USE OF WATER MIST TO REDUCE THE RISK OF FROST DAMAGE IN TREE FRUITS

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ABSTRACT

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Climate variability and change have been major threats to global food security historically and will almost certainly continue to be threats in the future given the sensitivity of agricultural production systems to their surrounding environment. Recent changes in temperature and seasonality have significantly impacted commercial fruit production in the Great Lakes region. Michigan's sour cherry and apple production in 2012 was reduced by about 90% and 88%, respectively, compared to the previous year's production due to a series of spring freeze events (USDA, 2013). The timing of the seasonal warm up in the spring and resulting onset of phenological development is a key factor in determining potential cold damage risk for overwintering perennial tree fruit crops, as the vulnerability of vegetation to freeze injury increases rapidly with the stage of development. Application of water prior to the onset of growth has been used in the past to delay early vegetative development of temperate tree fruit crops. Evaporative cooling associated with this approach effectively reduces plant tissue temperature, slowing the rate of growth and leaving it less vulnerable to freezing temperatures. There are several potential drawbacks, like higher volume of water use, nutrient leaching.

This study examined the potential effectiveness of water applied as a spray mist via a new plant management technology, the solid set canopy delivery system (SSCD), to suppress tree fruit bud temperatures and delay the phenological development of the buds. There were two major portions: 1) A detailed collection of field-based phenological and physiological observations associated with the operation of a prototype SSCD cooling system and: 2) Development of a deterministic model of tree fruit bud temperature that was used to examine the potential of water-based cooling of buds in Michigan. The observational study aimed to identify the timing and discharge rate of mist applications on cherry and apple trees was carried out in a growth chamber and at five Michigan orchards (apple at St. Joseph, Charlotte, and Hillsdale, sweet cherry at SWMREC, and sour cherry at Traverse City,) during the 2014, 2015, and 2016 growing seasons with automated instrumentation to monitor and control the water mist flow rate based on environmental conditions. Water mist was applied to apple and cherry buds via the SSCD system after the end of endo-dormancy until king bloom in the non-misted buds based on ambient air temperature and relative humidity. Overall, in three years of the field study misting delayed bloom by 4-9 days in apple and 7- 11 days in cherry, all using substantially less water than that reported in earlier studies; 8.4 to 26 cm/ha in apple and 5.5 to 10.8 cm/ ha in sweet cherry. The deterministic heat transfer model of a tree fruit bud was developed with observational data from growth chamber, potted plant based studies. The model was calibrated using growth chamber data and validated using potted plant and field data. In a model validation study, model simulated one-minute bud temperatures were generally found to be in good agreement with observed bud temperatures, with overall mean average differences of -0.5±0.3^{0}C (lab observations) and -0.3±0.15 ^{0}C (field observations), mean absolute differences less than 1^{0}C and R-square values of 0.80 or greater. The model was then run with ten years of climate data at three major fruit-producing regions of Michigan (2006-2015). Overall, the model estimated a delay in bloom of misted buds by more than a week compared to non-misted buds, which translates into a potential reduction in the frequency of damaging freeze events of 50-75 %, and decrease in freeze injury severity by 10-60 % in misted apple buds and 45-100% in misted cherry buds. Collectively, the results suggest that the spray mist technique as a straightforward and effective indirect frost control strategy with relatively few environmental impacts.

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KEY TO ABBREVIATIONS

C	Conductive Heat Transfer
DD	Degree Days
GDD	Growing Degree Days
H	Convective Heat Transfer
HC	Honey Crisp
HTRC	Horticulture Teaching and Research Center
LE	Latent Heat Transfer
MAWN	Michigan Automated Weather Network
NASS	National Agricultural Statistics Service
RD	Red Delicious
RH	Relative Humidity
Rn	Net Radiation
SSCD	Solid Set Canopy Delivery
SWMREC	Southwest Michigan Research and Extension Center
Tair	Air Temperature
Tbud_obs_misted	Observed Temperature of the Misted Buds
Tbud_sim_misted	Simulated Temperature of the Misted Buds
Tbud_sim_nonmisted	Simulated Temperature of the Non-Misted Buds
USDA	United States Department of Agriculture

CHAPTER 1: INTRODUCTION

Michigan's climate is impacted by the Great Lakes. It also has great impact on the horticultural crops grown in the proximity of Great Lakes region in Michigan ranging from north to south towards the downwind shore of Lake Michigan. The total annual economic value of Michigan's fruit production is approximately $ 800 million and apple is the largest and most valuable fruit crop grown in the state (USDA/ NASS, Michigan field office 2014). Within the last few decades, Michigan leads the United States in states producing sour cherries, and for the last 30 years the state has ranked third in the production of apple, contributing to highest amount in the economy of the state. In 2013, the preliminary farm level values of sour cherry was $72.9 million and apple was $228 million (USDA/ NASS, Michigan field office 2015). Also, sweet cherries ($25.8 million), peaches ($6.61 million), grapes ($19.3 million), pears, plums, etc. are grown in the state.

The fruit crops in the state are influenced by the change in climate. The winter temperature of the state is moderated by the ice coverage in the Great Lakes (Andresen et al. 2012). Within the last few decades, lower ice coverage in the Great Lakes region is responsible for warmer winters in the area, increasing the minimum winter temperature (Andresen and Winkler 2009; Wang et al. 2012). This resulted in the fulfillment of the chilling units earlier than normal. While buds began to develop earlier, there is a relatively smaller change in the date of the last day of spring frost (Winkler et al. 2013), causing frost damage to buds in the later parts of spring. The state’s fruit production in 2002 and 2012 was reduced by spring frost damage to buds/flowers in Michigan. In 2012, the unprecedented heat waves of March brought the buds out of their dormant stage, at least a month earlier than normal. A series of freezing temperatures in April followed the warm temperature of March, killing the buds/flowers. This reduced the production rate of apples by 88 %, sour cherries by 90 %, and sweet cherries by 78% compared to previous year (USDA/ NASS, Michigan field office 2013), causing the a huge economic loss for state fruit economy. While the damage was more drastic in 2012, it was not the first time this occurred, in 2002, apple production of the state was reduced by 42 % and sour cherry production by 50% due to early spring warming followed by frost. Similar damage to fruit buds was observed in Utah, Washington (state), and North Carolina.

Climate-related constraint is the major threat to the temperate fruit crops all over the world. Late spring frost, early fall frost, low winter temperature, and sudden changes in temperature causes several injuries to plants. Chilling injuries such as freezing injury (early and late frost), frost cracking, winter desiccation, and salt damage can be observed in plants. Freeze injury in temperate fruit plants may occur in fall before dormancy, at mid-winter during dormancy, or in spring during bud development.

