early 2000's (Martin and Luxton, 2005), has expanded to represent almost half of New Zealand's export by mass and surpasses green kiwifruit by income during some months (Statistics New Zealand, 2018).

Kiwifruit are a high-investment, high-return crop. Orchard establishment represents a high initial cost, as kiwi vines require expensive irrigation and support systems (Judd et al., 1989). High installation costs, plus the high labor involved with grafting, pruning, pollinating, and otherwise maintaining vines, contribute to the high price of kiwifruit growing. This represents a high input cost for growers, and vines that have been winter-killed must be re-established, requiring many of these processes to be done again. Despite the high costs of orchard establishment, the southeastern United States can profit from growing kiwifruit due to its increasing popularity and potential for high returns. For example, New Zealand's 11,700 hectares of kiwifruit production produced $232,976,775 USD in green and golden kiwifruit exports alone (Statistics New Zealand, 2017). This eclipses the $161,000,000 that Alabama's entire fruit, nut, and vegetable industry produced in the same year (Fields et al., 2017). Unfortunately, high rates of freeze injury can result in substantial losses by freezing vines to the ground, which may cause the kiwifruit industry to struggle in the southeastern region until preventative measures are installed.

Kiwifruit of Alabama

There are three female cultivars of *A. chinensis* in use in the southeastern United States (Spiers et al., 2018). Two kiwifruit cultivars, 'AU Golden Sunshine' (Dozier et al., 2010a) and 'AU Golden Dragon' (Dozier et al., 2010b), were patented in collaboration with the Fruit and Tea Institute of Hubei, China. The third cultivar, 'AU Gulf Coast Gold', was derived later. Both 'AU Golden Sunshine' and 'AU Golden Dragon' are early-ripening cultivars that produce fruit given 700 to 800 hours of chilling (Wall et al., 2008) that produce sweet fruit with low acidity. The fruit size of 'AU Golden Sunshine' varies from medium to quite large, with many fruits exceeding 100g. This cultivar has been known to suffer from a preharvest fruit drop, an uncommon issue among kiwifruit vines. Vines that are affected by preharvest fruit drop begin dropping their fruit ~1-2 weeks prior to harvest. Most kiwifruit vines retain their fruit well into the dormant season, so preharvest fruit drop was an unexpected problem that may prevent 'AU Golden Sunshine' from entering commercial production. 'AU Golden Dragon' produces slightly smaller fruits than 'AU Golden Sunshine'. 'AU Golden Dragon' has a low growing degree hour requirement 9,500 hours, so it flowers early in the growing season, which renders it vulnerable to early spring frost damage but allows it to produce fruits that ripen much earlier than the fruits of other cultivars in the same growing area (Wall et al., 2008). It does not suffer from preharvest fruit drop, though its fruits have an unusual heart-like shape that many kiwifruit sellers do not prefer. The most recently patented southeastern cultivar is 'AU Gulf Coast Gold' (Dozier et al., 2016), a bud mutation of 'AU Golden Sunshine' with many similar qualities to 'AU Golden Sunshine', but with slightly smaller fruit and without preharvest fruit drop issues. Kiwifruit production in Alabama has focused mostly on 'AU Golden Sunshine' and 'AU Gulf Coast Gold'.

Kiwifruit Cultural Requirements

Because kiwifruit vines do not have the structural means to support themselves, they are usually grown on trellises or pergolas for support. These structures train the vines to fruit just over six feet above the ground, making maintenance easier and fruit easy to access (Hopping et al., 1993). During the early life of an orchard, non-fruiting growth is frequently grown up strings mounted above the trellis system because it allows the canopy to fill out quickly and helps growers reach commercial production more quickly (Patterson and Currie, 2011). Kiwifruit vines also demand consistently moist, well-drained soils for healthy development and good fruit set, so most orchards use sprinklers mounted near each vine to administer water directly to each plant (Judd et al., 1989). Kiwifruit fruits are sensitive to abrasion caused by strong winds, so shelter belts are frequently implemented to minimize winds in the orchard (McAneney et al., 1984). The high demand of kiwifruit vines means that establishment costs per plant in a kiwifruit orchard are quite high, so plant loss (as from freeze injury) represents a major loss to growers.

Kiwifruit Production Challenges Related to Cold

Radiation and advection freezes are the main kinds of freezes that commonly affect agriculture. Radiation freezes are caused by the stratification of warm air and cold air on still, clear nights, with a layer of warm air forming above a blanket of cold air three or more meters thick. The layer of cold air can damage crops (Perry, 1998). Protection against radiation freezes once involved heating the cold layer of air by setting small, contained fires throughout the orchard. This method was costly and fuel-inefficient, so it has fallen out of favor (Jackson and Parsons, 1994). Anecdotal evidence estimates that fuel costs of orchard heating can be as high as $210 per hectare per night. Assuming an average of 38 days below 0°C per year, which is the average for central Alabama, this represents a cost of $7,978 per hectare per year in fuel alone.

The costs of treatments examined in these studies are substantially less. Yearly costs (all costs in dollars per hectare per year) for treatments tested in this experiment range from $25 (trunk paint), $882 (6-wrap), $1,545 (polyethylene wrap), $1,765 (12 wrap), and $3,580 (fiberglass wraps). The most expensive wrap treatment tested costs 44% less than the fuel costs of orchard heating. These estimates do not include the cost of heating units or installation costs.

Due to the high costs of orchard heating, other methods of cold protection have been developed. For example, a common method of freeze protection involves disrupting the inversion layer by using wind towers or by flying helicopters over the orchard. This physically mixes the inversion layer and can raise ground temperatures enough to protect the orchard crops from damage (Ribeiro et al., 2011, NZKGI Kiwifruit Book. 2018).

Another common method of protection is use of irrigation water to raise orchard tree temperatures through heat of fusion (Jackson and Parson, 1994). This only works during calm conditions when air temperatures are not far below freezing, as any heat generated by freezing water can quickly be sapped away by evaporative cooling, lowering temperatures further than they would have been before and causing injury that otherwise would not have occurred (Lu and Reiger, 1990). It is uncommon for radiation freezes to kill most temperate crops, though radiation freezes can generate temperatures low enough to damage cold-intolerant crops like oranges. Frost protection in kiwifruit-production is often focused on radiation freezes, which have different protection protocols than the advection freezes experienced in the southeastern United States (Perry, 1998). These protection methods are usually oriented around protecting flower buds, which are highly vulnerable during radiation freezes.

Advection freezes are caused by cold fronts that move into an area from colder regions. Unlike radiation freezes, they are associated with winds and cloudy skies. Advection freezes can

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lower temperatures very quickly and may fluctuate rapidly between relatively warm and cool temperatures. This can negatively impact cold hardiness, as kiwifruit plants can begin to deharden quite rapidly, and lose their cold resistance (Pyke et al., 1986). Advection freezes are difficult to protect against, as radiation freeze protection strategies are not effective. Low temperatures, combined with rapid removal of heat by the wind and freezing rain that frequently accompany advection freezes, leach heat away from plants (Boman and Parsons, 2001). Despite this, attempts have been made to increase the cold resistance of orchards grown on the edges of their range. Protection against advection freeze injury largely falls to passive factors, such as plant and site selection (Snyder, 2000).

Causes of Freeze Injury

In plants, freeze damage results from the formation of ice crystals inside the cell (Parker, 1963). Cold tolerance differs between species, with some plants receiving damage from 0°C temperatures, while other plants can survive temperatures well below freezing. Freeze resistance is primarily determined by the presence of water within tissue that is exposed to freezing temperatures (Burke et al., 1976). As temperatures drop, ice crystals begin to form in and around cells. Ice crystals that form within cells damage cellular machinery and pierce cell walls, causing cellular contents to leak out and killing the cell. If this kind of injury occurs en masse, it can kill enough tissue to severely stunt or kill a plant. Depending on the vigor of the plant in question, regrowth may occur from unaffected buds near the ground. Most kiwifruit vines that are frozen to the ground will grow back from the roots unless roots have been previously compromised, as by disease (Testolin and Messina, 1987). Vines that receive cold injury may die to the ground at the beginning of the season if injury is severe, though injury does not always kill outright. Fruit production may be harmed, or vines may begin to die or become stunted later in the season as

damaged vascular tissue prevents water from reaching growing tissue. In kiwifruit vines, injury

typically appears as cracking or sloughing of the bark. The cold hardiness of *Actinidia deliciosa,*

which has been more thoroughly researched than *A. chinensis,* is between -9°C and -12°C

(NZKGI Kiwifruit Book, 2018; Pyke et al., 1986).

Southwest Injury

Southwest injury, also known as sunscald, is a common cause of cold injury to woody

plants. It is believed to be caused by rapid freezing after a period of late-afternoon warmth

(Biggs, 1993). The warmth of the afternoon sun causes plants to experience sap flow, only for

sub-freezing nocturnal temperatures to freeze the freshly flowing sap, causing it to crystallize

and damage vascular tissue (Burke et al., 1976). This form of injury received its name by its

appearance on affected plants. Because the damage is caused by warming of trunk tissue, it

frequently appears on the side of the trunk that has received the most warmth from the sun in the

evening—in the northern hemisphere, this is the southwestern side of the tree. Damage manifests

as cracking and bark sloughing on the affected surface. These symptoms are remarkably similar

to those displayed by freeze-injured kiwifruit vines, which raises the question if southwest-injury

protection will reduce freeze injury in kiwifruit vines.

Freeze Resistance

Under normal conditions, plants protect themselves against freeze through hardening. As

nights grow cooler and days become shorter, most deciduous plants begin to store energy in roots

and shoots (Dickson, 1989). Further into the fall, dioecious plants begin dropping leaves to

reduce energy and water costs. According to Burke et al. (1986), there are a variety of factors

associated with the beginning of plant dormancy. Transpiration decreases, and water inside

vascular tissue is reduced. Depending on the species, some plants may secrete freeze-prevention

proteins into their cytoplasm, or they may concentrate sugars in their cytoplasm, lowering the freezing point of intercellular water (Burke et al., 1986). Some plants will also alter the lipid structures of their cell walls, substituting a ratio of unsaturated lipids for saturated lipids (Chen et al., 2014; Genitsariotis et al., 1999). Every plant species has a different approach to cold tolerance, resulting in different cold tolerances for different species. Furthermore, genetic variation among conspecifics affects cold hardiness (Burak et al., 2004). Hardening does not occur instantly; plants build resistance over time during conditions that encourage hardening. Similarly, plants will reverse the hardening process and begin to become active again as weather warms (Hewett and Young, 1981). This poses an issue for many crops in the southeast, as plants frequently interpret unseasonable warmth in January as the beginning of spring, leading them to break dormancy only to experience freeze injury when the weather becomes cold again (Gu et al., 2008). For many plants, this manifests as early blooms which are killed by frost. Winter warmth can also lead kiwifruit to break bud early in the year, leaving flower buds susceptible to damage. Kiwifruit cultivars that are currently used in the southeast appear to be poorly adapted to southeastern growing conditions, as they can begin active growth after a few weeks' warmth, developing fully formed leaves as early as January, only to be frozen back during subsequent freezes. Solutions to this early dormancy breakage are still being explored in the southeastern United States, but likely involve the use of germplasm with higher growing-degree hour requirements than those currently in use. *Actinidia deliciosa* reportedly tolerates temperatures much lower than the temperatures experienced in the southeast (Ebrahami et al., 2011; Lawes et al., 1995), but continues to experience freeze damage in the southeast. This may be due to rapid fluctuations in temperature. Cold hardiness is not only affected by the species of a plant, but also by temperature fluctuations and length of cold periods. If temperatures drop quickly, as they

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often do during advection freeze events, plant tissues may still contain substantial amounts of water that can freeze, expand, and cause trunk cracking that is frequently seen in injured kiwifruit vines (Sakai and Larcher, 1987). Cold damage has traditionally been visually categorized or based on vine mortality, but advancements in technology have allowed for more sophisticated methods of damage measurement. The leakage of cell contents caused by ice crystal formation can be recorded by measuring the leakage of electrolytes from damaged tissue. This technique provides quantifiable data on an individual-plant basis, but it requires the use of small cuttings, so it is not viable for trunk wrap evaluations (Murray et al., 1989).

Factors Relevant to Kiwifruit Cold Hardiness

There is limited research on methods of protecting *A. chinensis* from ground-killing caused by advection freezes. There is less still on the protection of kiwifruit orchards in the southeastern United States. Most of the data that exists focuses on *A. deliciosa*, which is better understood crop due to its market seniority. In spite of the dearth of data focused on kiwifruit protection, we can estimate the effectiveness of cold protection strategies based on their usage in other crops.

Several factors can contribute to cold injury in kiwifruit. Vine age appears to influence vulnerability. As is the case for many woody plants, younger specimens are more sensitive to cold, but sensitivity tapers off with maturity. This may be a function of changes in dormancy behavior as plants mature (Vitasse et al., 2014).

Cold hardiness in kiwifruit is somewhat variable, but it is between -9°C and -12°C in *Actinidia deliciosa*, a species commonly used as a rootstock by kiwifruit producers in New Zealand (NZKGI Kiwifruit Book, 2018). Other members of the genus, like *A. kolomikta* and *A. polygama* are capable of resisting lower temperatures. This is reflected in a study by Joelle Chat

(1995), which subjected *A. kolomikta*, *A. polygala*, and multiple cultivars (therefore multiple genetic profiles) of *A. deliciosa* to cold temperatures at intervals of -2°C, -10°C, and -18°C (Chat, 1995). *Actinidia deliciosa* was not able to tolerate temperatures below -10°C, though both *A. kolomikta* and *A. polygala* were. This study indicates that *A. deliciosa* should be able to withstand temperatures well below those frequently seen in the southeastern United States, where mean low temperatures are approximately 0°C (NOAA, 2020). Despite the warm temperature of the site on which kiwifruit vines are being grown in the southeastern United States, they continue to receive freeze damage. This damage above hardiness range may be due in part to the influence of fluctuating temperatures on vine cold hardness.

A study by Pyke et al. (1986) in New Zealand tested the freeze resistance of kiwifruit under controlled conditions. Rooted cuttings of *A. deliciosa* 'Hayward' were exposed to temperatures between -0.5°C and -13°C at different times of year. Plant injury was inversely correlated closely with dormancy levels—plants that were not dormant received damage at temperatures as warm as 0.5°C, while vines that were fully dormant could resist temperatures as low as -7°C. Electrolyte leakage was strongly correlated with vine mortality as well (Pyke et al., 1986).

Role of Trunk Protection in Reducing Freeze Injury

In the case of crops that have not been adapted to new growing environments, like kiwifruit, it is essential to provide protection from the elements. The trunk is a vital structural component to orchard crops and is easier to protect from cold than branches, so it is a prime target for protective measures. A simple method of protecting against cold is the act of banking soil at the bases of trunks, providing a great deal of insulation (Rose and Yelenosky, 1978). Banking and un-banking is a labor-intensive process, and moist soil piled around the bases of

plants can invite disease. Trunk wraps are similar in function to soil banking, as they retain heat around the trunk—but are less labor-intensive to apply.

Protective Abilities of Trunk Wraps

Further studies into protection of southeastern crops reveal that trunk wraps behave in a somewhat predictable fashion. For example a study of four-year-old *A. deliciosa* in Clanton, Alabama conducted by Dozier et al. (1992) compared the effectiveness of microsprinkler irrigation and clip-on trunk wraps made of polystyrene with a reservoir of heat-retaining liquid, the makeup of which was undisclosed, to untreated control vines of various cultivars. Vines were subjected to low temperatures ranging between -4.4 to -15 °C during an advective freeze. The study measured how high above the ground injuries were found and how many vines were injured and compared injury across treatments. In this experiment, trunk cracking was used as the metric for injury. When applied to vines, both trunk wraps and microsprinkler irrigation caused injury to occur closer to the ground than in the control. In control vines, trunk cracking occurred between 55 and 164 cm above the ground. On wrap-treated vines, damage occurred between 6.4 and 80 cm above the ground. Microsprinkler-treated vines in this experiment had damage occurring even closer to the ground—between 14.1 and 20.5 cm high—but more cultivars were damaged overall. Trunk wraps completely prevented injury in three cultivars: 'Tomuri', 'AU 1F', and 'Hayward', while microsprinkler irrigation only managed to prevent injury in one: 'AU 1F'. Even in cultivars that sustained injury, the amount of injury was greatly reduced by both trunk wraps and microsprinkler irrigation. Only ~17% of vines in both treatments were injured. By comparison, ~85% of controls were injured. Of the injured vines, 3% of the trunk-wrapped plants were killed by freezes, compared to 6% of irrigated plants and

11% of the control group. Temperatures were not compared between treatments, but the low incidence of injury in trunk wrapped vines indicates that wraps may be favorable.

Yelenosky and Reese (1979) used trunk wraps with a similar design to those of Dozier et al. This study was focused on citrus trees. These wraps were made of polystyrene and contained a plastic bag partially filled with water. Water inside the bag would freeze as temperatures inside the wraps fell, and heat released during the freezing process would help increase the internal temperature of the wrap, allowing them to retain temperatures up to 7°C higher than the ambient temperature. These wraps were occasionally confronted with the phenomenon of supercooling, where water inside the wrap would drop below its freezing point without crystallizing, greatly reducing the wrap's effectiveness. To solve this, Yelenosky and Reese added phenazine crystals to the bags. These crystals provided ice nucleation sites, reducing the chances that a wrap would supercool. Latent heat of fusion, coupled with the high insulative capacity of polystyrene, allowed the wraps to maintain an even temperature at 0°C for hours even as ambient temperatures continued to drop, outperforming wraps described by other researchers (Yelenosky and Reese, 1979).

Rose and Yelenosky (1978) indicated that trunk wraps without water pouches are also able to provide some protection to citrus trees. The study compared the protective prowess of fiberglass wraps, aerolite generated foam, polyurethane foam wraps, and soil banks across multiple years. It found that soil banks were better at moderating temperature than wraps, maintaining temperatures up to 8°C above ambient temperature, but the high costs associated with soil banking is not feasible for large-scale commercial applications. Fiberglass insulation did not insulate as strongly as soil banks, but its ease of installation coupled with its still-effective heat retention (approximately 2°C above ambient temperature) made it a viable strategy

against freezes that were not too long and intense, according to the study. In some of their experiments, plants protected by wraps were only frozen back to the tops of their wraps. In another experiments where weather reached -7°C, the plants were killed completely regardless of the treatment (Rose and Yelenosky, 1978).

Pyke et al. (1988) conducted another study, testing a diversity of wrap materials while looking at effects on temperature. They tested the insulative capacity of several materials including hay, paper, insulating foil, fiberglass, and polyethylene foam. Most wraps were found to slow changes in the temperature of air beneath the wraps, with polyurethane wraps and sawdust berms producing the most gradual changes. Polyurethane wraps and wraps made of black paper tended to become quite warm during the daytime, with temperatures under wraps exceeding ambient atmospheric temperatures by 3°C. Foam wraps provided an average of 1.4°C of protection, with fiberglass and straw wrap providing around 0.5°C protection each. Wraps that incorporated natural materials, like hay-stuffed wraps and sawdust banks, had the disadvantage of being used as shelter by insects and rodents, which put kiwifruit vines at risk of disease or damage from gnawing. Furthermore, natural wraps were more labor-intensive to install and held moisture more effectively than synthetic wraps, making natural wraps less desirable for use on orchards (Pyke et al., 1988).

A more recent study by Kwack et al. (2014) found that foam padded wraps were able to raise minimum surface temperatures of kiwifruit vines by 8.3°C in Feb. 2013 and 5.1°C in Feb. 2014, with similar but less extreme results in Jan. (3.9°C and 5.4°C) and March (2.8°C and 2.7°C). This study also tested simple wraps made of straw, but they had little insulative capacity, raising vine temperature approximately 1°C above ambient temperature (Kwack et al., 2014).

Across these studies, trunk wraps behaved in a predictable fashion. They did not permanently increase temperatures around plants, but in the case of Dozier et al. (1992) and Rose and Yelenosky (1978), they slowed heat loss dramatically enough to increase survivorship of protected plants versus unprotected specimens (Dozier et al., 1992; Rose and Yelenosky, 1978).

Nature of Trunk Wraps

While any flexible material can be used as a trunk wrap, not all materials are created equal in terms of insulative capacity. Many materials have been tested, but most fall into a few categories. Wraps are usually made of natural materials (like leaves, straw, or sawdust), or they are made of paper, rubber foam, or fiberglass.

As demonstrated by Rose and Yelenosky (1978), Polyurethane and polyethylene wraps are moderate insulators with the advantage of being flexible and conforming to the trunks of the plants they are attached. They tend to retain rainwater, however (Pyke et al., 1988).

Polystyrene (branded as Styrofoam™) wraps are rigid and non-conforming, making them difficult to apply in most situations, but they are competent insulators (Dozier et al., 1992; Yelenosky and Reese, 1979). Fiberglass wraps are also moderately strong insulators (Rose and Yelenosky, 1978). They may not insulate as well as polystyrene wraps, but their flexibility, affordability, and tendency to dry more quickly than polyethylene (Rose and Yelenosky, 1978), make them desirable alternatives. Paper wraps, as demonstrated by Pyke et al. (1988), are weak insulators and may hold water against the trunks of the plants they are wrapped around. Wraps rely heavily on external heat sources for warmth, as plants produce little to no heat themselves. Therefore, as suggested by Pyke et al. (1988), wraps likely offer the most protection in conditions where temperatures are tolerable for some time before becoming dangerously cold, which is common throughout the southeastern United States (Pyke et al., 1988).

Cold Resistance by Cultivar

Ultimately, control of kiwifruit freeze injury will likely depend on cultivar. Cold-resistant cultivars do not need cold protection and need not be grafted if they reliably produce good-quality fruit. This would represent a huge labor savings to growers, but research on cold-resistant cultivars in the United States is lacking. At the time of writing, growers do not commonly use other, more cold-resistant species of kiwifruit as rootstocks, though they exist. Rather, most kiwifruit rootstocks are *A. deliciosa* or *A. chinensis* (NZKGI Kiwifruit Book, 2018). This is likely due to a multitude of factors, not the least of which is the impact of other *Actinidia* species on vigor when used as rootstocks. While other kiwifruit species can accept grafts from commercial species, the grafts are not always healthy. For example, notoriously cold-hardy species like *A. kolomikta* and *A. arguta* reduce vigor of vines grafted to them (Clearwater et al., 2007), and grafts made between them and *A. deliciosa* and *A. chinensis* have a high failure rate (Chartier and Blanchet, 1997). Until more cold-hardy cultivars are implemented in the field, cold protection measures, such as trunk wraps, will be necessary.

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CHAPTER 3

Comparison of Trunk Wraps in their Ability to Protect Kiwifruit Vines from Freeze Injury

Introduction

Growers in the southeastern United states are beginning to attempt to grow golden kiwifruit (*Actinidia chinensis* Planch.), which is a high-value crop that fares well in humid subtropical climates. Golden kiwifruit has the potential to become a very profitable crop in the Southeast. New Zealand, which is a large global exporter of kiwifruit, has seen golden kiwifruit approaching the popularity of green kiwifruit. In particular, the mass of gold kiwifruit exported is approaching 50% of kiwifruit exported from New Zealand (Statistics New Zealand, 2018), and income from the golden kiwifruit is surpassing the green kiwifruit at certain times of the year (Statistics New Zealand, 2019). Three cultivars of golden kiwifruit are currently being grown in Alabama: 'AU Golden Sunshine' (Dozier et al., 2010a), 'AU Golden Dragon' (Dozier et al., 2010b), and AU Gulf Coast Gold' (Dozier et al., 2016; Spiers et al., 2018. Kiwifruit vines are demanding, requiring extensive trellis systems to support the vines, and frequent irrigation, as the vines do not tolerate drought well (Judd et al., 1987). Many kiwifruit orchards also incorporate shelter belts, as strong winds can abrade kiwifruit, making them unsellable (McAneney et al., 1984). These factors, coupled with high labor involved in kiwifruit orchard maintenance, make input per kiwifruit vine quite high. If vines die before they fruit reliably, these costs may be difficult to recover.

A limiting factor for kiwifruit vine establishment in the southeastern U.S is the susceptibility of young vines to freeze injury. In kiwifruit, freeze injury frequently manifests as bark cracking (Fig. 3.1) and softening of the cambial layers (Fig. 3.2), which can stunt vines or

kill them to ground level. Kiwifruit vines have been reported to tolerate temperatures lower than those typically seen in the Southeast, with hardiness of *Actinidia deliciosa*, a major species of rootstock used for supporting *A. chinensis* scions, reported to be between -5°C and -12°C (Lu and Reiger, 1990; New Zealand Kiwifruit Growers Kiwifruit Book, 2018; Pyke et al., 1986). In spite of this proposed cold tolerance level, kiwifruit vines frequently experience cold injury at higher temperatures when not completely dormant (Pyke et al., 1986). Temperature fluctuations during winter months can occur in the southeastern U.S. There can be differences of as much as 10°C within a 24-hour period, and temperatures in the months preceding freezes may not reach sustained low temperatures in a way that causes dormancy. In the 2018 and 2019, the years in which these studies were performed, average temperatures a month ahead of the first freeze events only dropped below 10°C, a dormancy-inducing temperature for kiwifruit, for 2 and 5 days, respectively (Lionakis, S., and W. Schwabe, 1984). Fluctuating temperatures may lead to sap flow during the daytime (Goffinet, 2004). If this sap refreezes at night, it can cause injury (Sakai and Larcher, 1987). The same thawing-and-freezing phenomenon is responsible for sunscald, which is caused when the temperature of bark that has been warmed by the sun (in the northern hemisphere, this is the southwestern side) rapidly drops below freezing (Biggs, 1993). Tissue below the warmed bark begins to experience some thawing, and when refrozen can cause cracking in the cambial layers, similar to that seen in kiwifruit vines. Protection from sunscald typically involves some form of shade or reflection applied to the trunk. This can be achieved through use of white latex paint (Ophardt and Hummel, 2016).

Radiation freezes are known to cause injury to reproductive buds in the early springtime. They typically occur during calm nights with clear skies, which allow stratification of warm air above a layer of cool air to occur. The cool layer of air becomes progressively cooler with time,

eventually reaching critical temperature and injuring plants. Protection against radiation freezes frequently involves disruption of layer formation using wind machines, but it may also involve microsprinkler irrigation. Microsprinkler irrigation uses water that is above freezing temperature to warm target plants above critical temperatures and works very well under radiation freeze conditions, but it begins to falter under advection freezes, which are common in the winters of the southeastern United States. The strong winds common in advection freezes can cause substantial loss of heat by evaporative cooling (Perry, 1998). The winds of advection freezes also prevent air from stratifying, so wind machines are rendered useless. Because of these traits, Advection freezes can be difficult to protect against. Protection strategies for advection freezes usually rely on directly warming plant tissues, insulating them, or both. The cost of directly warming more than a few plants quickly becomes prohibitive, as smudge pots and their fuel are costly. Therefore, insulation is a preferable protection method against advection freezes. Insulation not only helps to keep the protected material warmer at night, but can also help reduce temperature fluctuations.

While little research has been done pertaining to the efficacy of trunk wraps to reduce freeze injury of *A. chinensis*, research on the closely-related *A. deliciosa*, as well as other horticultural crop in the Southeast, indicate that trunk wraps may be able to reduce or prevent damage. Styrofoam wraps containing water-filled pouches greatly reduced freeze injury in young kiwifruit (*A. deliciosa*) compared to untreated vines (Dozier et al., 1982). Microsprinkler irrigation was also able to reduce the incident of vine death, but not to the same extent as trunk wraps (Dozier et al., 1982). The trunk wraps used in their study are no longer manufactured, so it was not possible for us to use them in the current study.

Several studies have determined that trunk wraps are able to slow heat loss from plant tissue, reducing the amount of time vines are exposed to minimum temperatures. In South Korea, it is common to cover kiwifruit trunks with rice straw to preclude freeze injury (Kwack et al., 2014). However, trunk wraps made of padded foam coated in silver foil were able to maintain temperatures at the vine surface of 5 to 6 year-old 'Hayward' *A. deliciosa* 3.5°C - 7.3°C greater than minimum temperatures experienced by vines wrapped in rice straw. The minimum temperature experienced by vines wrapped in rice straw was 0.4°C – 1.0°C greater than unwrapped vines (Kwack et al., 2014). Pyke et al. (1988) discovered that foam wraps could provide an average of 1.4°C of protection, with fiberglass and straw wraps providing 0.5°C of protection. The wraps in this study produced a lag period, where wrapped vines took longer to cool than untreated vines. This lag period varied by treatment, and was greater in vines protected with stronger insulators, such as the hay-and-polyethylene wrap and foam wraps described by Pyke et al. (1988). This delayed cooling was more pronounced when there were greater differences between day and night temperatures (Pyke et al., 1988). In a separate study, fiberglass wraps provided up to 2°C of insulation to citrus trees, protecting the graft union from death in some instances (Rose and Yelenosky, 1979). Temperature lags were also reported in this study, with temperatures under wraps changing more slowly than the ambient temperature.

These studies used a variety of treatments, demonstrating that different materials can behave very differently in trunk protection applications. Styrofoam has shown great promise as an insulator, (Dozier et al., 1982; Pyke et al., 1988), but its rigid nature makes it impractical to install throughout an orchard of kiwifruit, the twisted vines of which make installation of rigid insulators difficult. Wraps such as polyurethane foam and fiberglass have also been successfully

used to slow heat loss and reduce cold injury (Pyke et al., 1986; Rose and Yelenosky, 1978), and their flexibility makes them more suited to routine application.

This experiment was designed to determine the usefulness of several available materials as trunk wraps and the efficacy of these trunk wraps to moderate temperature fluctuations and prevent freeze injury of young kiwifruit vines.

Materials and Methods

Four studies were conducted to determine the efficacy of treatments to protect young kiwifruit vines from freeze injury. These studies were conducted on-site in locations known to experience advection freeze injury at Southeast Kiwi Farming Cooperative, Reeltown, AL, USDA hardiness zone 8a. The soil in this location was a sandy loam.

Each study used a randomized block design. Each study had a minimum of five blocks, though study 1 had eight blocks. The number of treatments varied from three treatments (study 1) to six treatments (study 4). Treatments were replicated 5 times in each block, with each replication consisting of a single vine. Of these five vines, one was assigned a data logger that recorded temperature every 30 minutes. The loggers were mounted 30.5 cm above the ground, underneath trunk wraps if applicable. They were mounted on the north-facing side of the vines to ensure direct sunlight did not heat the loggers during daylight hours (Fig. 3.3).

Due to the sheer number of data points recorded by the data loggers it was not practical to analyze the entirety of the data points collected. Therefore, only the coldest five nights (those with the absolute lowest ambient temperatures) were analyzed. The nights selected were based on the mean minimum and maximum temperatures of the control vines in each block, which varied by study. Once the coldest nights had been selected, mean temperatures for those nights were calculated for each treatment in a given study. For each treatment, the lowest mean value

over a 24-hour period became the "minimum temperature" for the treatment, while the highest

mean value became the "maximum temperature" for that period. The temperature data for the

duration of each study was grouped into hours below -5°C, -3°C, 0°C, and above 25°C and 30°C

for further analysis.

An analysis of variance was performed on all high/low temperature responses using PROC

GLIMMIX in SAS version 9.4 (SAS Institute, Cary, NC). The experimental design was a

randomized complete block with blocks random. The treatment design was one-way. Where

residual plots and a significant Chi square, covariance test indicated heterogeneous variance

among treatments, a RANDOM statement with the GROUP option was used to correct

heterogeneity. Least squares means comparisons among treatments were done using the

simulated method. All significances were at α=0.05.

Study 1. Effect of polypropylene trunk wraps (6× and 12×) on freeze protection of young kiwifruit

vines (27 Nov. 2018 to 20 March 2019).

This study consisted of three treatments: control, 6-wrap, and 12-wrap across eight

blocks. Each of the three treatments were replicated once per block, with five vines in each

replication. The control treatment in this and all subsequent studies was composed of unwrapped

vines, as would be seen in an orchard not employing any cold protection strategies.

Vines in this study were one-year-old un-grafted *A. deliciosa* seedlings descended from

'Hayward' with two to three trunks, each with an approximate diameter of 1.3 cm on most vines

(Fig. 3.4). On vines that received wrap treatments, all trunks were bound together inside a single

wrap. The vines received three rounds of pruning per year, with two summer prunings performed

once during May, and again in July. A winter pruning was performed in midwinter, between

December and February. Vines were fertilized with a mixture of liquid Ammonium Nitrate

applied at a rate of 23 liters per hectare every two weeks through microsprinkler irrigation

between April and July. Irrigation was applied throughout the year as soil became dry, but water

was withheld when atmospheric temperatures were below the freezing point of water. Both wrap

treatments were created using a spun-bound polypropylene product typically marketed as a row

cover (GG-51, Gro-Guard UV^{TM}, Atmore Industries, Inc., Atmore, AL). The density of the

product used in this study (GG-51) is 50 g·m^{-2}. The product was wrapped around the vine

trunk(s) 6× for the 6-wrap treatment (Fig. 3.5) and 12× for the 12-wrap treatment (Fig. 3.6). The

cloth was then cut and zip tied around the vines with at least three zip ties—one at ground level,

one at mid-height, and one near the top of the wrap. The wrap extended from the ground to ~2m

the height of the trunk.

The dates of the coldest freeze events for this study were 27 Nov. 2018,

5 Dec. 2018, 11 Dec. 2018, 29 Jan. 2019, and 30 Jan. 2019. All five freeze events in this study

were advective in nature. Mean minimum and maximum temperatures, as well as the mean

amount of time each treatment was exposed to very low and very high temperatures, were

assessed for each of these freeze events and used to determine efficacy of trunk wrap treatments.

Study 2. Effect of polypropylene trunk wraps (6× and 12×), polyethylene trunk wraps, and white

latex trunk paint on freeze protection of kiwifruit vines (12 Dec. 2018 to 22 March 2019).

The wraps in study 2 were applied to two-year-old seedling *A. deliciosa* vines descended

from 'Hayward'. with single trunks (Fig. 3.7). Vines had a diameter of approximately 5.5 cm.

The vines in this study received three rounds of pruning per year, with two summer prunings

performed once during May, and again in July. A winter pruning was performed in midwinter,

between December and February. Vines were fertilized with a mixture of liquid Ammonium

Nitrate applied at a rate of 46 liters per hectare every two weeks through microsprinkler

irrigation between April and July. In addition to this, vines were dressed with a mix of fertilizers in Feb. The fertilizers used in the Feb. dressing were Potassium Sulfate (168 kg/ha), Potassium Chloride (84 kg/ha), Sulfur (56 kg/ha), Iron (16 kg/ha), Boron (10 kg/ha), and lime (3.36 tonnes/hectare). Irrigation was applied throughout the year as soil became dry, but water was withheld when atmospheric temperatures were below the freezing point of water. Study two used five treatments: control, 6-wrap, 12-wrap, polyethylene, and paint treatments across five blocks, with 5 sub-samples per block. The control, 6-wrap, and 12-wrap treatments were created in the same way as study 1.

The polyethylene treatment was created by wrapping two pieces of polyethylene insulation, which is frequently used to protect water-filled PVC pipes from bursting, around vine and zip-tying them multiple times (Fig. 3.8). Because polyethylene is less pliable than row cover material, more zip ties were necessary ensure a firm seal around the vines. Ten to fifteen were used per vine, opposed to the three ties used in 6-wrap and 12-wrap. For the "paint" treatment, a single coat of white latex paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.) was applied to vines using paintbrushes (Fig. 3.9).

The dates of the coldest freeze events for this study were 20 Jan. 2019, 25 Jan. 2019, 29 Jan. 2019, 30 Jan. 2019, and 5 Mar. 2019. All five of these freeze events were advective in nature. Mean minimum and maximum temperatures, as well as the mean amount of time wrapped vines were exposed to very low and very high temperatures, were assessed for each of these freeze events and used to determine efficacy of trunk wrap treatments.

Study 3. Effect of polypropylene trunk wraps (6× and 12×) and white latex paint on freeze protection of kiwifruit vines (12 Nov. 2019 to 17 Feb. 2020).

Study three used four treatments on two-year-old *A. deliciosa* seedlings: control, 6-wrap, 12-wrap, and paint, as previously described in studies 1 and 2. There were five blocks in this study, with five sub-replications of each treatment per block. The vines in this study were in the same field as study 1. In Sept., the vines were pruned to pruned to single-trunks, as opposed to the multi-trunked vines used in study 1. Vines had an average diameter of 1.7 cm. Because these vines were in the same plot as the vines used in study 1, they are also seedlings descended from 'Hayward'. Vines were fertilized with a mixture of liquid Ammonium Nitrate applied at a rate of 46 liters per hectare every two weeks through microsprinkler irrigation between April and July. Irrigation was applied throughout the year as soil became dry, but water was withheld when atmospheric temperatures were below the freezing point of water. Vines were inspected for damage at the end of the study and injury per treatment was compared by binomial probability distribution. The dates of the coldest freeze events for this study were 12 Nov. 2019, 18 Dec. 2019, 20 Jan. 2020, 21 Jan. 2020, and 27 Feb. 2020. All of these events were advective. Mean minimum and maximum temperatures, as well as the mean amount of time wrapped vines were exposed to low and very high temperatures, were assessed for each of these freeze events and used to determine efficacy of trunk wrap treatments.