The life cycle of temperate fruit crops includes dormancy, chilling requirement (endo-dormancy), bud break (driven by temperature), shoot and root growth, flower bud initiation, flower bud development, fruit growth, abscission, and dormancy. Dormancy, the period in which a plant experiences no visible growth, impacts plant development and flower initiation. According to Lang et al. (1987) "Dormancy is a temporary suspension of visible growth of any plant structure containing a meristem". The buds or plant could be in dormant phase at the different time and different stages of development. The wide range of dormancy is defined in three different terms; eco-dormancy, para-dormancy, and endo-dormancy (Lang et al. 1987). Eco-dormancy is caused by environmental factors such as temperature and water stress. It includes heat requirement for bud burst in spring (Sedgley 1990). Para-dormancy is due to physiological factors outside the plant for example apical dominance, photo periodic response.

Endo-dormancy is due to physiological factors within the plant (shoot apex). It is associated with the chilling and photo period response. The chilling requirement and bud break are influenced by weather conditions. The vegetative and reproductive buds do not break their dormancy until the chilling requirement is completed. The chilling requirement varies with crops and cultivar. Most of the fruit crops grown in Michigan have the chilling requirement of 700 to 1,300 chilling units (MSU extension 2013), which express the number of hours a plant is exposed to chilling temperatures between 0 and 7 ^{0}C (Sedgley 1990). The chilling requirement is completed by late January in Michigan; however, the plants and buds remain dormant because of cold weather (MSU extension 2013). Temperatures above 7 ^{0}C lead to the development of dormant buds. Dormant flower buds are less vulnerable to low temperature, but lose their resistance throughout the development of reproductive stages. The severity of injury depends both on the intensity and duration of critical temperature (Rodrigo 2000). Critical temperatures at different phenological stages are shown in Table 1.1, along with 10% and 90% bud damage thresholds after 30 minutes of exposure to the specified temperature.

Table 1.1: Phenological stages of bud and critical temperature in degrees C.

		Phenological stages of bud and critical air temperature							
Fruit	Percentage killed on different temperature (^{0}C)	Silver Tip	Green tip	Half inch green	Tight cluster	First pink	Full Pink	First bloom	Full bloom
Apple	10%	-9	-8	-5	-3	-2	-2	-2	-2
	90%	-17	-12	-9	-6	-4	-4	-4	-4
		Swollen bud	Bud burst	Tight cluster	First white/ popcorn	First bloom	Full Bloom		
Sweet Cherry	10%	-8	-4	-3	-3	-2	-2		
	90%	-15	-10	-8	-4	-4	-4		
Sour Cherry	10%	-9	-3	-3	-2	-2	-2		
	90%	-18	-6	-4	-4	-4	-4		

Source: WSU EB1128, WSU EB0913, MSU Research. Rpt. 220

The buds and flowers of temperate fruit crops are vulnerable to late spring frost in different parts of the world (Hewitt and Young 1980, Andersen and Seeley 1993, Perry 1998, Tsipouridis et al. 2006, Ghaemi et al. 2009, Darbyshire et al. 2014). If the temperature in early spring is higher than normal, the development of vegetative and reproductive bud advances and causes the bud break. Different parts of the world are reporting an earlier blooming of the apple compared to normal, due to rise in temperature (Wolfe et al. 2005, Guedon and Legave 2008, Grab and Craparo 2011). In the last 20-25 years, bud burst of apple has advanced by 2.5 days per decade (Eccel et al. 2009) with minimal or no change in last spring frost day. The frost event succeeding bud break in the later part of the season damages the flowers and buds.

There are two types of frost events: advection and radiation. An advection frost occurs when cold air blows into the area to replace the warmer air in the area. It is associated with moderate to strong winds and does not have temperature inversion. The temperature drops below freezing and remains there for the entire day. Radiation frosts are characterized by clear skies, calm wind and temperature inversion. On a clear night, more heat is radiated from an orchard than it received leading to drop in air temperature. The temperature drops faster near the surface resulting in an inversion. Most frost protection methods are effective when the temperature increases rapidly with height.

Several frost protection methods are widely practiced, such as site selection, mulching, trunk painting, and wraps. Site selection could be the first approach to reduce the risk to plant, buds/flowers. Planting the trees to the uphill in sloped topography could be one way to decrease the frost damage (Ashcroft 2012). The cold air formed uphill is drained towards the low lying areas due to pressure gradients and density causing cold air drainage. The gradient of 2-10% is optimal for cold air drainage (Ashcroft 2012). Some active frost protection methods include wind machines, orchard heaters, temperature inversion helicopters, micro sprinklers, and flooding. Orchard heaters replace the energy loss by adding the heat to the orchard. However, orchard heaters are not an efficient method, as a large portion of energy is lost in the sky, wind frequently interferes, and the heaters contribute to air pollution. Wind machines replace the colder air near the surface by pulling down the warmer air from above. It also breaks micro scale boundary layers over plant surfaces, which improves sensible heat transfer from the air to the plants. However, wind machines are not effective on windy days (Morrow and Martsolf 2004), and initial investment cost is high. Like wind machines, helicopters move warm air from aloft in a temperature inversion to the colder surface. However, flying a helicopter at night and at a lower height (close to the ground) in the orchard is always a risk. Also, refueling helicopter in between the flights in frost night and longer pass period could increase the risk of frost damage and chances of ice nucleation (Morrow and Martsolf 2004). Even with all those drawbacks, orchard heaters, smudge pots, wind machines, and helicopters are popular in Michigan. Compared to above discussed methods sprinklers and flooding application are an environment friendly method. These systems apply water frequently and do not allow plant tissue temperature to fall below freezing. This system is used in different parts of the world (discussed in chapter 2). However, these systems have high installation costs and use a higher volumes of water that could cause water logging, nutrient leaching, pathogens, and problems with diseases in plants.

Water application should neither limit the evaporative cooling nor exceed the required amount of water causing soil saturation. Water may either lead to evaporative cooling or release latent heat of fusion if it freezes. Water application to the plant also influences the net radiation and sensible heat flux in the plant body. Besides, surface long wave radiation is the driving force in nocturnal cooling and frost is common at night with clear skies because the outgoing long wave radiation is transmitted easily to the sky. However, during cloudy nights, clouds re-radiate the heat back to the surface and warm it. The temperature of a fruit bud is largely dependent on a balance between radiative, convective, and latent heat fluxes (only when wet). The rate of heat transfer and cooling is, in turn, dependent on the specific heat of the air (2020 J/kg K), the specific heat of water (4187 J/kg K) and the latent heat of vaporization of water (2250 J/kg). This means 1 kg of water evaporated from a surface removes heat at a rate more than 50 times that cooled by the water itself. Thus, the latent heat of vaporization is a critical factor in the cooling. The use of water to reduce frost damage is a very convenient method because it is capable of slowing down the rate of phenological development of bud through evaporative cooling and reducing the temperature of the bud and plant tissue. Also, the energy input is low compared to other traditional heaters, and it is relatively more environment-friendly (Barfield et al. 1981).