Study 4. Effect of polypropylene trunk wrap (6× and 12×), polyethylene trunk wraps, fiberglass trunk wraps, and white latex trunk paint on kiwifruit vines (5 Dec. 2019 to 6 March 2020).

This experiment contained five treatments across five blocks, with five sub-replications in each block. This experiment used six treatments: control, 6-wrap, 12-wrap, polyethylene, paint, and fiberglass wraps. The first five treatments are the same as described in studies 1 and 2, but the fiberglass treatment is unique to this experiment. To create it, a single piece of fiberglass

insulation, commonly used to protect water-filled PVC pipes from cold, was wrapped around the base of the vine and secured with zip ties (Figure 3.8).

These vines had single trunks and located in the same field as study 2 was in the previous year. They were four-year-old *A. deliciosa* seedlings descended from 'Hayward' grafted with *A. chinensis* 'AU Golden Sunshine'. Vines had an average diameter of 4 centimeters. Vines were pruned once in Feb. to control canopy growth, and one in Sept. to remove suckers that began to arise from the base of the trunk. Vines were fertilized with a mixture of liquid Ammonium Nitrate applied at a rate of 46 liters per hectare every two weeks through microsprinkler irrigation between April and July. Besides this, vines received a dressed of additional fertilizers in Feb. The fertilizers used in the Feb. dressing were Potassium Sulfate (168 kg/ha), Potassium Chloride (84 kg/ha), Sulfur (56 kg/ha), Iron (16 kg/ha), Boron (10 kg/ha), and lime (3.36 tonnes/hectare). Irrigation was applied throughout the year as soil became dry, but water was withheld when atmospheric temperatures were below the freezing point of water. At the end of the study, vines were inspected for damage and injury per treatment was compared by binomial probability distribution. The dates of the coldest freeze events for this study were 18 Dec. 2019, 20 Jan. 2020, 21 Jan. 2020, 15 Feb. 2020, and 27 Feb. 2020. All of these events were advective except for 15 Feb. 2020, which was a radiative freeze. Mean minimum and maximum temperatures, as well as the mean amount of time wrapped vines were exposed to very low and very high temperatures, were assessed for each of these freeze events and used to determine efficacy of trunk wrap treatments.

Results

Study 1

The 6-wrap and 12-wrap trunk wraps performed similarly in regards to minimum temperatures experienced during the freeze events (Table 3.1). The minimum temperature reached by vines under the trunk wraps were slightly higher for all dates, but only significantly higher on two of the freeze events. The minimum temperature experienced was ~1°C higher under the trunk wraps during the freeze event of 27 Nov. 2018. Temperature of the vines under the 6-wrap treatment was ~0.5°C higher than the minimum temperature of control vines on 11 Dec. 2018, whereas the 12-wrap treatment performed similarly to both control and 6-wrap on this date. The maximum temperatures were quite variable among the treatments for the dates of the freeze events (Table 3.1). The 6-wrap treatment had a greater maximum temperature compared to the control on two of the dates and a greater maximum temperature compared to 12-wrap on 29 Jan. 2019, while the vines under both trunk wrap treatments had a lower maximum temperature on 11 Dec. 2018. The maximum temperature was similar among treatments on 27 Nov. 2018. As observed in Figs. 3.11-3.15, the unwrapped vines (control) experienced greater temperature fluctuations compared to the wrapped vines (Figs. 3.11-3.15).

There were no differences in the number of hours <-5°C for this study (Table 3.2). However, vines with trunk wraps experienced ~10 h less than control vines at <-3°C and ~16 h more than control vines at <0°C. Vines with 6-wrap treatment experienced more hours >25°C than the 12-wrap treatment, and there were no differences in the number of hours >30°C. The incidence of cold injury was not recorded for this study, but it was observed to be minimal.

Study 2

During freeze events, the minimum temperatures of vine which received the trunk wrap treatments were consistently higher than the control and the paint treatment (Table 3.3). Mean temperatures of 12-wrapped vines were the warmest, between 1.3°C and 3.2°C higher than the control. On 20 Dec. 2019, the minimum temperature was different for each of the wraps, with 12-wrap being the warmest of the wraps, followed by 6-wrap, then polyethylene. During the other freeze events, trunk wrap treatments were more difficult to distinguish from one another. The 6-wrap treatment remained higher than the control on all nights except 25 Jan. 2019, and was similar to 12-wrap on 25 Jan. 2019, 29 Jan. 2019, and 5 March 2019. The mean minimum temperature of the 6-wrap was 1.26- 2.4°C higher than the control. The polyethylene wrap treatment kept trunks between 0.5°C and 1.98°C higher than the control on all nights except 5 March 2019, when it was similar to the control. The temperature of the vines treated with white trunk paint treatment could not be distinguished from the control at minimum or maximum temperatures for all freeze events. Wrap treatment effects were less distinguishable from one another at maximum temperatures. The 6-wrap and polyethylene treatments did not differ from the control or each other on any days monitored. 12-wrap was cooler than the control on all days monitored except 20 Jan. 2019 and 5 March 2019. The effect of the paint treatment was not distinguishable from 12-wrap on any day except 30 Jan. 2019, and it did not differ from the control on any day.

Figs. 3.16-3.20 reveal that both 6-wrap and 12-wrap treatments were higher than the control at night and cooler during the day. Polyethylene wraps performed similar to the other wrap treatments, but became warmer than the control during the day (Figs. 3.16- 3.20).

All treatments except the paint treatment were exposed to temperatures below at -5°C and-3°C for less time than the control (Table 3.2). Only the polyethylene treatment, which spent

34 more hours below 0°C than the control, was distinguishable from the control for hours <0°C. At higher temperatures, polyethylene became even further removed from the control. The polyethylene-wrapped vines spent 111 more hours above 25°C than the control. Other treatments did not differ from the control at this temperature. Similarly, polyethylene-wrapped vines spent 68 more hours above 30°C than the control, while other treatments were similar to the control. 12-wrap, while not differing from the control at these temperatures, did differ from 6-wrap. It spent 23 fewer hours below 0°C than 6-wrap did, and 70 fewer hours above 25 than 6-wrap.

When vines were inspected for injury, only polyethylene-wrapped vines experienced more damage than the control (Table 3.4). A total of nine vines in the treatment were damaged. Damage seen among polyethylene-wrapped vines was characterized by many small, shallow fissures with mean length of 27 cm. These fissures were often accompanied by enlarged lenticels, which are a symptom of cold injury in kiwifruit vines.

Study 3

The 12-wrap treatment maintained a minimum temperature 1.17 - 1.6°C higher than the control on four of the five nights analyzed, while 6-wrap maintained temperatures 1.08-1.9°C warmer than the control. (Table 3.4). The 6-wrap treatment was 1.08°C higher than the control on 18 Dec. 2019, and it was 1.68°C higher than the control on 21 Jan. 2020. Neither 6-wrap nor 12-wrap were different from each other during any of the freeze events analyzed. Maximum temperatures of wraps did not differ from each other nor the control during this study.

As demonstrated by Figs. 3.21-2.25, control vines experienced more extreme temperature changes than those protected by wraps (Figs 3.21-3.25). No treatments reduced rates of injury below those of the control. The 6-wrap and 12-wrap treatments spent ~ 8 hours fewer than the

control at -5°C and ~ 17 fewer hours below -3°C than the control. Treatments were not distinguishable at higher temperatures.

Study 4

All wrap treatments had minimum temperatures higher than the control for each of the freeze events analyzed (Table 3.6). The 6-wrap treatment was 1.4 - 2.56°C higher than the control on the five freeze events. The 12-wrap treatment was 1.5 - 2.93°C higher than the control, fiberglass wraps were 1.7 - 2.79°C higher than the control, and polyethylene was 1.2 - 2.3°C higher than the control. Polyethylene wraps had maximum temperatures between 3.92°C and 5.62°C higher than the control, while fiberglass was able to maintain maximum temperatures that were 7.4°C to 8.1°C cooler than the control. The maximum temperatures of the 6-wrap and 12-wrap treatments did not differ from the control on any day except 27 Feb. 2020, where their maximum temperatures were 1.38°C cooler than the control for 6-wrap and 3.95°C cooler for 12-wrap.

Figs. 3.26-3.30 illustrate similar the warming and temperature moderating effects of wraps, similar to those in previous studies (Figs. 3.24-3.30). Treatments did not affect vine injury in this study, nor did wrapped vines differ from the control in the amount of time they spent at any temperature.

Discussion

The results indicate that the trunk wrap treatments had greater effect on the vines in studies 2 and 4 than on vines in studies 1 and 3. When the trunk wrap treatments were applied to 1-2-year-old vines (Studies 1 and 3), the efficacy of the wraps to insulate the vines were inconsistent during freeze events, or only slightly effective. The wraps provided more consistent insulation and predictable results when applied to the thicker, older vines (Studies 2 and 4). The discrepancies between the studies 1 and 3 versus studies 2 and 4 may be due to the size of the vines. The wraps were likely less capable of trapping and retaining heat during the warmth of the day on the smaller diameter vines. Furthermore, the vines used in study 1 were multi-trunked. While all vines were wrapped as tightly as possible, all the trunks of multi-trunked vines were included within a single wrap. Some air space remained inside the inside wraps of multi-trunked vines, trapped between the individual trunks. This allows more convection to occur within the wraps that could result in heat loss.

Interestingly, the spun-bound polypropylene had a mild daytime warming effect on vines when wrapped around vines 6× in studies 1, 2, and 3, while it resulted in a cooling effect when wrapped 12×. This seems strange because 12-wrap has more insulative capacity than 6-wrap, which makes it seem more likely to warm vines, but this phenomenon likely has to do with light and heat penetration. The 12-wrap treatment is twice as thick as 6-wrap and therefore is more subject to self-shading, reducing the amount of light entering and being trapped in the wrap's innermost layers. The outer six layers of 12-wrap are likely being heated in the same way as 6-wrap, but the inner layers of 12-wrap may block the heat from reaching the vine. This trapped daytime heat may also help explain why 12-wrap is able to maintain higher nighttime temperatures than 6-wrap.

Polyethylene wraps frequently became 3-7°C hotter than other wraps in mid-day. This is

likely due to the material absorbing solar radiation. Tan polyethylene was used in lieu of black

polyethylene as an attempt to circumvent this kind of solar heating, but the wraps still became

higher than the control. This heating reaction may be responsible for the increased incidence of

damage observed on the polyethylene-treated vines. No other treatments increased or decreased

damage to the vines. Pyke et al. (1988) described a similar phenomenon in their study, where

dark-colored wraps became more than 3°C higher than the control during the daytime (Pyke et

al., 1988).

White latex paint was used in studies 2, 3, and 4 to see if it would reflect sunlight and

lower vine temperature, possibly reducing damage. Sunscald is caused by a sudden change in

temperatures between the late afternoon and early evening, when bark that has been warmed by

the afternoon sun quickly drops to freezing when the sun sets (Biggs, 1993). Cells that were

beginning to break dormancy in the cambium are re-frozen, causing cracking that closely

resembles the injury seen in kiwifruit vines. White paint is known to reduce sunscald (Ophardt

and Hummel, 2016), so it was used in these studies to see if it affected injury. Painted vines were

not expected to deviate from the control, and temperature data collected in study 2 revealed that

they did not. Because the temperatures of painted vines were so similar to the control,

temperature was not tracked on painted vines in subsequent studies. There was hope that the

white paint would reduce injury, but no difference was seen between painted vines and the

control. This indicates that southwest injury may not be the prevailing cause of injury to kiwifruit

vines in the southeast.

Lack of proper acclimation leading to reduced cold hardiness is a likely contributor to the

damage seen in these studies. In the month preceding the first freeze events of 2018 and 2019,

the average temperatures of only 2 days in 2018 and 5 days in 2019 were below 10°C, which is the temperature at which *Actinidia chinensis* begins to gain cold resistance (Lionakis, S., and W. Schwabe, 1984). Otherwise, temperatures were closer to 20°C and 15°C. This lack of chilling temperatures before the onset of freezing conditions may well have worsened damage experienced by vines.

This is supported by vine injury patterns in study 3. In study 3, freeze injury was observed at two different times—once in early January, and once at the end of the experiment. Most of the damage that occurred over the course of the experiment had occurred by the first observation, with 24 of the 100 vines in the study receiving damage. Only 9 vines received damage between the first and second observations. This is likely due to an incomplete hardening in the vines before initial winter freezes, as mentioned above. Damage seen in the late-season damage was likely loss of cold hardiness. This is described by Pyke et al. (1986) who stated that kiwifruit vine lose their cold tolerance quickly as temperatures increase (Pyke et al., 1986). There were several periods in late Dec. 2019 and early Jan. 2020 spanning multiple days where temperatures never fell below 5 °C. Many of the vines in study 3 had begun to break dormancy and had developed small, fully-formed leaves at the tips of their branches by 15 Jan. 2020. Interestingly, no vines in study 4, which were less than a kilometer away, had broken dormancy. This may also help explain the lack of damage seen in mature vines—perhaps, as vines mature, their dormancy periods become more stable, reducing their likelihood of receiving freeze damage. This is supported by Vitasse et al. (2014), who found that juvenile deciduous trees (*Fraxinus excelsior* and *Prunus avium*) were more likely to be damaged by cold when they flushed out earlier than their mature counterparts, which were slower in leaf production (Vitasse et al., 2014).

Damage throughout studies did not appear to be strongly correlated to treatment usage. This is likely due to genetic variability. These studies used seedling *A. deliciosa* rootstocks (grafted with *A. chinensis* 'AU Golden Sunshine' for studies 2 and 4). The freeze injury observed at this location that prompted this research was quite variable, and not observed to be closely correlated with location. Hence, the genetic variability of the seedling rootstocks is thought to be the primary factor for freeze injury observed. Differences between cultivars of *A. deliciosa* have indicated that intraspecific cold tolerance can vary measurably (Burak et al., 2004). It was expected that a highly effective treatment might prevent injury in spite of this variation, but this was not substantiated. Use of asexually propagated clonal rootstocks vines might improve correlation between treatments and incidence of freeze injury.

There was a trend of wrap-treated vines being exposed to extremely low temperatures of -5°C and -3°C for less time than the control—the 12-wrap treatment is particularly notable in this regard. Interestingly, vines of some of the wrap treatments spent more time below freezing than the control (6-wrap and 12-wrap in study 1, 6-wrap and polyethylene in study 2 all display this trait). This is due to the temperature-moderating effect of the wraps, which remain slightly below zero as the control fluctuates across it. This is supported by comparisons of the average amount of time wrap-treated vines were exposed below -1°C and -2°C (not reported), which shows that the control still spends more time below these temperatures than the other treatments. This implies that the control vines are able to move more freely across the 0°C mark than the wrap-treated vines, while the wrapped vines, which are experiencing temperature lag as described by Rose and Yelenosky (1978) appear to stay cooler longer than the control, even though the difference in temperature is slight (Rose and Yelenosky, 1978).

The desirable attributes for trunk wrap materials are the ability to keep vine temperatures higher than the control at night, cooler than the control during the day, and the ability to regulate the changes between minimum and maximum temperatures into a gentle curve, as opposed to the harsh changes that the ambient temperature may go through. No wrap treatment was able to keep vines above freezing temperatures entirely, which is in line with other studies (Kwack et al., 2014; Rose et al., 1978). The 6-wrap treatment only provided moderate insulation, if any, during the freeze events. Polyethylene wraps performed similar to 6-wrap at minimum temperatures, but treated vines became much hotter during the day. Overheating is an undesirable trait in a trunk wrap treatment, so polyethylene wraps like the ones used in this experiment will not likely prevent freeze injury, and may increase the incidence of freeze injury as observed in this study. On the other hand, the 12-wrap and fiberglass treatments both maintained minimum temperatures of the vines between 0.52°C and 2.95°C higher than the control. The fiberglass wraps maintained a maximum temperature between 5.87°C and 7.99°C cooler than the control. Both the 12-wrap treatment and fiberglass wraps demonstrate more gradual heating and cooling of kiwifruit vines than the control. Overall, 12-wrap and fiberglass were promising trunk-wrap materials tested in these studies. The spun-bound polypropylene product used for the 6-wrap and 12-wrap treatments displays attributes that are desirable for a trunk-wrap material. Increasing the thickness of the material may continue to enhance its protective abilities, as demonstrated by the differences in efficacy between the 6-wrap and 12-wrap treatments.

Conclusion

Due to high cost of trunk wraps, it is unlikely that they will be a viable long-term solution to cold injury in kiwifruit vines. Instead, a better long-term strategy likely lies in the development of cold-resistant cultivars. At the time of writing, strongly cold-resistant varieties of *A. deliciosa* and *A. chinensis* have yet to be discovered. Until the discovery of cold-resistant alternatives to current methods, trunk wraps may be the best tool at our disposal. Even after cold-resistant cultivars are discovered, trunk wraps may still be useful in protecting against unexpected cold fronts under certain conditions.   The trunk wrap materials tested in this study did not have strong impacts on injury received by kiwifruit vines, though some of them are capable of regulating trunk temperature well. The lack of damage prevention in these studies may not be due to shortcomings of any particular treatment, but rather genetic variability among the seedlings used in the experiments. Based on their ability to regulate temperature fluctuation while keeping vine minimum temperature higher and maximum temperatures lower, spun-bound polypropylene (12-wrap) and fiberglass treatments have the most potential for use as trunk wraps, while polyethylene, 6-wrap, and trunk paint did not provide adequate protection.

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Table 3.1. Effect of trunk wrap treatments [z] on the minimum and maximum temperatures recorded for 23.5-h (5:00pm -4:30pm) on 1-year-old *A. deliciosa* seedlings during the five coldest freeze events (27 Nov. 2018- 20 March 2019) in Reeltown, Alabama.

Study 1 Dates (Minimum Temperatures)	Control Min	6-wrap Min	12-wrap Min	P-value
27 Nov. 2018	-4.36b[y]	-3.27a	-3.13a	<0.0001
5 Dec. 2018	-5.0	-4.5	-4.4	0.0609
11 Dec. 2018	-4.12b	-3.60a	-3.66ab	0.0339
29 Jan. 2019	-5.7	-5.1	-5.1	0.0567
30 Jan. 2019	-5.3	-5.0	-4.9	0.2008
Study 1 Dates (Maximum Temperatures)	Control Max	6-wrap Max	12-wrap Max	P-value
27 Nov. 2018	13.7	14.7	13.6	0.3824
5 Dec. 2018	17.20b	21.96a	19.32ab	0.0082
11 Dec. 2018	16.53a	11.44b	9.36b	<0.0001
29 Jan. 2019	15.35ab	17.27a	15.02b	0.0257
30 Jan. 2019	21.79b	25.49a	22.86ab	0.0177

[z] Treatments used in study 1 were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap).

[y] Means followed by the same letter within each row are not significantly different. Least squares means comparisons among treatments were done using the simulated method. All significances were at α=0.05.

Table 3.2. Effect of trunk wrap treatments on the amount of time *A. deliciosa* vines above or below specific temperature thresholds over the duration of four studies [z]. in Reeltown, Alabama.

Study 1	Hours<-5[y]	Hours<-3	Hours<0	Hours>25	Hours>30
Control [x]	9.31	50.88a[w]	175.88b	83.19ab	16.19
6-wrap	6.63	39.56b	192.19a	108.19a	27.06
12-wrap	6.69	40.81ab	191.69a	72.00b	11.56
P-value	0.1361	0.0409	0.0168	0.0460	0.1304
Study 2	**Hours<-5**	**Hours<-3**	**Hours<0**	**Hours>25**	**Hours>30**
Control	14.7a	38.6a	155.3bc	113.8bc	22.1b
6-wrap	2.1bc	22.1cd	159.5b	143.8b	33.4b
12-wrap	0.2c	16.3d	136.6c	73.3c	8.6b
Polyethylene	4.5b	30.3bc	189.3a	224.3a	90.0a
Paint	14.5a	36.8ab	154.9bc	111.3bc	17.0b
P-value	<.0001	<.0001	<.0001	<.0001	<.0001
Study 3	**Hours<-5**	**Hours<-3**	**Hours<0**	**Hours>25**	**Hours>30**
Control	14.4a	45.5a	188.0	95.2	7.0
6-wrap	5.5b	28.7b	172.4	132.7	27.1
12-wrap	6.3b	29.2b	191.6	88.9	19.5
P-value	0.0126	0.0360	0.0591	0.2834	0.3292
Study 4	**Hours<-5**	**Hours<-3**	**Hours<0**	**Hours>25**	**Hours>30**
Control	8.0a	50.9a	225.2a	51.3b	2.3b
6-wrap	0.0b	9.1b	175.6bc	42.1b	0.7b
12-wrap	0.0b	4.0b	153.1c	7.6b	0.0b
Polyethylene	0.0b	18.1b	207.4ab	152.7a	39.9a
Fiberglass	0.0b	4.3b	205.4ab	1.6b	0.0b
P-value	<.0001	<.0001	0..0016	<0.0001	0.0070

[z] Study 1 and study 2 take place in the winter of 2018-2019. Study 3 and study 4 take place during the winter of 2019-2020.

[y] Columns contain the mean number of hours each treatment stayed within the range indicated by the column header.

[x] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), tan-colored polyethylene 2cm thick, and fiberglass insulation 2.2cm thick.

[w] Means followed by the same letter in each column are not significantly different. Least squares means comparisons among treatments were done using the simulated method. All significances were at α=0.05.

Table 3.3. Effect of trunk wrap treatments [z] on 2-year-old *A. deliciosa* seedling rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' on the minimum and maximum temperatures recorded for 24-h (5:00pm -4:30pm) during the five coldest freeze events (12 Dec. 2018, 22 March 2018) in Reeltown, Alabama.

Study 2 Dates (Minimum Temperatures)	Control Min	6-wrap Min	12-wrap Min	Paint Min	Polyethylene Min	P-value
20 Jan. 2019	-3.67d[y]	-2.41b	-1.93a	-3.65d	-2.91c	<0.0001
25 Jan. 2019	-4.79b	-3.79ab	-2.90a	-4.12ab	-3.53ab	0.0125
29 Jan. 2019	-6.61c	-4.21ab	-3.46a	-6.56c	-4.80b	<0.0001
30 Jan. 2019	-6.02c	-4.16b	-3.19a	-6.17c	-4.04ab	<0.0001
5 Mar. 2019	-3.14c	-2.12ab	-1.80a	-2.44abc	-2.83bc	0.0024
Study 2 Dates (Maximum Temperatures)	**Control Max**	**6-wrap Max**	**12-wrap Max**	**Paint Max**	**Polyethylene Max**	**P-value**
20 Jan. 2019	12.64ab	13.42a	8.75b	11.82ab	14.16a	0.007
25 Jan. 2019	17.15a	18.60a	12.26b	16.22ab	18.26a	0.0065
29 Jan. 2019	13.73ab	13.56ab	9.21c	12.02bc	15.26a	0.0002
30 Jan. 2019	18.54a	16.61a	10.97b	18.41a	19.00a	0.0023
5 Mar. 2019	13.61ab	15.79a	12.53b	12.56b	16.40a	0.313

[z] Treatments used in study 2 were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), and tan-colored polyethylene 2cm thick.

[y] Means followed by the same letter are not significantly different. Least squares means comparisons among treatments were done using the simulated method. All significances were at $\alpha = 0.05$.

Table 3.4. Effect of trunk wrap treatments [z] on incidence of cold injury to *A. deliciosa* seedlings and seedling rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' over the duration of four studies [y] in Reeltown, Alabama.

Study 1			Study 2		
n/a			P=0.0227		
Treatment	**Damaged**	**Undamaged**	**Treatment**	**Damaged**	**Undamaged**
Control	n/a	n/a	Control	3ab[x]	22
6wrap	n/a	n/a	6wrap	1b	24
12wrap	n/a	n/a	12wrap	2b	23
			Paint	2b	23
			Polyethylene	9a	16

Study 3			Study 4		
P=0.4548			P=0.8848		
Treatment	**Damaged**	**Undamaged**	**Treatment**	**Damaged**	**Undamaged**
Control	17	8	Control	0	25
6wrap	13	12	6wrap	0	25
12wrap	17	8	12wrap	1	24
Paint	13	12	Paint	0	25
			Polyethylene	4	21
			Fiberglass	0	25

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), tan-colored polyethylene 2cm thick, and fiberglass insulation 2.2cm thick.

[y] Vines in study 1 were one-year-old ungrafted *A. deliciosa* seedlings, vines in study 2 were 2-year-old *A. deliciosa* seedlings grafted with *A. chinensis* 'AU Golden Sunshine' scions, vines in study 3 were 2-year-old ungrafted *A. deliciosa* seedlings, and vines in study 4 were 3-year-old *A. deliciosa* seedlings grafted with *A. chinensis* 'AU Golden Sunshine' scions. Studies 1 and 2 took place over the winter of 2018-2019 and studies 3 and 4 took place over the winter of 2019-2020.

[x] Means followed by the same letter are not significantly different. Least squares means comparisons among treatments were done using the simulated method. All significances were at $\alpha=0.05$.

Table 3.5. Effect of trunk wrap treatments ^{z} applied to 2-year-old *A. deliciosa* seedling rootstocks on the minimum and maximum temperatures recorded for 24-h (5:00pm -4:30pm) during the five coldest freeze events (12 Nov. 2019- 27 Feb. 2020) in Reeltown, Alabama.

Study 3 Dates (Minimum Temperatures)	Control Min	6-wrap Min	12-wrap Min	P-value
12 Nov. 2019	-7.2b	-5.3a	-6.0ab	0.0254
18 Dec. 2019	-4.42b^y	-3.34a	-3.20a	0.0115
20 Jan. 2020	-5.47b	-4.52ab	-4.30a	0.0281
21 Jan. 2020	-6.93b	-5.25a	-5.33a	0.0281
27 Feb. 2020	-4.49b	-3.27a	-3.29a	0.0136
Study 3 Dates (Maximum Temperatures)	Control Max	6-wrap Max	12-wrap Max	P-value
12 Nov. 2019	20.0	20.4	22.0	0.5752
18 Dec. 2019	20.60	23.84	19.97	0.0559
20 Jan. 2020	14.55	17.91	14.78	0.0615
21 Jan. 2020	18.56	22.19	18.69	0.086
27 Feb. 2020	22.8	23.8	21.6	0.0993

^{x} Treatments used in study 3 were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap).

^{y} Means followed by the same letter within each row are not significantly different. Least squares means comparisons among treatments were done using the simulated method. All significances were at α=0.05.

Table 3.6. Effect of trunk wrap treatments [z] applied to 3-year-old *A. deliciosa* seedlings on the minimum and maximum temperatures recorded for 24-h (5:00pm -4:30pm) during the five coldest freeze events (18 Dec. 2019- 27 Feb. 2020) in Reeltown, Alabama.

Study 4 Dates (Minimum Temperatures)	Control Min	6-wrap Min	12-wrap Min	Fiberglass Min	Polyethylene Min	P-value
18 Dec. 2019	-5.90b[y]	-3.36a	-3.08a	-3.17a	-3.60a	<0.0001
20 Jan. 2020	-5.85c	-3.32ab	-2.92a	-3.06a	-3.96b	<0.0001
21 Jan. 2020	-5.55c	-2.99a	-2.72a	-2.89a	-3.82b	<0.0001
14 Feb. 2020	-4.3c	-2.9ab	-2.8ab	-2.6a	-3.1b	<.0001
27 Feb. 2020	-5.50b	-3.41a	-3.13a	-3.29a	-3.50a	<.0001
Study 4 Dates (Maximum Temperatures)	**Control Max**	**6-wrap Max**	**12-wrap Max**	**Fiberglass Max**	**Polyethylene Max**	**P-value**
18 Dec. 2019	19.95b	18.48b	15.51bc	12.40c	25.57a	<0.0001
20 Jan. 2020	12.96b	12.64b	10.89b	5.30c	18.06a	<0.0001
21 Jan. 2020	17.99b	16.85b	14.34b	10.00c	22.45a	<0.0001
14 Feb. 2020	26.2b	24.8b	22.8b	18.1c	31.7a	<0.0001
27 Feb. 2020	23.24b	21.86c	19.32c	15.74d	27.16a	<0.0001

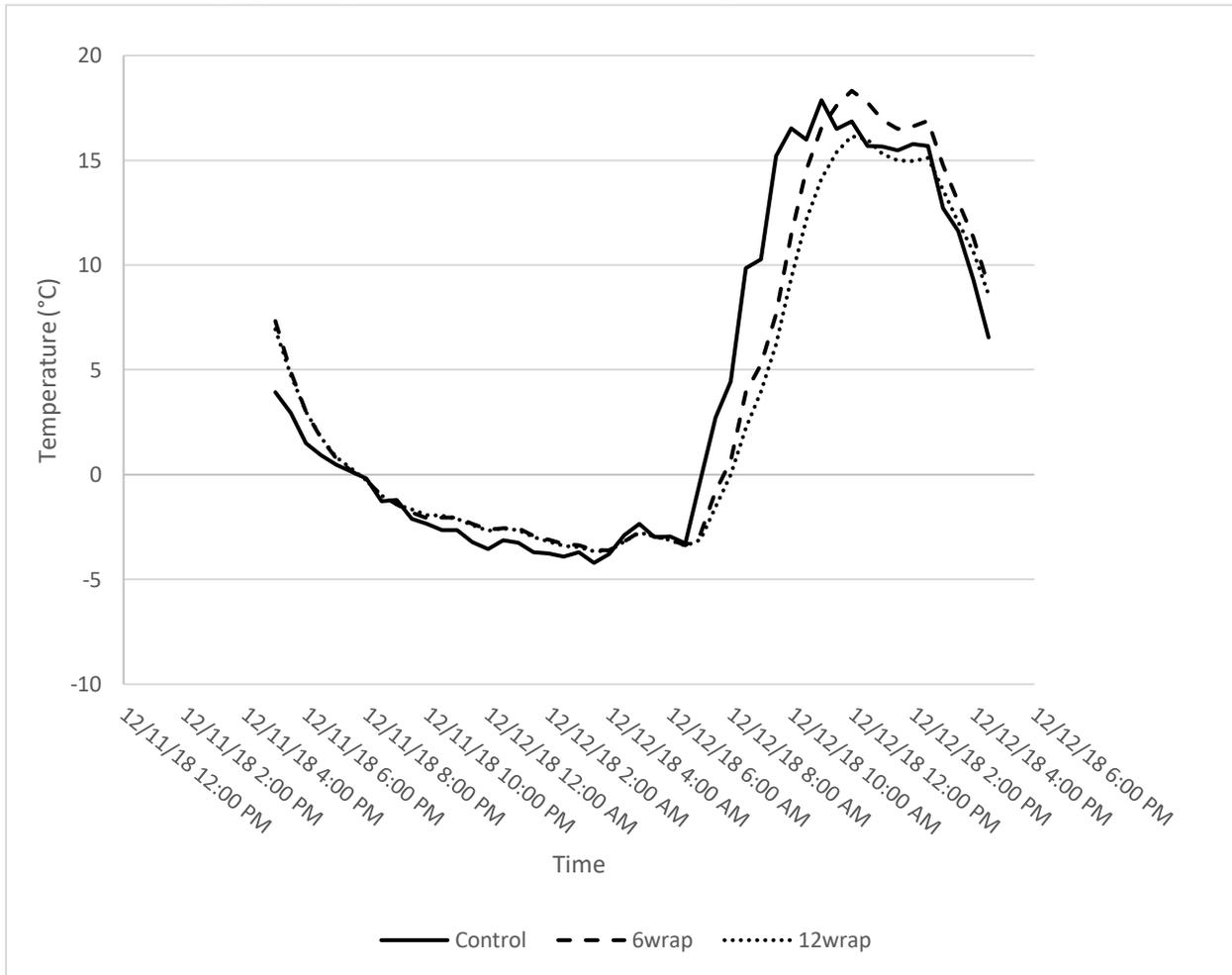[z] Treatments used in study 4 were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick.

[y] Means followed by the same letter within each row are not significantly different. Least squares means comparisons among treatments were done using the simulated method. All significances were at α=0.05.

Fig. 3.1. Cold injury manifesting as trunk cracking in two-year-old *A. deliciosa* rootstock grafted to *A. chinensis* 'AU Gold Sunshine' in Reeltown, Alabama on 29 March 2019

Fig. 3.2. Cold injury manifesting as a delicate cambial layer in two-year-old *A. deliciosa* seedling in Reeltown, Alabama, 19 Dec 2019.

Fig. 3.3. Hoboware datalogger mounted on the north-facing side of a one-year old *Actinidia deliciosa* seedling in Reeltown, Alabama on 8 Jan. 2019.
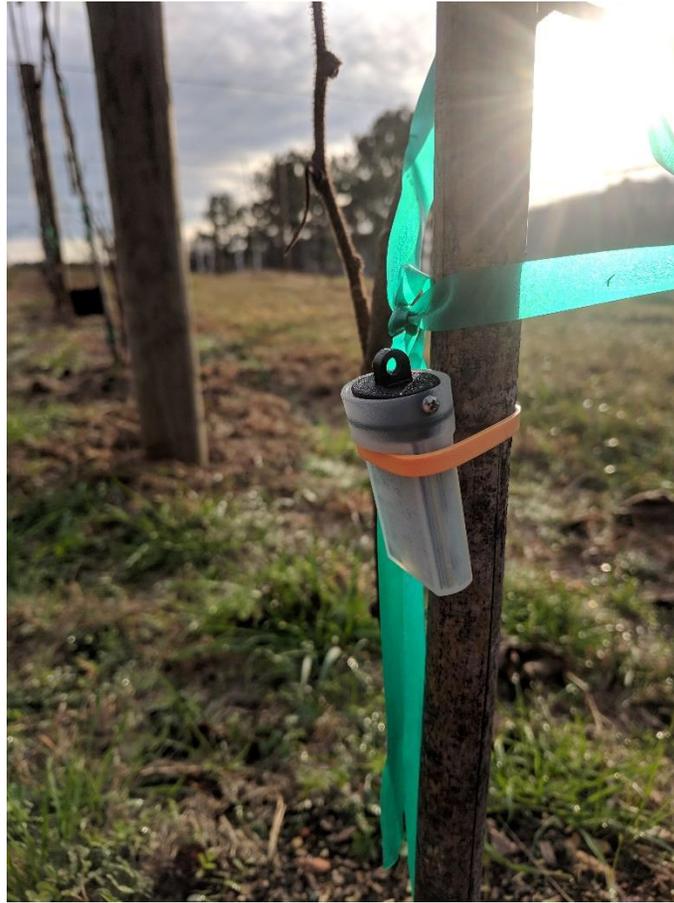
Fig. 3.4. Multi-trunked one-year-old *A. deliciosa* seedling being fitted with a data logger in Reeltown, Alabama on 27 Nov. 2018.

Fig. 3.5. The 6-wrap treatment is composed of Atmore Industries Gro-Guard UV GG-51 row cover wrapped six times around one-year-old *A. deliciosa* seedling.

Fig. 3.6. The 12-wrap treatment is composed of Atmore Industries Gro-Guard UV GG-51 row cover wrapped twelve times around two-year-old grafted *A. deliciosa* seedling rootstock grafted with *A. chinensis* 'AU Golden Sunshine' scion in Reeltown, Alabama.

Fig. 3.7. Two-year-old grafted *A. deliciosa* seedling rootstock used as a control in Reeltown, Alabama on 18 Dec. 2018.

Fig. 3.8. Two-year-old grafted *A. deliciosa* seedling rootstock wrapped with polyethylene insulation in Reeltown, Alabama on 19 Jan. 2020.

Fig. 3.9. Two-year-old grafted *A. deliciosa* seedling rootstock painted with a coat of latex trunk paint in Reeltown, Alabama on 13 Dec. 2018.

Fig. 3.10. Three-year-old grafted *A. deliciosa* seedling rootstock surrounded by fiberglass insulation in Reeltown, Alabama on 19 Jan. 2020.