One potential approach to reducing the vulnerability of tree fruit to freeze events is the application of water during the late stages of dormancy and early vegetative stages to cool the plant tissue and delay the rate of growth and development. The buds vulnerability to cold damage increases rapidly from the end of dormancy through bloom. And so, any delay in phenological development potentially increases the chance of the bud tissue survival in spring freeze events. Water in the form of mist is a potentially convenient and environment-friendly method to reduce the frost damage by delaying the development of the phenology of the bud. A promising new variant of this approach is the application of water mist through solid set canopy delivery system (SSCD). The SSCD can theoretically provide the water necessary for cooling at a lower rate in the form of mist. This system is comprised of micro-emitters attached to the main or lateral pipe lines and dropped partially into the canopy using drop-tubing. The SSCD system is increasingly being used in high-density orchards for application of pesticides spray applications (Agnello and Landers 2006, Lang 2009, Grieshop 2015). The SSCD system consists of micro-sprayers placed above the canopy. The main or lateral lines are connected to the pumping. Main/lateral lines run through the orchard above the canopy. The system requires a pressurized application. Currently, the prototype is used at Michigan State University, Cornell University, and Washington State University to apply pesticides and insecticides. The goal of this research is to apply mist to the buds via the SSCD system to delay the blooming. The required volume of mist, mist discharge, and heat transfer can be determined from heat transfer theory.

The objectives of this dissertation are:

(1) Use prototype SSCD study to determine the potential delay in early reproductive development of cherry and apple buds by evaporative cooling,

(2) Develop a deterministic, process-based model of water mist applications on fruit bud,

(3) With the developed model,

a) Identify optimal water application rates based on ambient temperature and relative humidity for the effective rate of cooling and associated delay in phenological development.

b) Examine the potential applicability of SSCD under a variable and/or changing climate.

Dissertation organization

This dissertation is organized into two papers (Chapter 2 and Chapter 3) prefaced by general abstract and introduction and followed by general conclusions. Chapter 2 includes field research, use of prototype SSCD study to determine the delay in the apple, cherry, and apricot orchard. Chapter 3 includes model development, validation of the model and examination of the potential applicability of SSCD system under different climatic conditions.

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CHAPTER 2: MIST- COOLING TO DELAY BLOOM AND PREVENT FROST DAMAGE:- OLD IDEA, NEW TECHNOLOGY

Abstract

The primary weather-related constraint for most temperate tree fruit crops in the Great Lakes region is the frequency and severity of spring freeze events. The frequency of spring freeze events following initial phenological development has increased during the past few decades. Michigan's sour cherry and apple production in 2012 was reduced by about 90% and 88%, respectively, compared to the previous year's production due to a series of spring freeze events. The onset of phenological development in the spring is a key factor in determining potential cold damage risk, as the vulnerability of vegetation to freeze injury increases rapidly with the stage of development. Evaporative cooling with water prior to bud break has been used in the past (mid 70's and early 80's) to delay early development of flowers; one to three week delay was observed. However, related problems (more disease, poor fruit set, and large applications of water) reduced its potential for commercial use. This study re-examined the potential of mist-cooling to delay bloom by adapting a solid set canopy delivery system (SSCD), and evaporative cooling by application of water based on changes in temperature and humidity. Mist via SSCD system was applied in apple and cherry buds after endo-dormancy to king bloom emergence and full bloom of non-misted (control) reproductive buds. The rate of mist application and the interval between applications was based on the ambient air temperature and relative humidity from an evaporative cooling equation derieved under experimental (lab and field) conditions. The SSCD system used 8.4 to 26 cm per ha of water to delay the apple bloom by 4-9 days, and 5.5 to 10.8 cm per ha of water to delay the sweet cherry bloom by 9-11 days. The water use was substantially lower than the water reported in the earlier studies. The result

suggested the potential applicability of the mist reduce the risk of spring frost damage on tree fruits by delaying the bloom.

1. Introduction

The majority of the world's fruit crop production are constrained by the climatic variables of the amount and timing of precipitation and the occurrence of high or low temperature extremes during the dormant or summer seasons. However, the primary weather-related constraint for most temperate tree fruit crops such as apple and cherry is the frequency and severity of spring freeze events (Flore 1994). In the Great Lakes region, temperatures are significantly moderated by the proximity of the lakes, which has allowed successful commercial production of tree fruit for more than 150 years. Despite the Great Lakes influence, temperatures have increased significantly in the region during the past few decades, especially during the winter and spring seasons, and the amount and duration of ice cover on the Great Lakes have decreased (Wang et al. 2001; Andresen et al. 2012). In addition, the region is experiencing earlier spring (warming about 1-1.5 weeks) on average than just 40 years ago, with relatively less change in the date of last spring freezes (Winkler et al. 2013). Unfortunately for tree fruit producers in the Great Lakes region, the frequency of spring freeze events following initial phenological development has increased during the past few decades, resulting in relatively greater risk of production losses with time (Andresen et al. 2012). These trends have had profound impacts on regional fruit production in recent years. An unprecedented heat wave in March 2012 brought fruit crops out of their dormant state more than one month earlier than normal. A subsequent series of freeze events during April and May resulted in catastrophic freeze damage, with sour cherry and apple yields reduced by 90% and 88% relative to the previous year’s production, respectively (USDA 2013). Similar early warm up and freeze events in Michigan reduced yields by more than half during the 2002 season.

Given the increasing trend in spring freeze events some type of new technology or strategy is immediately needed to help reduce climate-related risks for fruit producers. Development of new, more freeze-resistant varieties may be a long-term solution, but they will likely not be available immediately. Though conventional frost protection methodology offers some defense, they are not feasible due to cost or pollution (smudge pots). Orchard heaters and wind machines are less popular because of higher cost and pollution (Ghaemi et al. 2009).

More environment-friendly methods for frost protection are surface irrigation, sprinklers (Anderson and Seeley 1993; Perry 1998; Ghaemi et al. 2009) and misting (Anconelli et al. 2002). Also, the use of water to reduce the vulnerability of tree fruit to freeze events by delaying the bloom is one potential approach (Anderson et al. 1975). Buds vulnerability to cold damage increases rapidly from the end of dormancy through bloom (Chapter 1 Table 1.1, Washington State University Extension), so any delay in phenological development potentially increases the chance of survival of bud tissue from early spring freeze events as ambient temperatures increase during the spring season. Sprinkler systems were practiced earlier to protect the plants from frost (Heinemann et al. 1992; Heisey et al.1994) and delay blooming (Hewitt and Young 1980; Anderson and Seeley 1993;Perry 1998; Ghaemi et al. 2009). However, the amount of water required in such systems were large, in some cases more than 500 mm per season per ha (534533 gal/ac), which can be costly as well as lead to flooding and leaching of nutrients (Anderson and Seeley 1993). Sprinkler system used to delay bloom to protect buds from spring frost did not get much popularity because it uses a high volume of water which causes soil saturation, disease and pathogens problems. Over - tree sprinkler tends to cause ice coatings in fruits which triggers limb breakage due to ice formation and cracking in fruits and was not feasible in windy areas (Gerber and Harrison 1964).