Fig. 3.11. Effect of trunk wrap treatments [z] on trunk temperature of 1-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama during the freeze event on 27-28 Nov. 2018
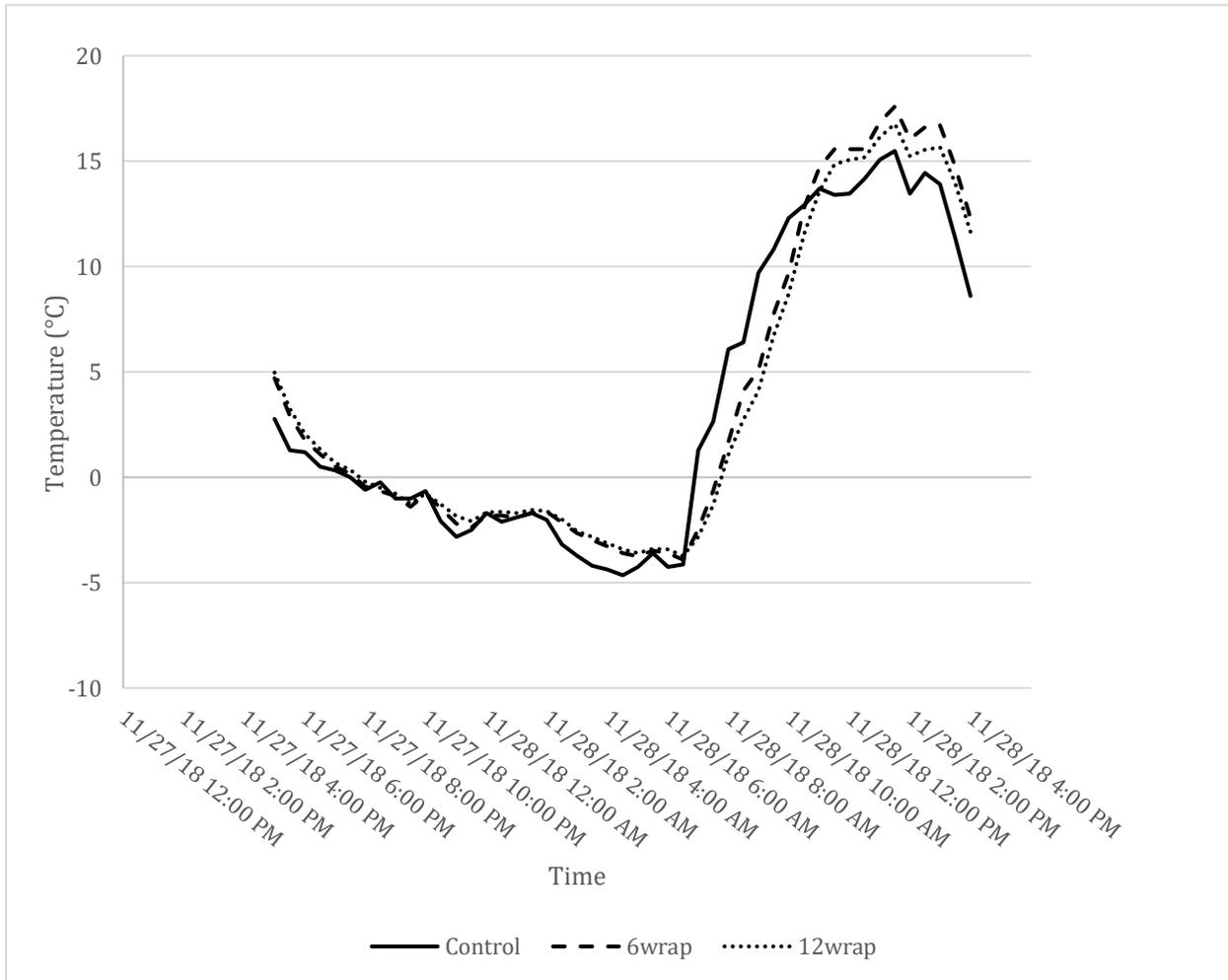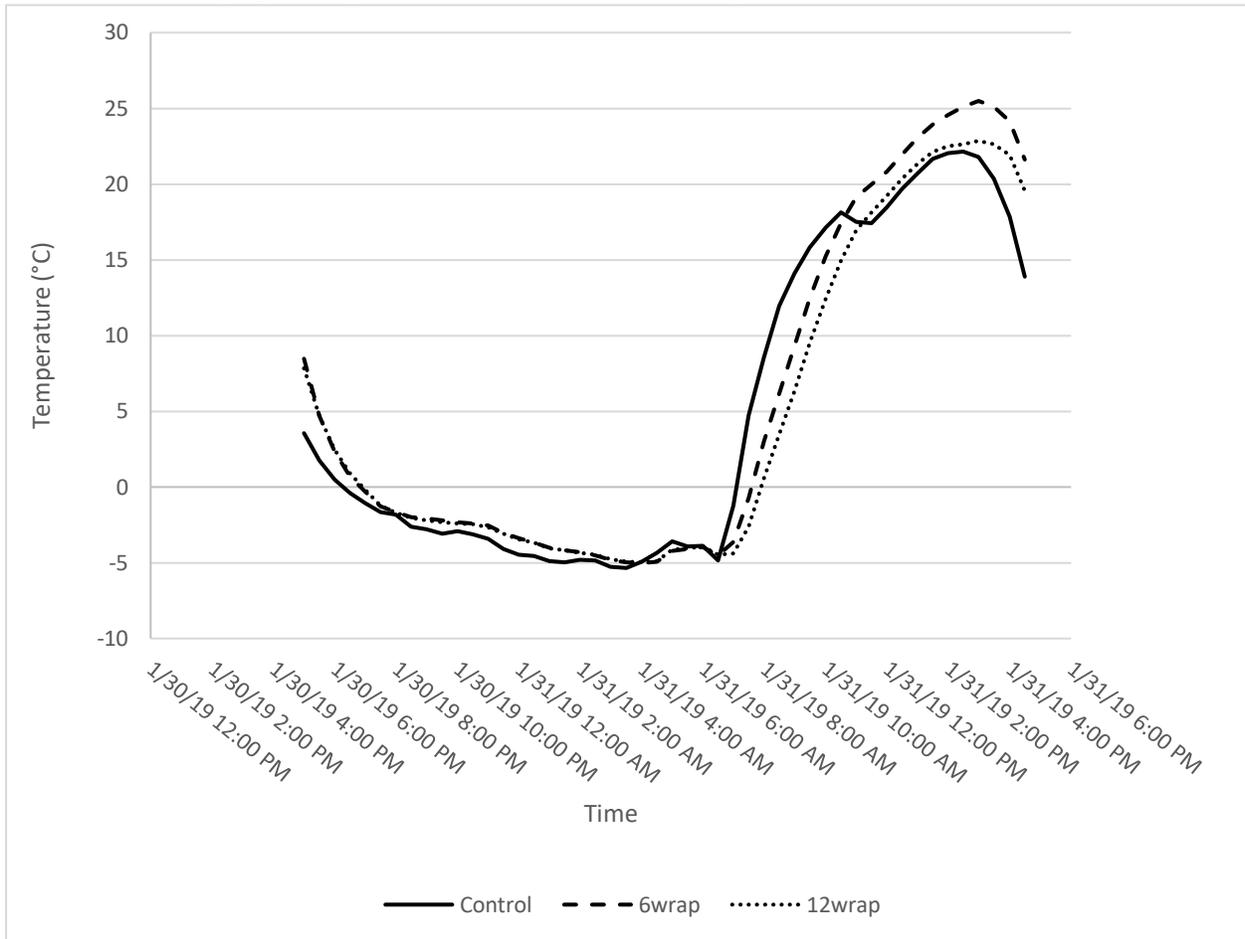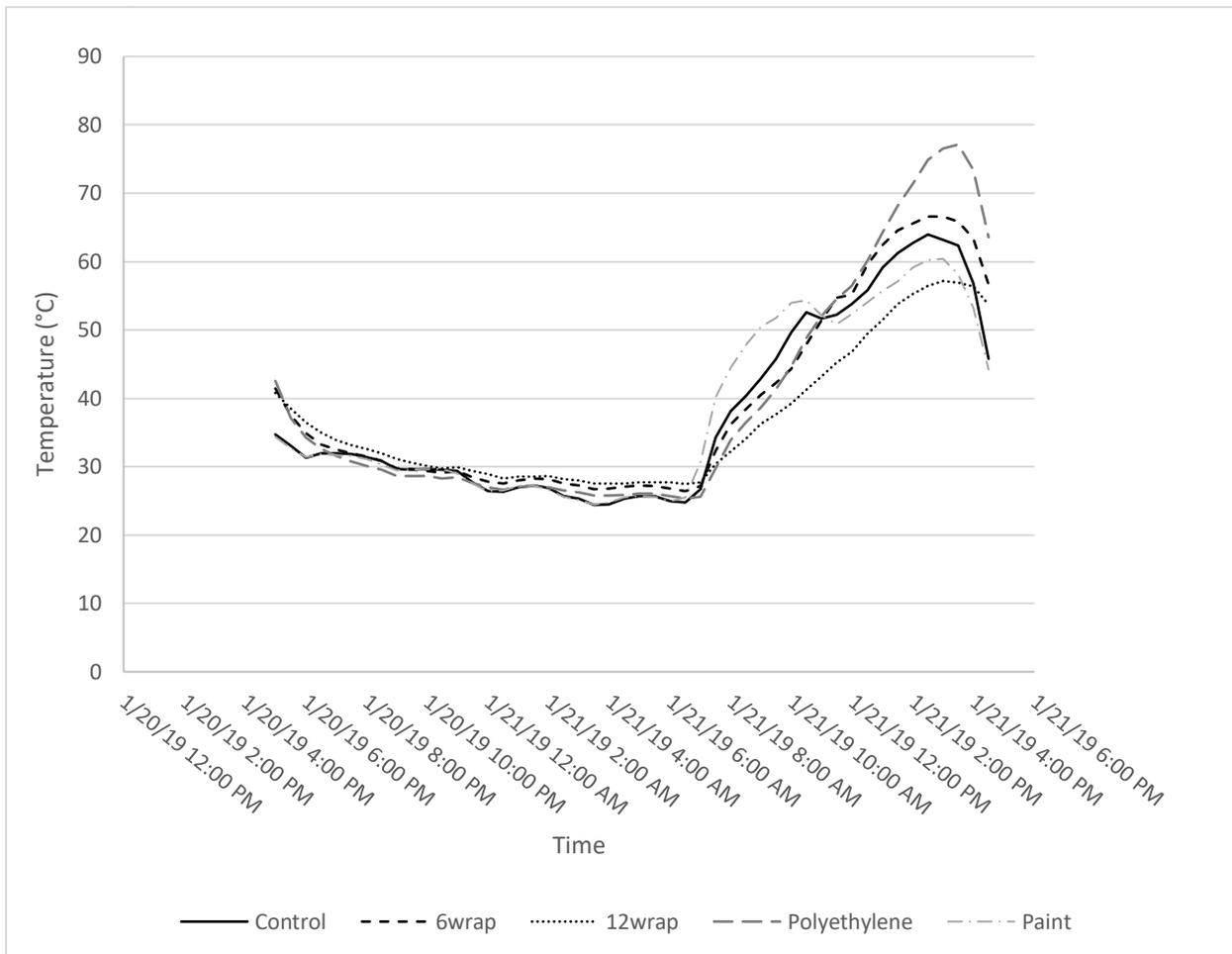

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap).Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 27 Nov. 2018 and 4:30 PM on 28 Nov. 2018.

Fig. 3.12. Effect of trunk wrap treatments [z] on trunk temperature of 1-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama during the freeze event on 5-6 Dec. 2018.
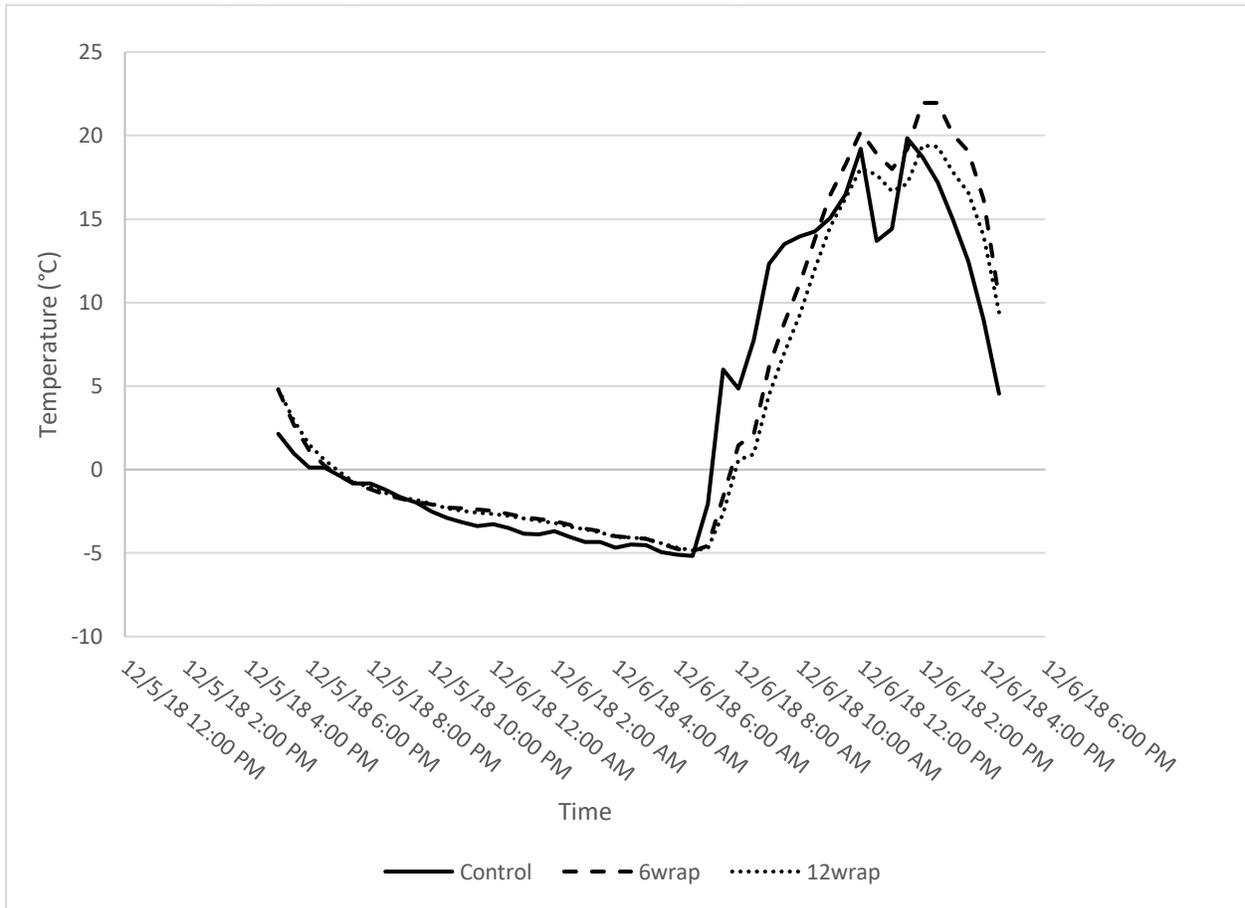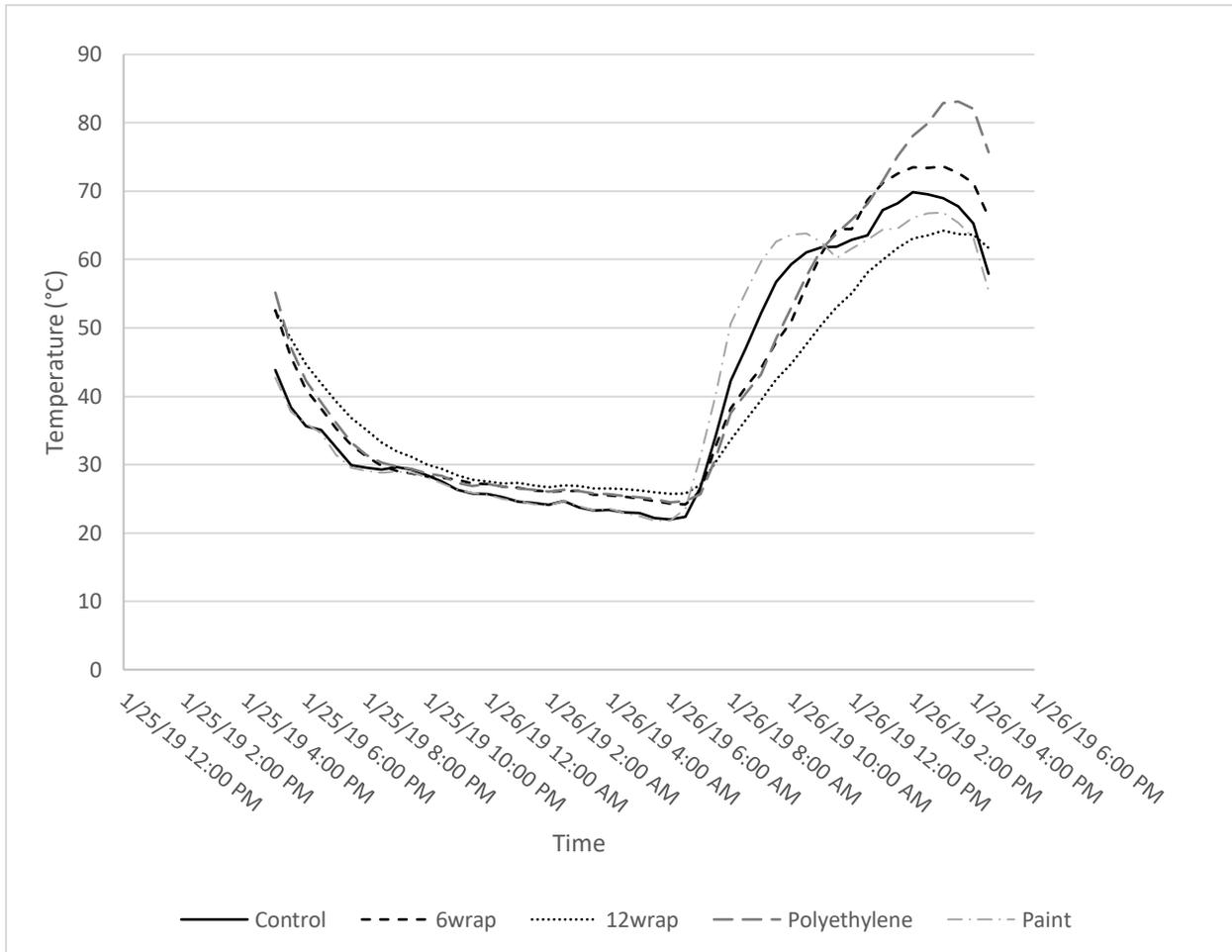

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 5 Dec. 2018 and 4:30 PM on 6 Dec. 2018.

Fig. 3.13. Effect of trunk wrap treatments [z] on trunk temperature of 1-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama during the freeze event on 11-12 Dec. 2018.

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 11 Dec. 2018 and 4:30 PM on 12 Dec. 2018.

Fig. 3.14. Effect of trunk wrap treatments [z] on trunk temperature of 1-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama during the freeze event on 29-30 Jan. 2019.
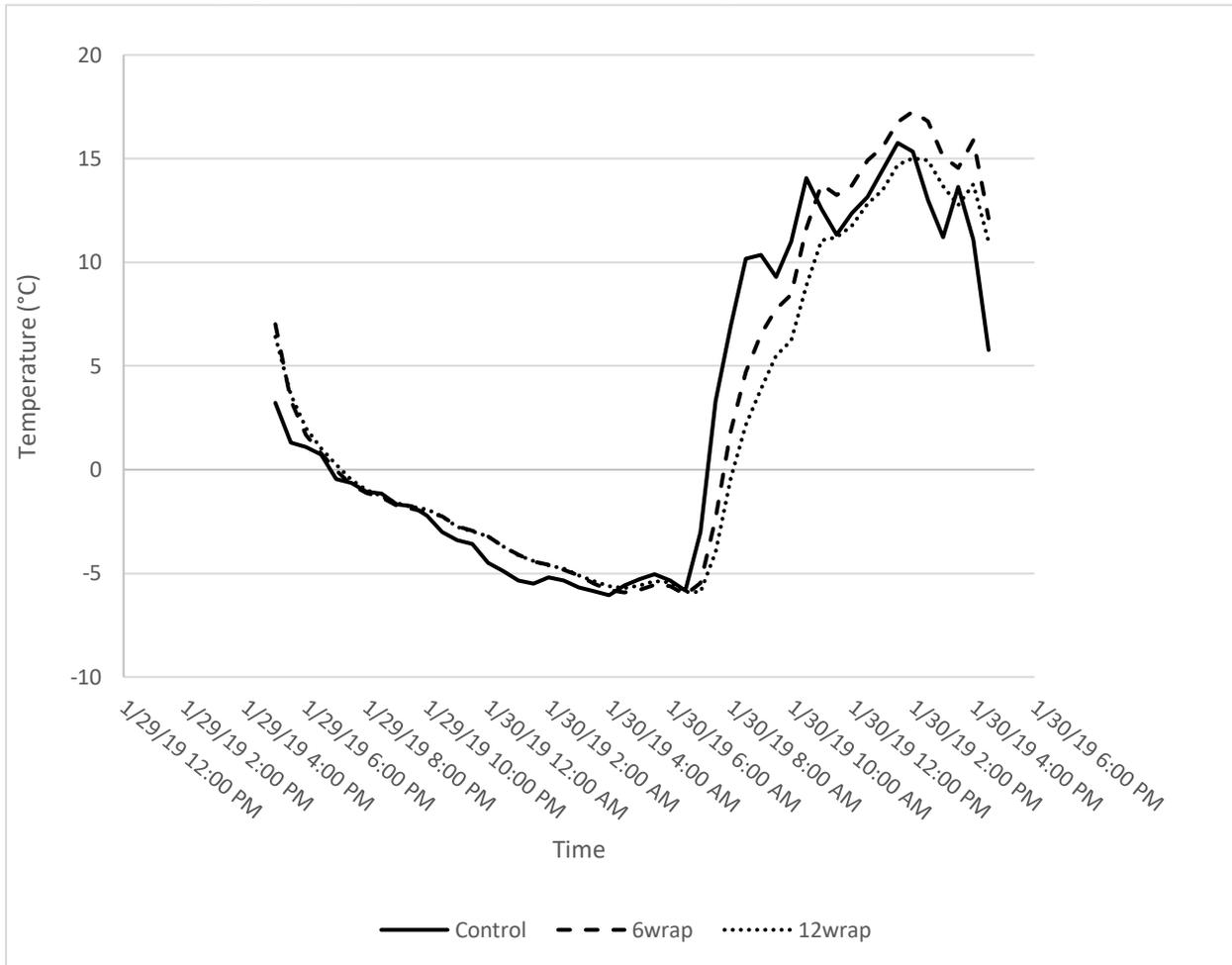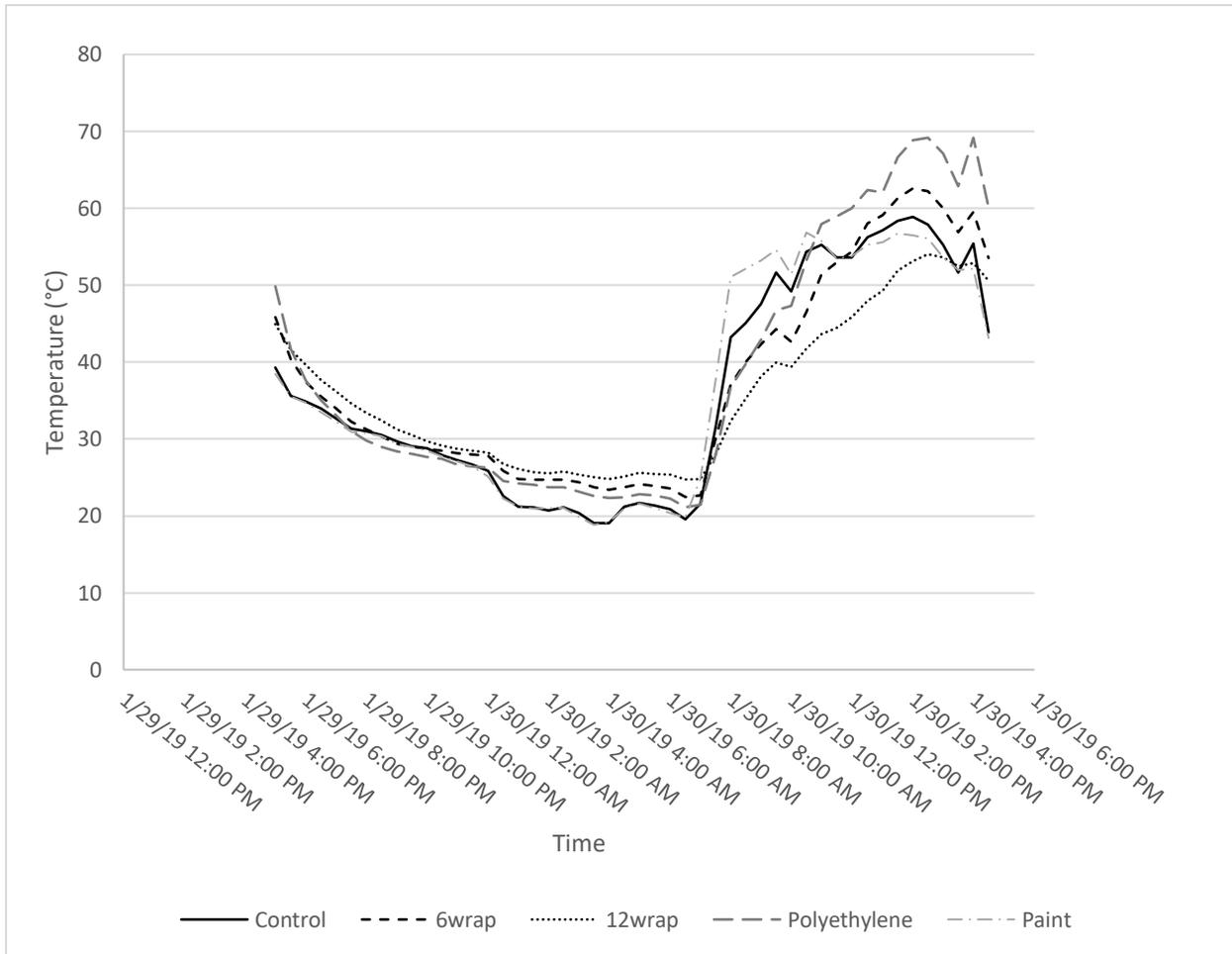

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 29 Jan. 2019 and 4:30 PM on 30 Jan. 2019.

Fig. 3.15. Effect of trunk wrap treatments [z] on trunk temperature of 1-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama during the freeze event on 30-31 Jan. 2019.
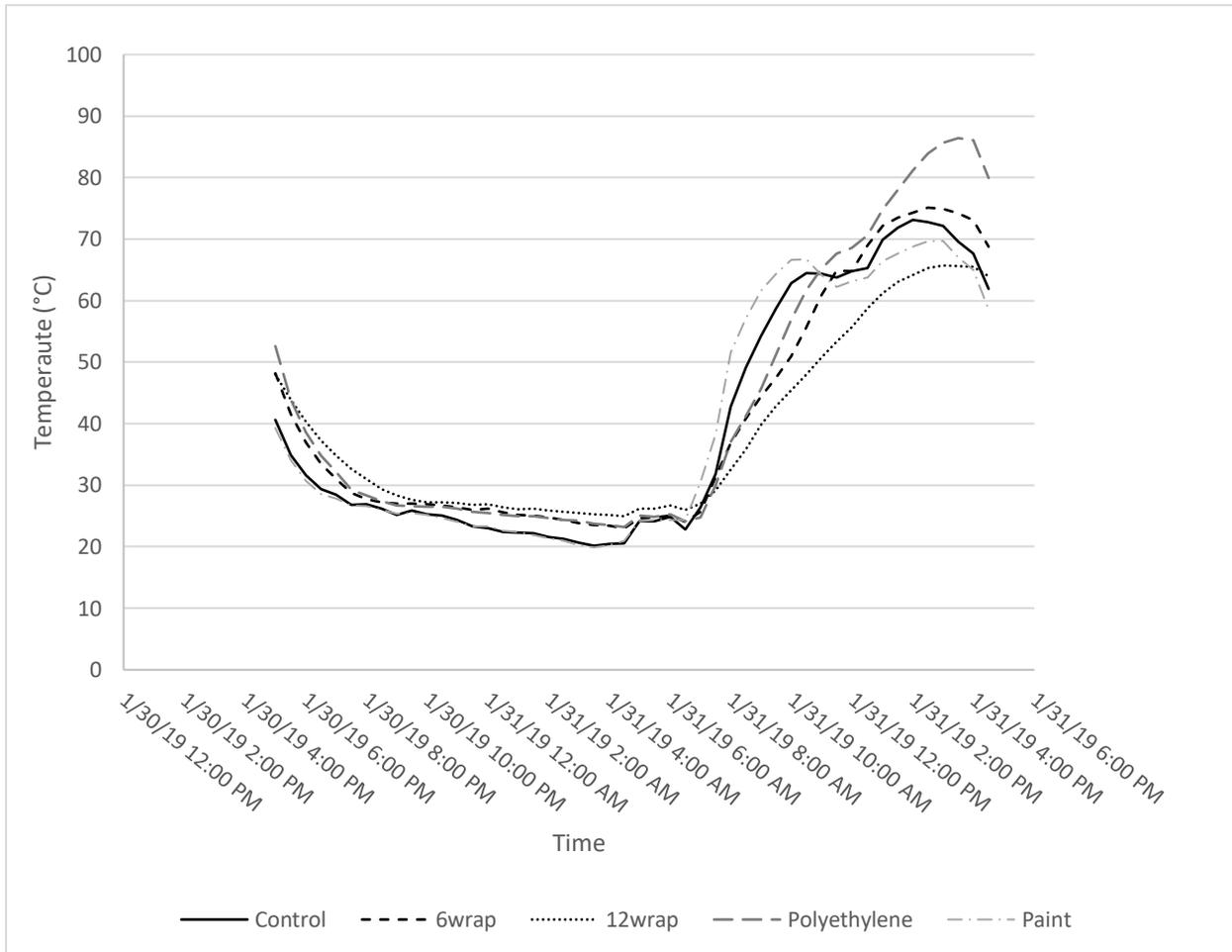

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Control vines were not wrapped. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 30 Jan. 2019 and 4:30 PM on 31 Jan. 2019.

Fig. 3.16. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 20-21 Jan. 2019.
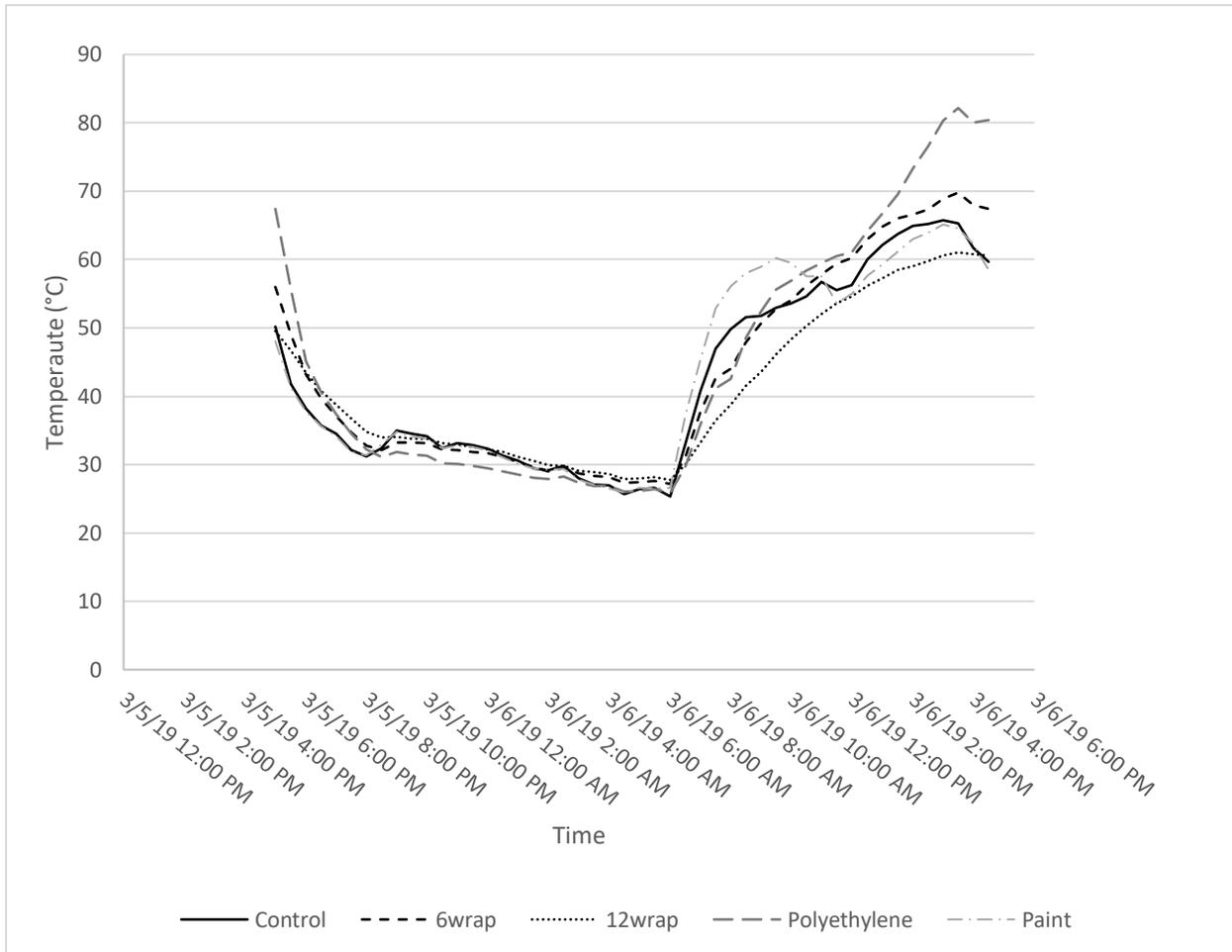

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 20 Jan. 2019 and 4:30 PM on 21 Jan. 2019.

Fig. 3.17. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 25-26 Jan. 2019

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 25 Jan. 2019 and 4:30 PM on 26 Jan. 2019.

Fig. 3.18. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 29-30 Jan. 2019.
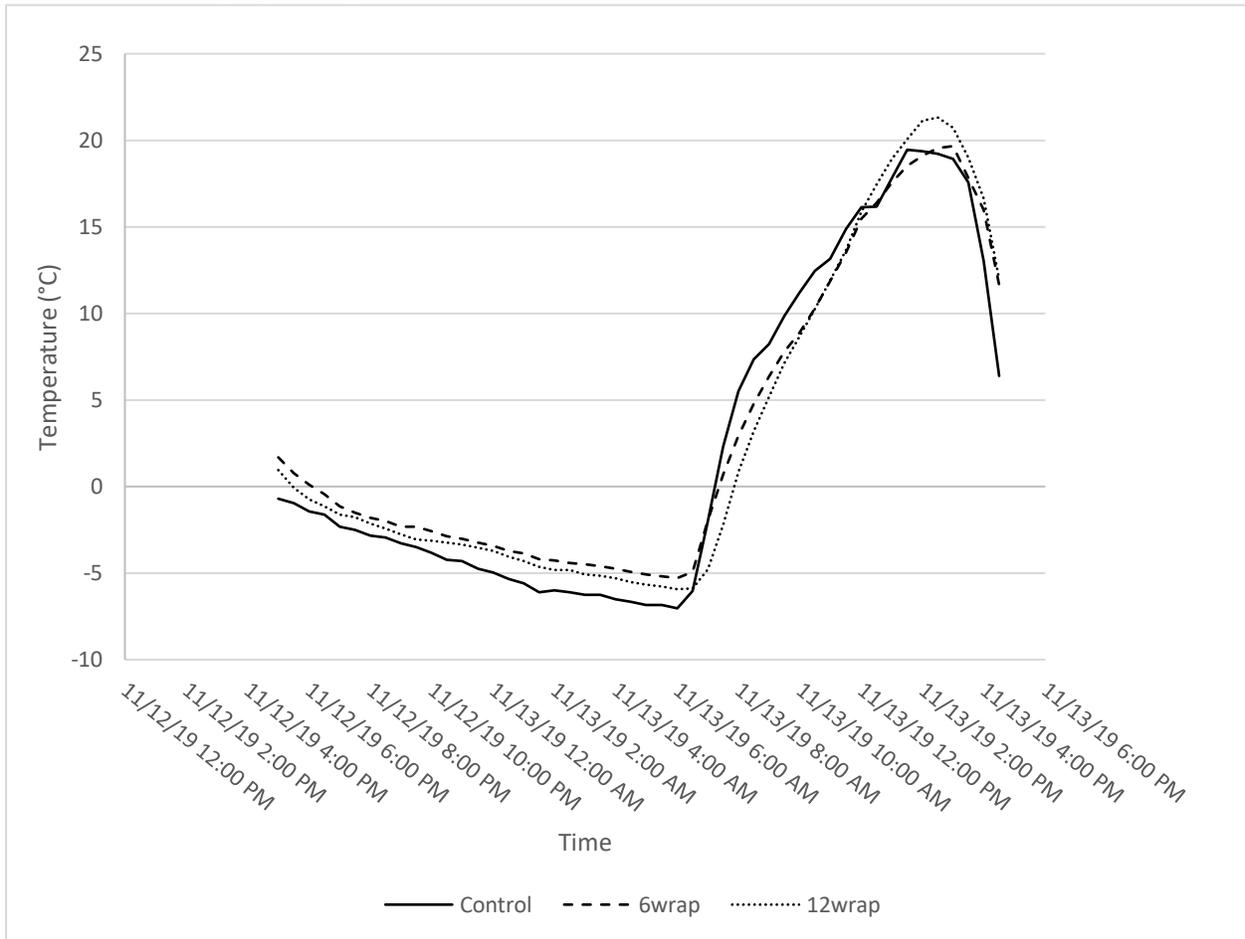

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 29 Jan. 2019 and 4:30 PM on 30 Jan. 2019.