Applying small volumes of water in the form of mist lead to more days of bloom delay compared to sprinkler (Collins 1977). Misting uses a small fraction of water compared to conventional irrigation or sprinkler systems. Misting is popularly being used in poultry to reduce the heat stress (Timmons and Baughman 1983) and it could reduce the air temperature by 8-11 ^{0}C (Landsberg et al. 1979). Misting has been successfully applied to moderate interior microclimates of greenhouses (Baille et al. 1994; Katsoulas et al. 2001; Gamez et al. 2012) and pear orchards (Collins 1977) via evaporative cooling. Misting delayed the bloom of pear buds by 15 days (Collins 1977). So, a promising new variant of this approach is the application of water mist through solid set canopy delivery system (SSCD) to cool the buds. This system is comprised of micro-emitters attached to the main or lateral pipe lines and dropped partially into the canopy using drop-tubing. The SSCD can theoretically provide the water necessary for cooling at a smaller rate in the form of mist. The set up potentially reduces the drift (Sharda et al. 2013) and water loss. The SSCD system integrated with modern control computer systems helps to manage the application and the interval based on the weather parameters. Also, SSCD system is increasingly being used in high-density orchards for application of pesticides spray applications (Agnello and Landers 2006, Lang 2009; Grieshop, 2013).This research used the water mist through SSCD system, as an environment-friendly climate change adaptation method to protect cherry and apple buds and flowers from spring frost damage, by delaying bloom through the mist- cooling of the buds once the endo-dormancy was satisfied. Successful application of such technology could sustainably reduce the risk of freeze damage, and increase production efficiency and grower profitability.

2. Materials and methods

2.1 Study area

Research initiated in the laboratory and greenhouses in the Plant and Soil Science building at Michigan State University and field research was conducted at two apple orchards located in Southwest Michigan (St. Joseph, MI) and Charlotte, MI, and sweet cherry at the Southwest Michigan Research and Extension Center (SWMREC), MI. The study was conducted on 10 year old apple trees (tree to tree spacing 2.1 m and row to row spacing 5.48 m) of variety Gala, Honey Crisp and Red Delicious in Budagovsk 9, Geneva 16 and Malling 26 rootstocks respectively at St. Joseph, MI. At Charlotte, MI study was conducted on Honey Crisp variety (tree to tree spacing 1.98 m and row to row spacing 4.57 m) of apple in Geneva 30 rootstock. Sweet cherries (Rainer and Skeena) were 8 years old in Gisela 5 rootstock. The sweet cherry plants planted under a 3m tall plastic tunnel (Haygrove, Inc., Mount Joy, PA). In 2014, the study was extended to an apple (Honey Crisp) orchard in Hillsdale, MI, and thirteen years old sour cherries (Montmorency variety in Mahaleb rootstock) in Traverse City, MI, and apricots in Baroda, MI making altogether five stations. In 2015, the study was repeated in St. Joseph (apple), Charlotte (apple), Traverse City (sour cherry) and Baroda (apricot), MI. A similar, experiment with dormant trees and cut tree branches (Red Dlicious and Cortland)were conducted in growth chamber and Michigan State University Horticulture Teaching and Research Center (HTRC) Holt, MI to estimate the mist interval at different temperature and relative humidity (RH) range(50-90 %).

2.2 Instrumentation

Instrumentation to accurately monitor environmental conditions and physical impacts of the misting system was a major part of this research. Air temperature and RH was monitored by air temperature and RH probe, *HMP60* (Campbell Scientific Inc.). The probe was sheltered in a radiation shield in order to eliminate the error due to sunlight and to protect the probe from radiation. Type E-chromium constantan thermocouples (Campbell Scientific Inc.) were used to measure the internal temperatures of buds and temperature of mist. It was inserted from the base of the bud adjacent to its connection to the branch, it was wrapped by duct tape such that it did not get displaced and come out. The temperature of mist was measured during different time in the season to see the variability, it ranged from 9.5 to 10.5 ^{0}C averaging at 10 ^{0}C. Type E thermocouple was suitable because of their low thermal conductivity and high sensitivity. Internal bud temperature was measured in three different field site; St. Joseph, SWMREC and Charlotte, MI. The data from the sensors were collected using a CR1000 datalogger (Campbell Scientific Inc.) The weather station was powered by a battery with continuous charging via SP10R solar panels (Campbell Scientific Inc.) (Figure 2.1 a). Water mist was applied to the buds via SSCD system (Figure 2.1 b). The water flow mist application was regulated by a two way solenoid valve (Asco RedHat 3/8"-3/4") connected to a datalogger via solid state panel mount relay (Crydom D1D07) and powered by a marine battery.

Figure 2.1: Experiment set up in the field a) Instrumentation b) lateral line and emitters

2.3 Solid Set Canopy Delivery (SSCD) system

Set of plots had three experimental rows with treated wood (0.1 m diameter, 4.267 m long, 0.9 m inside the soil) post to support high-density polyethene pipes (Trickl-eez BS20-500) of diameter 19 mm (Figure 2.2). SSCD system was installed in all the experimental orchards. The laterals were fixed above the height of the canopy and openings were made at required locations to attach emitters. The setup was such that each tree had 2 emitters, one on top and one/half on each side; two per tree (Figure 2.1b and 2.2). The distance between the emitter at the top of the canopy was same as a tree to tree spacing and the two half emitters were dropped down from the mid-point of two emitter located above the canopy. The distance between the emitters was 1.06 m (3.5 ft). The pressure gage was used before the valve in the main line to monitor the required pressure 275.79 kPa (40 Psi). Also, we used a spin clean filter (Trickl-eez company APG 712) with a maximum flow of 68.13 lpm before the pressure gage to filter suspended solid or sediments. The nozzle size of the emitter was 0.81 mm (0.032") with the discharge rate of 0.579 lpm at 275.79 kPa (Trickl-eez company, bridge NET 3000, nozzles NET-3036 and speeder NET 3044).

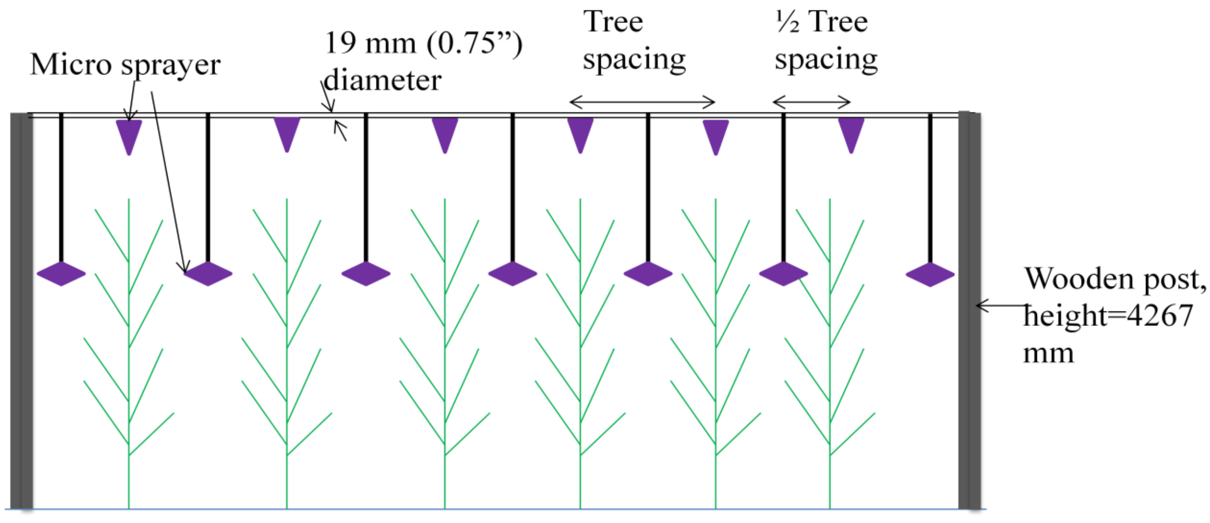

Figure 2.2: Field layout of the SSCD system (not in scale).

2.4 Misting, evaporative cooling, and data collection

The valve operation (mist ON/OFF) was programmed based on air temperature and RH. The growth chamber experiment and the initial two days (sunny and cloudy days) of field studies of water evaporation from the bud surface was used to determine the mist ON/OFF interval (Table 2.1). The cut apple twigs taken from the cooler were placed in the growth chamber and the mist was applied. The time of evaporation was recorded until the bud gets to temperature before misting. It was repeated for a different range of temperature and RH.

The internal bud temperature of both misted and non-misted (control) buds were measured at three different orchards (in apple buds at Charlotte and St. Joseph and sweet cherry buds at SWMREC) to understand the temperature difference between non-misted and misted buds. The changes in bud temperature was recorded every minute to estimate the cooling effect.

Table 2.1: The mist ON and OFF interval during 2013 and 2014.

2013		2014 and 2015		
Pump ON period was 45 or 105 seconds depending on location. Pump started once temperature >= 3 deg C and RH< 90%, OFF interval depended only on temperature range.		Pump ON period was 60 or 105 seconds depending on location. Pump started once temperature >= 4.44 ^{0}C and RH<90%. OFF interval depended on both the temperature and RH range		
Temperature range (^{0}C)	OFF interval (secs)	Temperature range (^{0}C)	RH range (%)	OFF interval (secs)
3 - 4	780	4.44 - 9	0 - 50	660
4 - 9	720		50 - 75	720
9 - 14	600		75 - 90	750
14 - 20	480	9 - 14	0 - 50	510
20 - 24	360		50 - 75	540
> 24	240		75 - 90	570
		14 - 20	0 - 50	420
			50 - 75	450
			75 - 90	480
		20 - 24	0 - 50	330
			50 - 75	360
			75 - 90	390
		> 24	0 - 50	240
			50 - 75	270
			75 - 90	270

At all experimental orchards misting was started after endo-dormancy. At St. Joseph (2013 and 2014) and SWMREC (2013) there were two sets of misted buds (treatment 1 and treatment 2). In treatment 1, mist was turned OFF after the full bloom of non-misted buds and in treatment 2, mist was turned OFF after the first bloom of non-misted buds. Two treatments were done to see the effectiveness of misting if applied until first bloom and full bloom of non-misted buds. At St. Joseph the mist was started from April 4, 2013 (after endo-dormancy) where treatment 2 was turned OFF on May 7, 2013 (first bloom of control) and treatment 1 was turned OFF on May 15, 2013 (full bloom of control). In 2014, misting was started on April 2, 2014, where treatment 2 was turned OFF on May 13, 2014, and treatment 1 on May 16 (after full bloom of non-misted buds). At Charlotte, MI mist was applied from April 5 to May 15 (75 % bloom of control) in 2013 and from April 12 to May 17 (first bloom of control) in 2014 (Table 2.2). The mist was turned OFF after full bloom of control buds in Hillsdale (April 9 -May 19, 2014), MI. Similarly, in sweet cherry (SWMREC) the mist application in 2013 started on April 2, 2013 (after endo-dormancy), treatment 2 was turned OFF on May 4, 2013 (full bloom of control) and treatment 1 on May 15, 2013. In 2014, sweet cherry buds were misted between April 9, 2014 (after endo-dormancy) to May 8, 2014 (full bloom of control). In 2015, apple buds were misted between April 2 to May 7 at St. Joseph, April 4 to May 8 at Charlotte (Table 2.2).

Table 2.2: Time of mist start and stop date of mist at each location for different fruits

Fruits	Location	Year	Treatment	Mist start date	Mist end date
Apple	St. Joseph	2013	treatment 1	4-Apr	15-May
			treatment 2	4-Apr	7-May
		2014	treatment 1	2-Apr	16-May
			treatment 2	2-Apr	13-May
		2015		2-Apr	7-May
	Charlotte	2013		5-Apr	15-May
		2014		12-Apr	17-May
		2015		4-Apr	8-May
	Hillsdale	2014		9-Apr	19-May
Sweet cherry	SWMREC	2013	treatment 1	2-Apr	15-May
			treatment 2	2-Apr	4-May
		2014		9-Apr	8-May
Sour cherry	Traverse City	2014		4-May	23-May
		2015		20-Apr	15-May

The bud phenology of apple (St. Joseph and Charlotte) and sweet cherry (SWMREC) was recorded twice a week by visual observation (20 observations per varieties per treatment). Also, the spurs were counted after full bloom and fruits per flowering spur were also determined in apples at St. Joseph and Charlotte, MI. The spurs were counted from the same trees whose buds phenology were studied; the number of fruits per spur were counted after the last thinning spray. The number of fruits were divided by the number of spurs to estimate the fruits per flowering spur.

Fruit diameters were measured on a weekly basis in selected trees in the same orchard to know the maturity of the crops. The fruit quality including brix, size, weight, firmness and redness (in apple) were examined in the laboratory and comparison were made between fruits misted and non-misted apple (St. Joseph) and sweet cherry (SWMREC) buds. Fruits per flowering spur was estimated and post harvest test of fruits were done to see if misting had any effect in the quantity and quality of the fruits. The standard deviation was calculated to identify the deviation of fruits per flowering spur in different treatment. The two tail T-test was conducted to identify the statistical difference in fruits per flowering spur per treatment and post harvest quality. Fruit set and post harvest test was done to see if misting has any effect in the fruit set, size and quality.