Fig. 3.19. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 30-31 Jan. 2019.
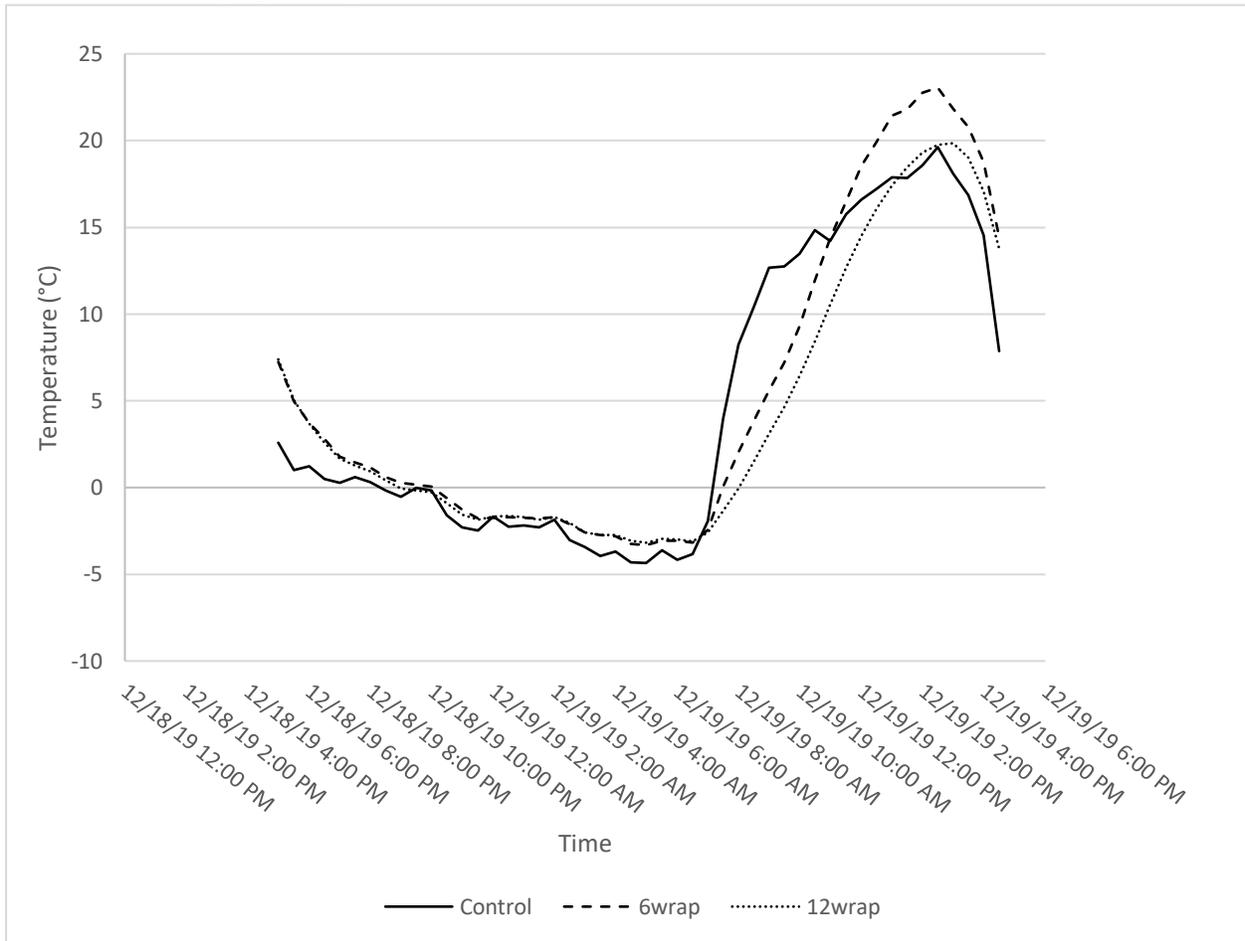

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 30 Jan. 2019 and 4:30 PM on 31 Jan. 2019.

Fig. 3.20. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 5-6 March 2019.

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), white latex trunk paint (Arizona's Best Tree Paint, Gro-Well Brands, Tempe, AZ.), and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 5 March 2019 and 4:30 PM on 6 March 2019.

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Fig. 3.21. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama on 12-13 Nov. 2019.
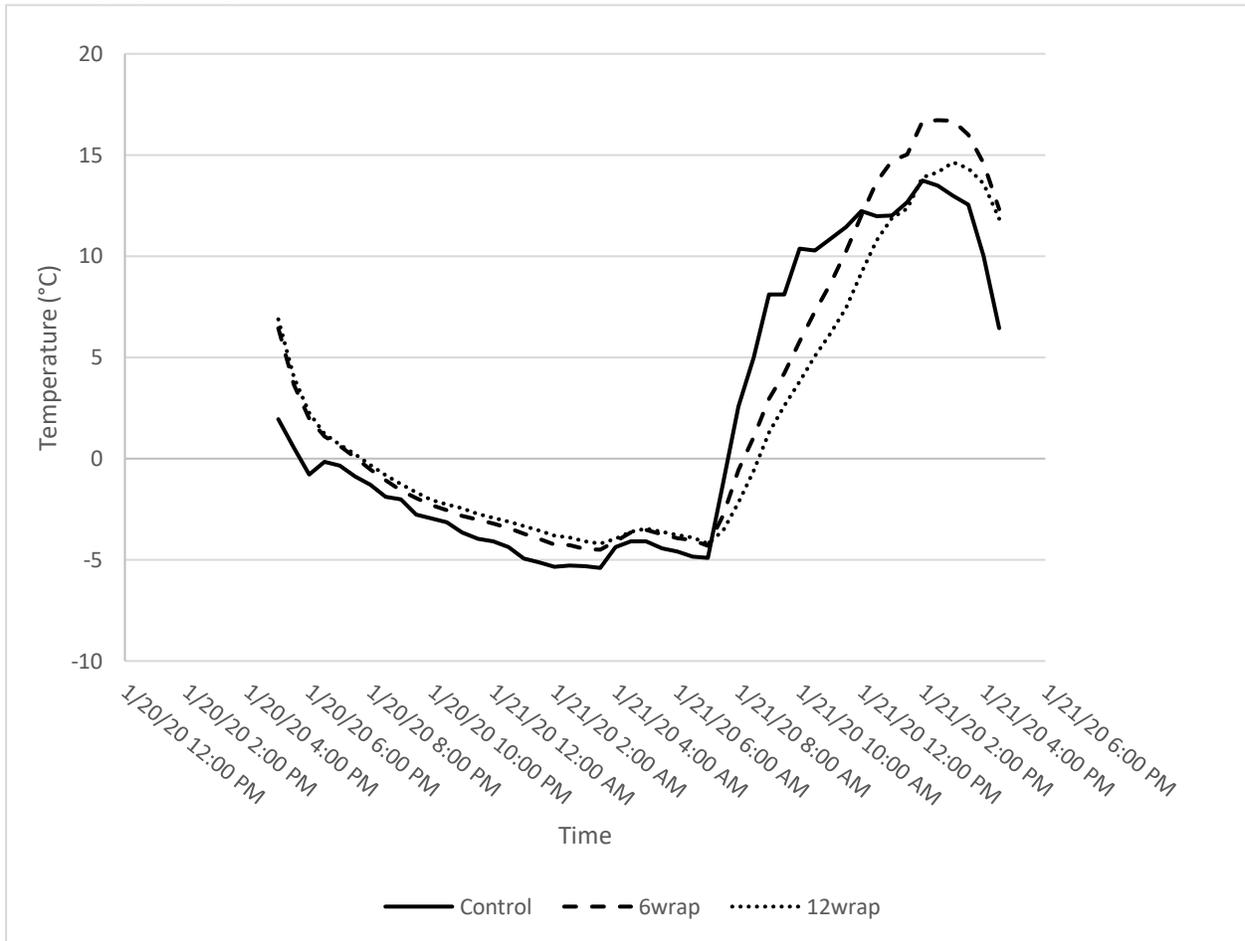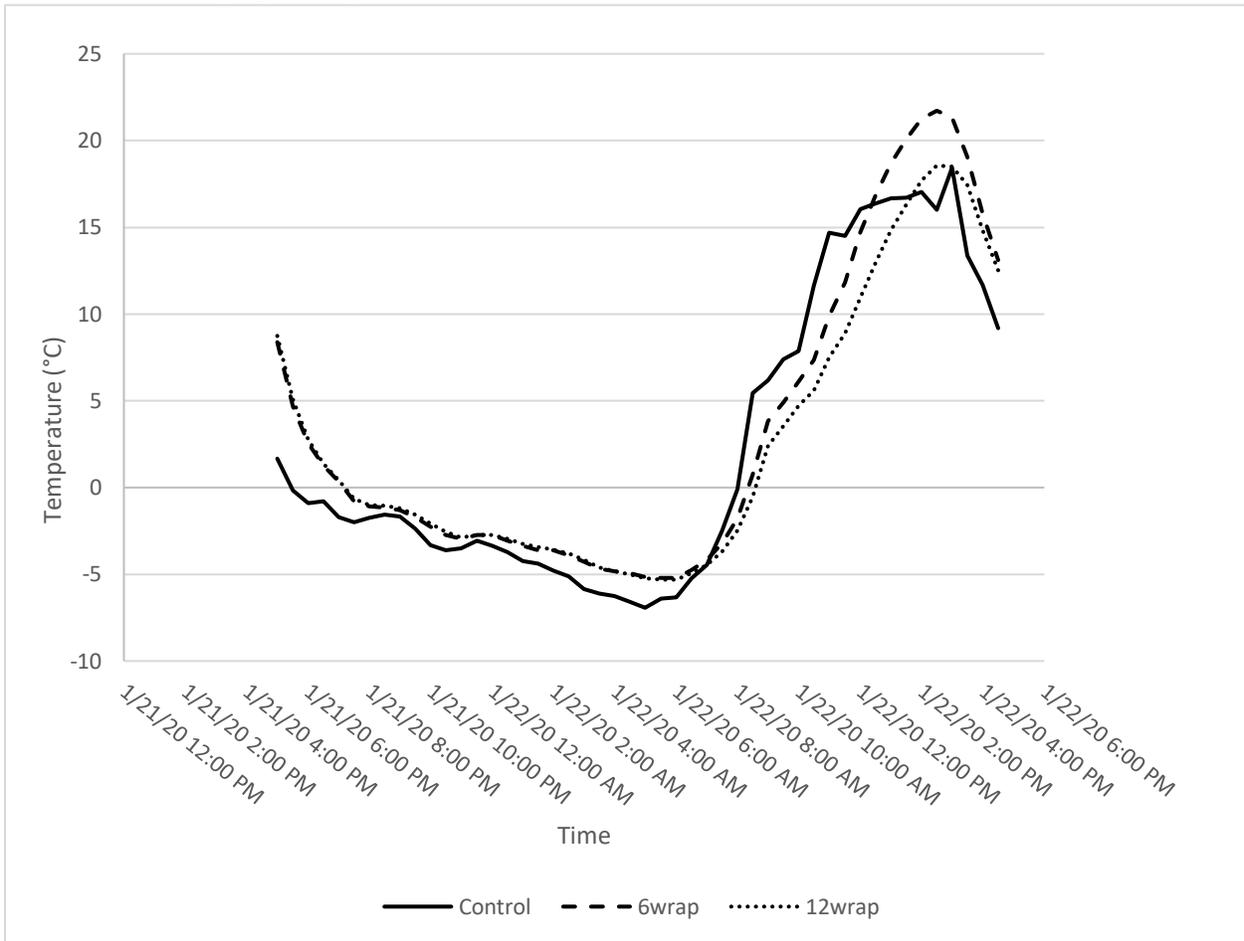

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 12 Nov. 2019 and 4:30 PM on 13 Nov. 2019.

Fig. 3.22. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama on 18-19 Dec. 2019.
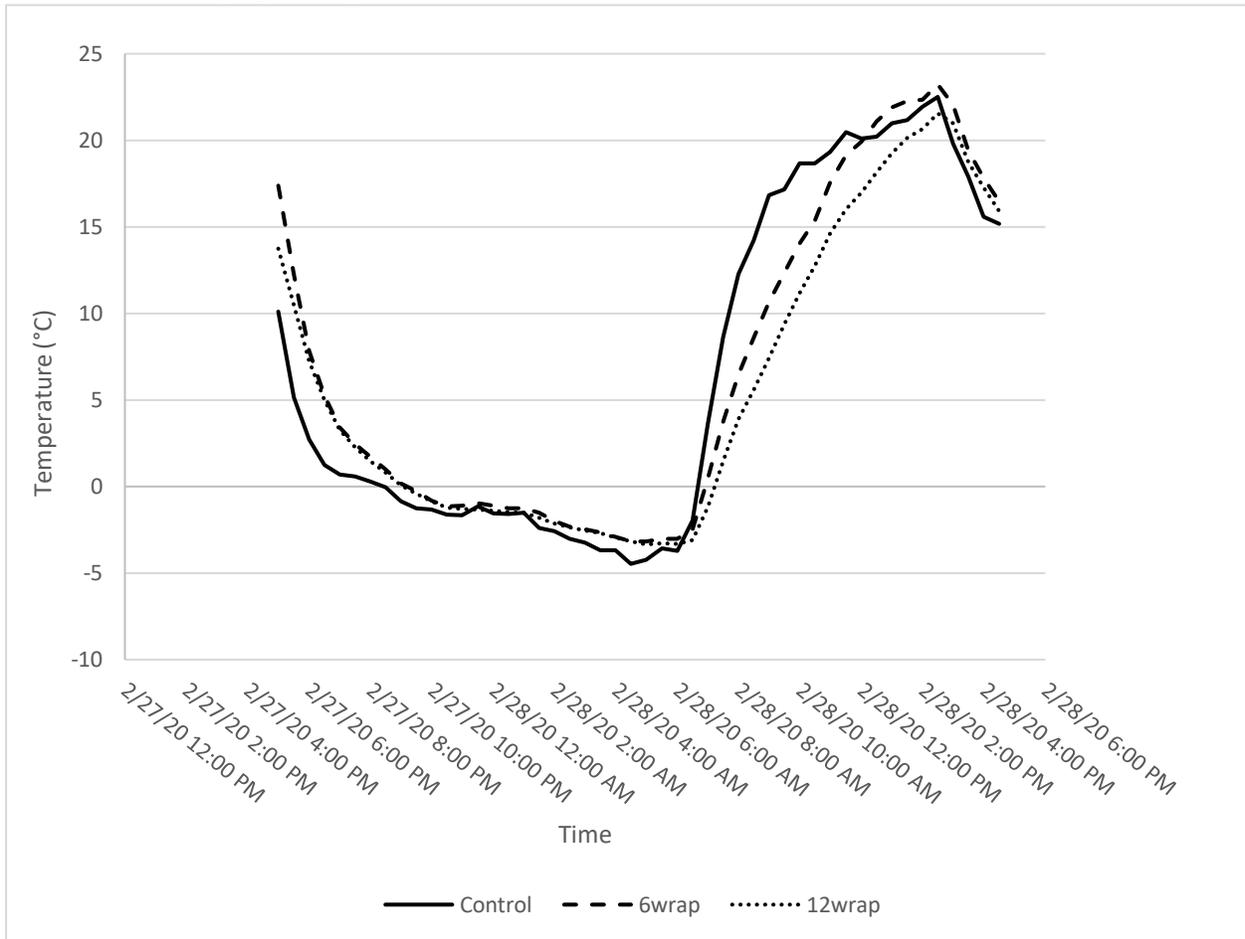

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 18 Dec. 2019 and 4:30 PM on 19 Dec. 2019.

Fig. 3.23 Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama on 20-21 Jan. 2020.

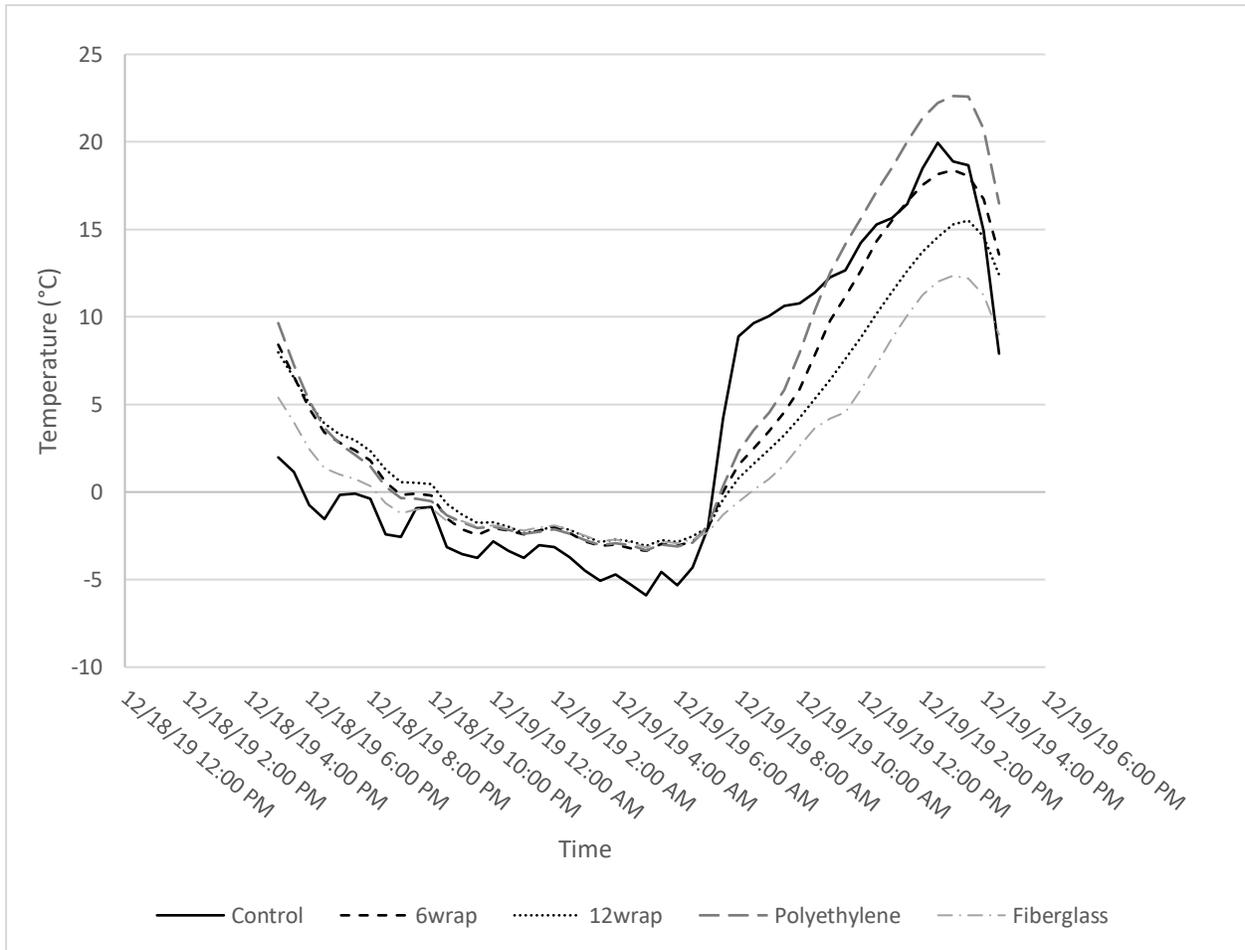[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 20 Jan. 2020 and 4:30 PM on 21 Jan. 2020.