Growing degree days were estimated using the daily minimum and maximum air temperature using standard method (McMaster and Wilhelm, 1997), which uses average temperature to estimate GDD. Base temperature was selected to be 4 ^{0}C and GDD was calculated using air temperature. The green tip was considered as the biofix (GDD=0 DD at Green tip) while calculating GDD.

3. Results

3.1 Mist application

Higher temperature and lower relative humidity were accompanied by frequent mist application compared to lower temperature and higher relative humidity. In the beginning of the season, water use was lower compared to the later part of the season (Figure 2.3). The figure 2.3

shows the daily mist volume along with average air temperature and RH. Higher air temperature and lower RH increased the rate of evaporation, causing higher amount of cooling.

The total volume of mist applied from the end of endo-dormancy to king bloom in apple and sweet cherry orchard depended on the location of the orchard, and treatment (Table 2.3). The depth of mist applied for the area of 1 ha at St. Joseph, MI (apple) was 11-14 cm in 2013, 13- 15 cm in 2014 and 10 cm in 2015 (Table 2.3). Likewise in Charlotte, MI 8.4 cm of water was applied in the form of mist in 2013, 15.3 cm in 2014 and 7.6 cm in 2015. In 2014, maximum amount of mist (26 ha-cm) was applied in Hillsdale, MI. The depth of mist applied was lower in the sweet cherry, 5.5 ha-cm of water was used in 2013 and 10.8 ha-cm in 2014.

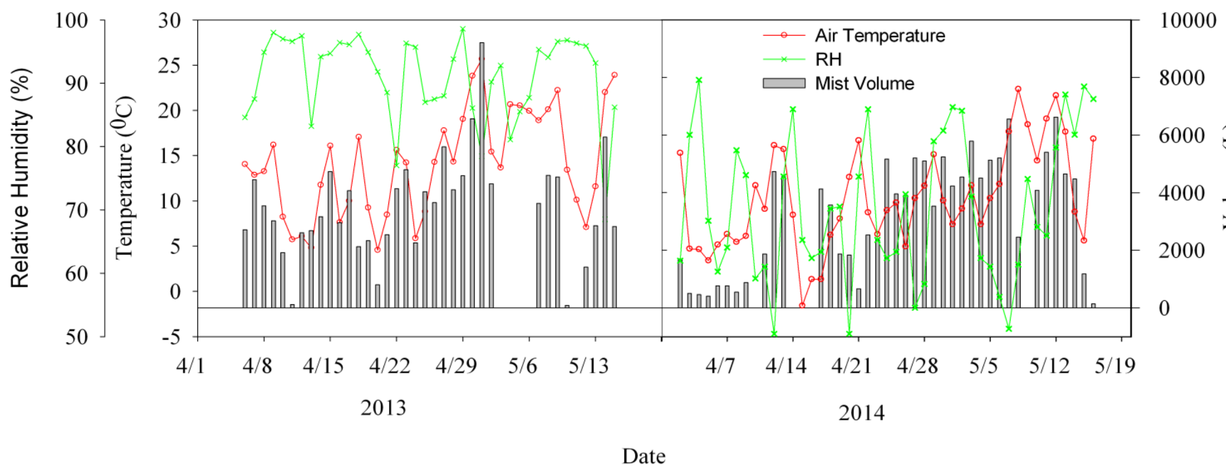

Figure 2.3**:** Daily mist volume in 3 rows of application, air temperature, and RH at apple orchard in St. Joseph, MI.

Table 2.3: Total duration and volume mist applied.

Horticultural crops	Experimental orchards	Year	Treatment	Total duration of misting (hours)	Depth of mist applied in 1 ha (cm)
Apple	St. Joseph	2013	Treatment 1	58.87	14.15
			Treatment 2	46.72	11.17
		2014	Treatment 1	61	15.00
			Treatment 2	57	13.00
		2015		55.7	10.00
	Charlotte	2013		45.96	8.40
		2014		62	15.30
		2015		42.85	7.60
	Hillsdale	2014		81	26.20
Sweet Cherry	SWMREC	2013		39	5.50
		2014		52	10.8

Note -Treatment 1- SSCD system was turned OFF on May 15, 2013, and May 16, 2014
Treatment 2- SSCD system was turned OFF on May 7, 2013, and May 13, 2014
Volume of water was estimated for the area of 1 ha.

3.2 Bud temperatures

The influence of evaporative cooling was evident by the difference of bud temperature between the misted and non-misted buds. The temperature in the misted buds was lower than that of non-misted buds throughout the season. In figure 2.4, misted and non-misted apple bud temperature from the late afternoon to evening of May 5 2014 at St. Joseph are shown. The misted bud temperature dropped about 2-3 ^{0}C right after misting of 45 seconds. In figure 2.5 misted and non-misted sweet cherry bud temperature in the afternoon of April 22, 2014 at SWMREC dropped by 2-3 ^{0}C right after misting of 60 seconds. The temperature in the misted buds continued to drop to a maximum of 6 ^{0}C until after 4-5 minutes of the misting, this could be due to latent heat loss. The greatest difference (>7 ^{0}C) between the non-misted and misted bud temperature was noticed when the air temperature ranged from 20-25 ^{0}C and RH between 45-

50%. The difference between the non-misted and misted bud temperatures was nominal when the relative humidity was higher (85 % or above). After a few minutes of mist application, buds started gaining back the temperature depending on the air temperature, wind speed, and relative humidity. The evaporation and heat loss from the bud is influenced by the wind and net radiation (Landsberg et al. 1974), this was clearly noticed in a potted plants study carried out in Holt. The study conducted on the potted plant (Cortland apple) at HTRC showed that for same air temperature and RH, the bud and stem dried faster, causing a higher rate of cooling on a sunny or windy day compared to a cloudy or calm day. Also, the misted bud returned to the original temperature faster on a windy and sunny day by 1-2 minutes for same RH and air temperature. However, non-misted buds did not show much variability in bud temperature during sunny or cloudy days for same temperature and RH. In open orchard, the non-misted bud temperature was higher than air temperature and the difference was greater during the day time. However, in a high tunnel (Sweet cherry) the air temperature was most of the time lower than both the misted and non-misted buds temperature (Figure 2.5). The high tunnel might have influenced the temperature inside it (green house effect).

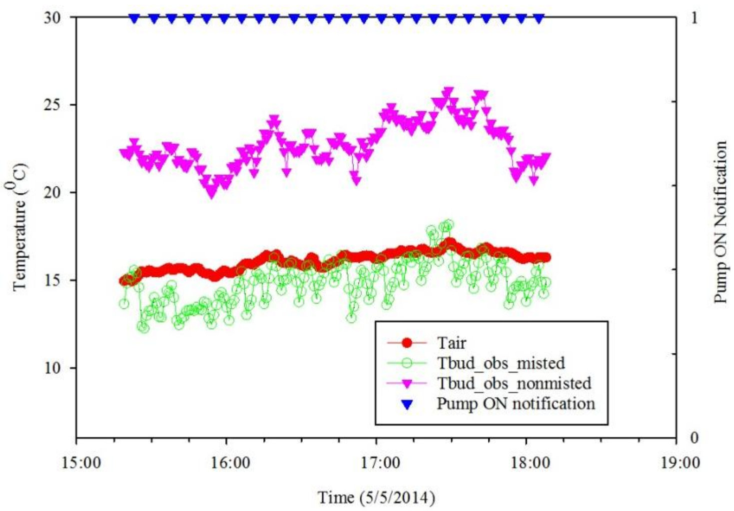

Figure 2.4: Air temperature, bud temperatures of apple (HC) and Pump ON notification at St. Joseph, MI

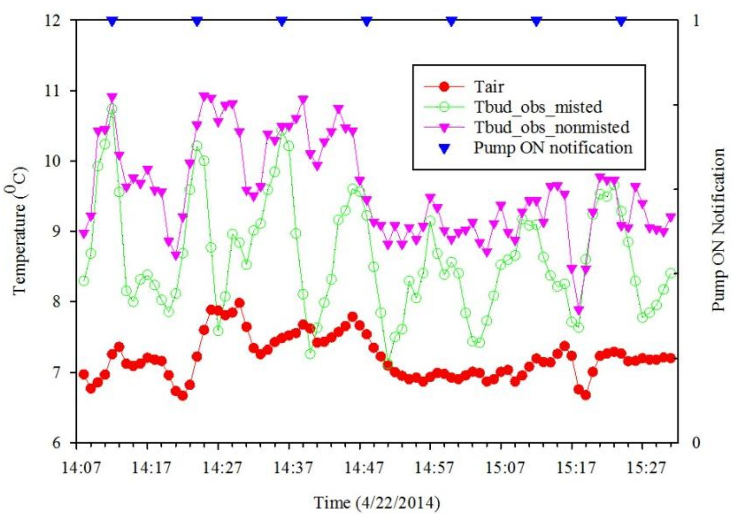

Figure 2.5: Air temperature, bud temperatures of sweet cherry and Pump ON notification at SWMREC

3.3 Bloom delay

3.3.1 Apple

The number of days delayed depended on mist volume, mist duration, variety of apple, and location of orchards (Table 2.4). In 2013, bloom was delayed by 8 days in Gala and Honey Crisp and 7 days in Red Delicious for treatment 1 at St. Joseph. Whereas, in 2014, bloom delay in treatment 1 was 8 days in Honey Crisp and Gala variety, 9 days in Red delicious (Table 2.3).

In 2015, bloom delay of 8 days was observed in Honey Crisp and Red Delicious and 7 days in Gala. Only 4-6 days of bloom delay was observed in treatment 2. At Hillsdale, 9 days of bloom delay was observed between non-misted and misted buds with 81 hours of mist operation. At Charlotte, 6 days of bloom delay was observed in Honey Crisp in 2013, 2014 and 2015. Misting also delayed different phenological stages. The differences in phenological stages of Red Delicious at St. Joseph in May 16, 2014, is shown in figure 2.6. All the phenological stages were delayed for example, green tip stage in misted buds were delayed by a minimum of 3 days to maximum of 5 days compared to non-misted buds. The phenological development of buds in both misted and non-misted buds was influenced by the thermal time. Both the misted and non-misted buds acted in similar ways to the thermal time. In 2013, the non-misted buds of Honey Crisp at St. Joseph, MI bloomed on May 14 (Table 2.4), treatment 1 bloomed on May 22 and treatment 2 bloomed on May 19 when GDD_{Tair4} was 274 DD and 215 DD. In 2014, the non-misted buds of Honey Crisp were bloomed on May 15 (229 degree days) and treatment 1bloomed on May 26 (232 degree days). In 2015, less heat was accumulated due to season; non-misted buds of Honey Crisp bloomed on May 9 (156 DD) and misted buds were bloomed on May 17 (207 DD). Similar behavior was noticed in GDD_{Tair4} of Gala and Red Delicious at St. Joseph and Honey Crisp at Charlotte (Table 2.4). Misted buds accumulated higher degree days from green tip to full bloom compared to non-misted buds. However, the difference did not show any statistical difference (P value>0.05).

Table 2.4: Bloom date of apples and GDD $_{Tair4}$ (from green tip based on ambient temperature) at St. Joseph, and Charlotte, MI.

Orchard Location	Variety	Study	2013			2014			2015		
			bloom date	GDD (^{0} C)	Fruits per flowering spur (%)	bloom date	GDD (^{0} C)	Fruits per flowering spur (%)	bloom date	GDD (^{0} C)	Fruits per flowering spur (%)
St. Joseph	Gala	Non-misted	10-May	204	69	15-May	191	44	8-May	162	54
		Treatment 2	16-May	221	40	20-May	175	44			
		Treatment1	18-May	253	48	23-May	210	62	15-May	180	66
	RD	Non-misted	12-May	195	40	16-May	204	100	9-May	171	22
		Treatment 2	16-May	164	29	22-May	175	47			
		Treatment1	19-May	215	32	25-May	205	66	17-May	207	48
	HC	Non-misted	14-May	208	45	20-May	229	84	9-May	156	31
		Treatment 2	19-May	215	47	26-May	222	94			
		Treatment1	22-May	274	32	28-May	253	84	17-May	207	30
Charlotte	HC	Non-misted	16-May	218	51	20-May	203	70	10-May	193	48
		Misted	22-May	274	52	26-May	217	75	16-May	225	31

Note: Treatment 1- SSCD system was turned OFF on May 15, 2013 and May 16, 2014
Treatment 2- SSCD system was turned OFF on May 7, 2013 and May 13, 2014

Figure 2.6: Non-misted (a), misted treatment 2 (b), misted treatment 1(c) apple (Red Delicious) buds/flowers on May 16, 2014 at St. Joseph.

3.3.2 Cherry and apricot

In 2013, the blooming between non-misted and misted sweet cherries (treatment 2, the mist turned OFF on May 4) was delayed by 11 days. In 2013, the non- misted buds were bloomed on May 2 and misted one on May 13. In 2014, the non-misted buds were bloomed on May 7 and misted buds on May 16. On May 7, 2014, misted buds were in a tight cluster while non-misted buds were in full bloom (Figure 2.7).