Fig. 3.24. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama on 21-22 Jan. 2020.

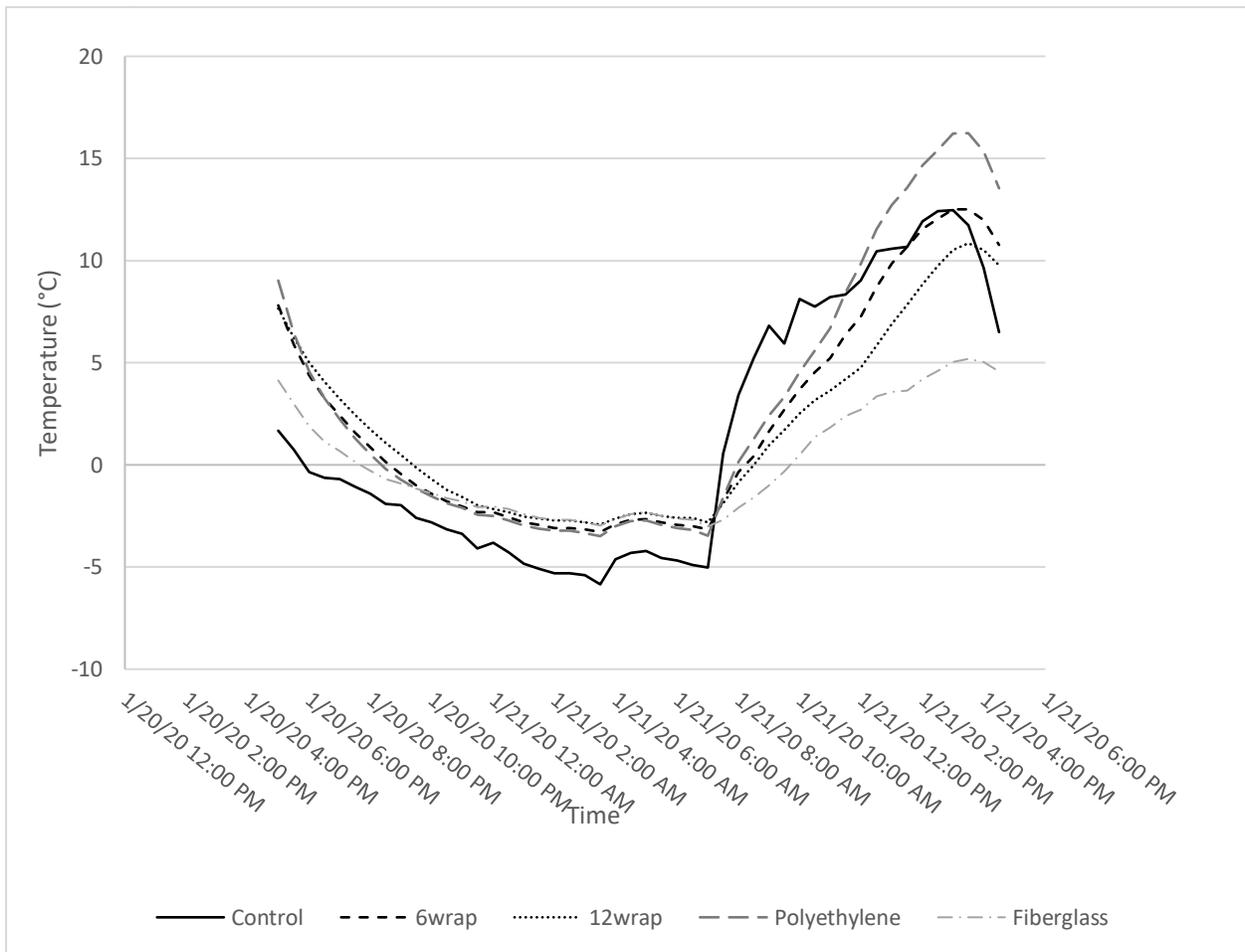[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 21 Jan. 2020 and 4:30 PM on 22 Jan. 2020.

Fig. 3.25. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings growing in Reeltown, Alabama on 27-28 Feb. 2020.

[z] Treatments were an untreated control and wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap). Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 27 Feb. 2020 and 4:30 PM on 28 Feb. 2020.

Fig. 3.26. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 18-19 Dec. 2019

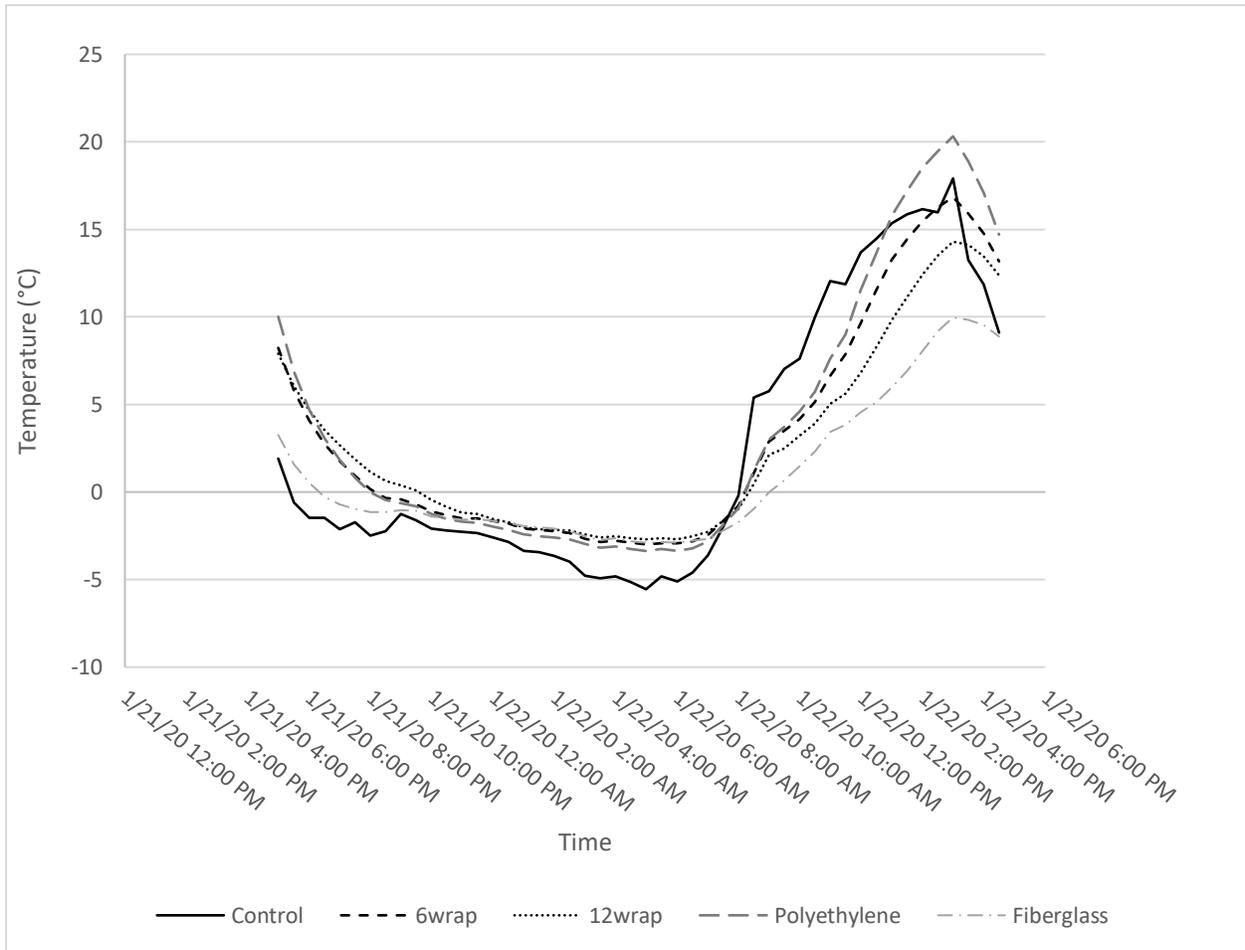[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 18 Dec. 2019 and 4:30 PM on 19 Dec. 2019.

Fig. 3.27. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 20-21 Jan. 2020.

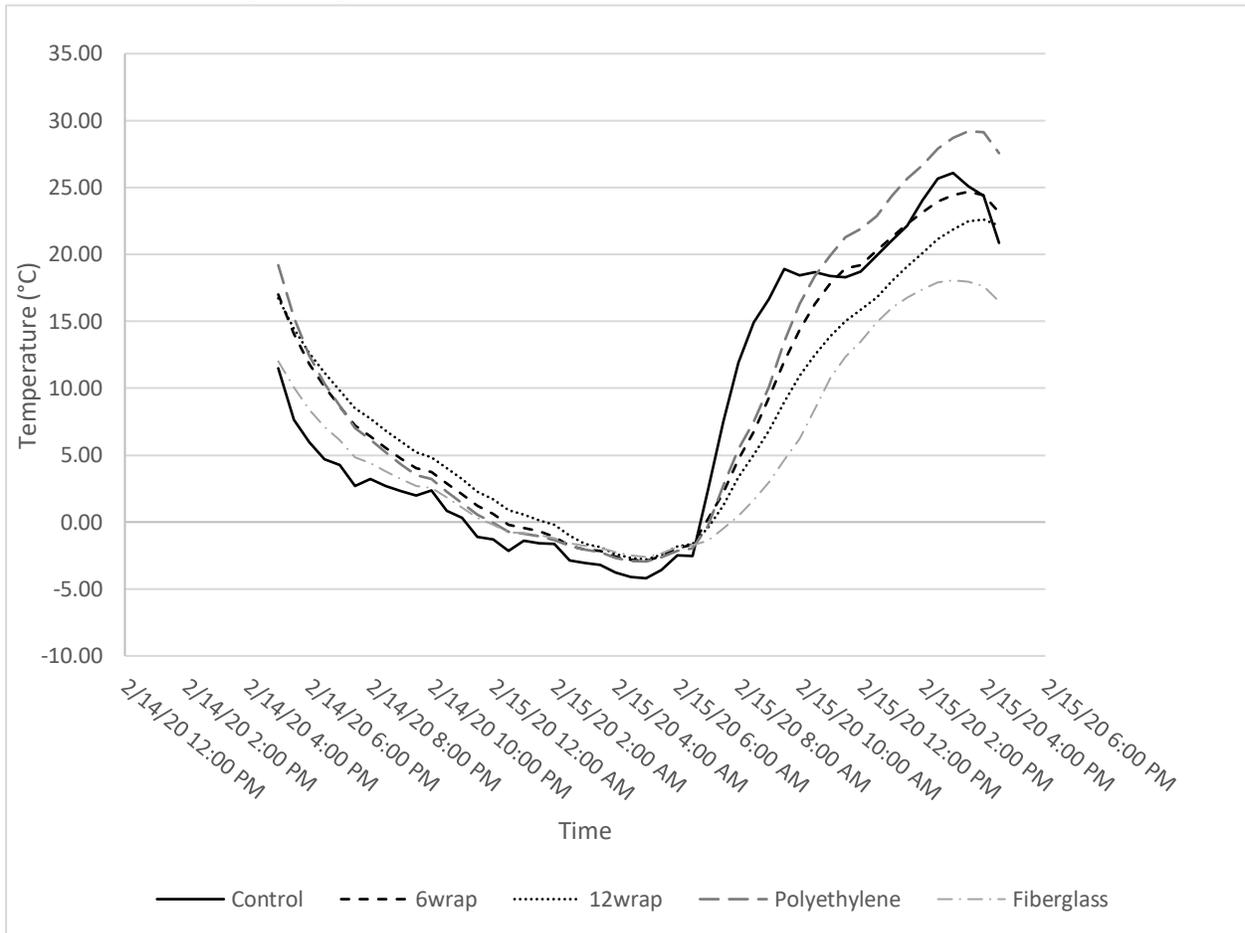[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 20 Jan. 2020 and 4:30 PM on 21 Jan. 2020.

Fig. 3.28. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 21-22 Jan. 2020.

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 21 Jan. /2020 and 4:30 PM on 22 Jan. 2020.
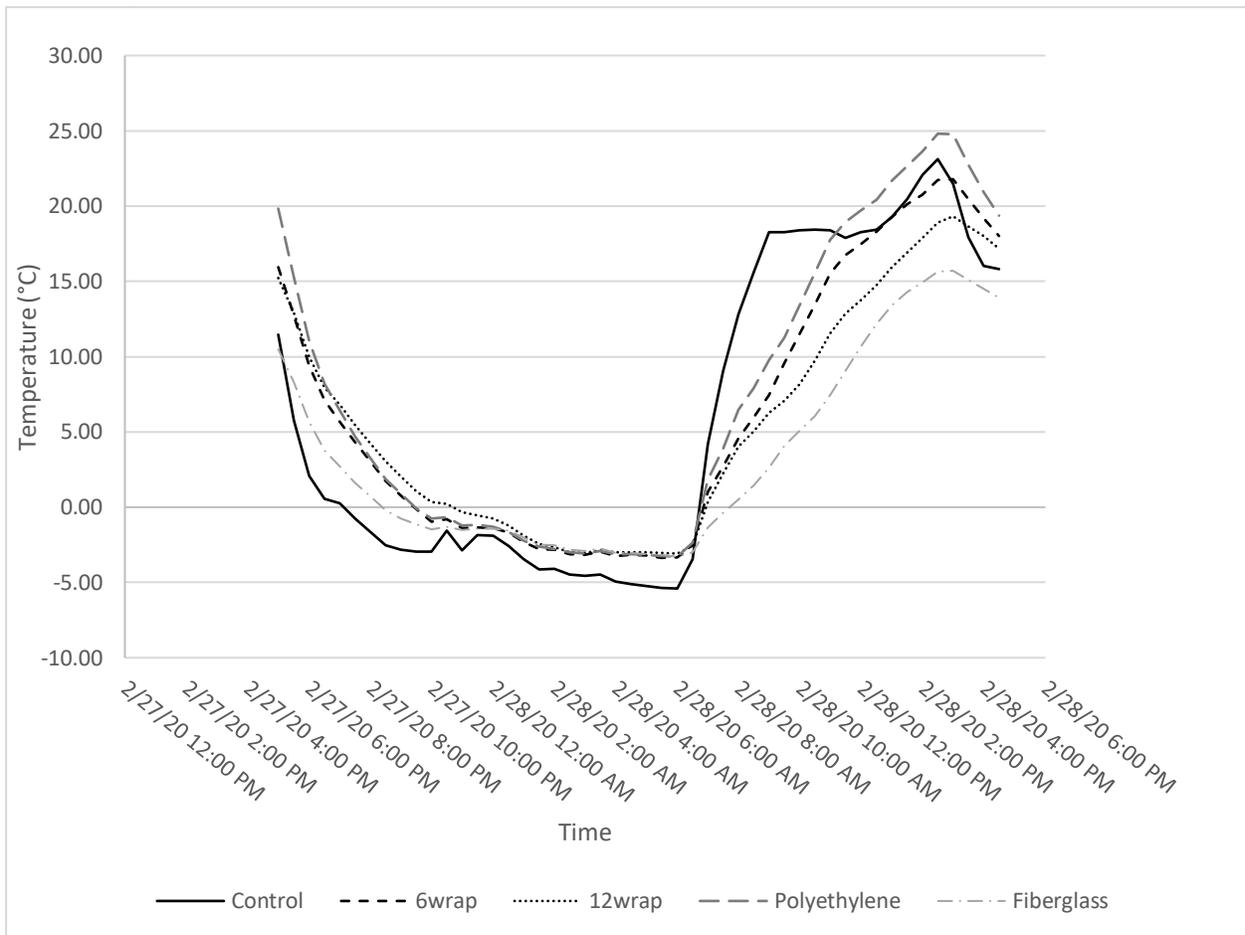
Fig. 3.29. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 14-15 Feb. 2020. Fig. 3.30. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 14-15 Feb. 2020.

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 27 Feb. 2020 and 4:30 PM on 28 Feb. 2020.

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 14 Feb. 2020 and 4:30 PM on 15 Feb. 2020.

Fig. 3.30. Effect of trunk wrap treatments [z] on trunk temperature of 2-year-old *Actinidia deliciosa* seedlings rootstocks grafted with *A. chinensis* 'AU Golden Sunshine' growing in Reeltown, Alabama on 27-28 Feb. 2020.

[z] Treatments were an untreated control, wraps made of spun-bound polypropylene (Gro-Guard UV GG-51, Atmore Industries, Atmore, AL) row covers wrapped around the vine 6× (6-wrap) and 12× (12-wrap), fiberglass insulation 2.2 cm thick, and tan-colored polyethylene 2cm thick. Temperatures were recorded at 30-minute intervals. Times shown are between 5:00 PM on 27 Feb. 2020 and 4:30 PM on 28 Feb. 2020.