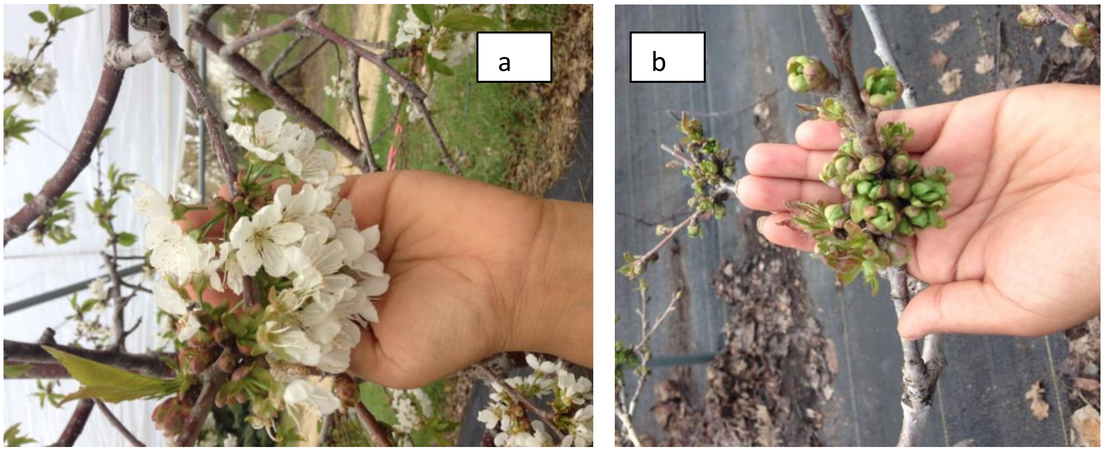

Figure 2.7: Non-misted (a), Misted (b) sweet cherry buds on May 8, 2014 at SWMREC.

Blooming of sour cherries were delayed by a week in 2015, however, no bloom delay was observed in 2014 due to equipment failure; dead battery that powered the solenoid valve. Figure 2.8 shows the difference in phenology between misted and non-misted sour cherry buds on May 13 2015: misted sour cherry buds were at tight cluster while non-misted buds had flowers. Application of mist in apricots from early calyx red stage until the first bloom in non-misted buds delayed the bloom of misted buds by 5 days. Misting also delayed the earlier phenology of the apricot bud (Figure 2.9).

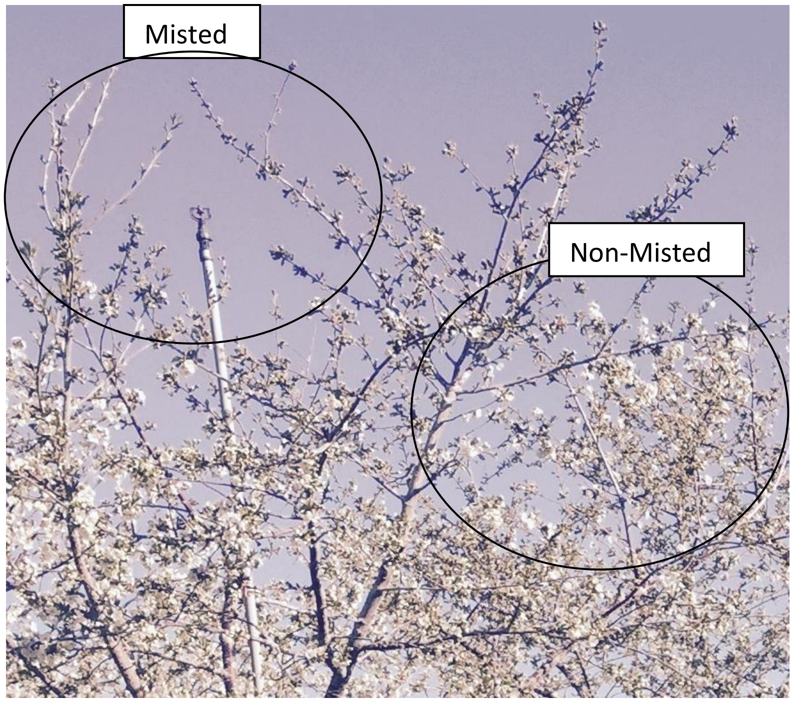

Figure 2.8: Misted and non- misted sour cherry buds on May 13, 2015 at Traverse city, MI.

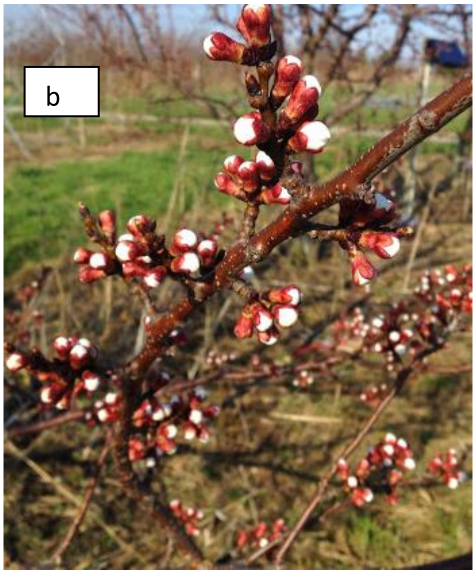

Figure 2.9: Misted (a) and non -misted (b) apricot buds on April 22, 2014 at Berrien Spring, MI. non-misted were at popcorn stage whereas misted were at red calyx.

3.4 Fruit set and fruit quality

At St. Joseph, fruits per flowering spur of Red Delicious on 2013 was 24.4±20.7 in treatment 1, 26.7±18.8 in treatment 2 and 37.6±15.6 in non-misted buds (Table 2.4). Similar results were seen in 2013, 2014 and 2015 for Gala, Honey Crisp and Red Delicious at St. Joseph and Honey Crisp at Charlotte, MI. Misted (treatment 2) Red Delicious had statistically lower (P value<0.05) fruits per flowering spur compared to control on 2014. Similarly, misted Honey Crisp had lower fruits per flowering spur compared to control on 2013. In another hand, misted Red delicious had statistically higher (Pvalue<0.05) fruits per flowering spur than non-misted in 2015. Otherwise, fruits per flowering spur were comparable between misted and non-misted. Also, treatment 1 and treatment 2 did not show any statistical difference.

The weight, firmness, and starch content did not show any statistical difference between misted and non-misted apples (Gala, Red Delicious, Honey Crisp) harvested on October 10, 2013, September 14, 2014, and September 10, 2015 but they have some visible patterns of changes. The weight, firmness, starch content, and brix of apples from both misted and non-misted buds are displayed in table 2.5. The brix was statistically lower (Pvalue<0.05) in fruits (Red Delicious and Gala) from misted (treatment 2) buds in 2013, and in Red delicious (treatment 1) and Honey Crisp (treatment 1 and 2) in 2014 and Honey Crisp in 2015 compared to apples from non-misted buds. However, the brix was higher (Pvalue>0.05) in Honey Crisp apples from misted buds in 2013 compared to apples from non-misted buds. Redness was statistically higher in misted Honey Crisp compared to non-misted in 2015. The comparable value of weight, firmness and starch suggested the maturity of the apple was not influenced by the bloom delay. There was no difference in the maturity by the time of harvest.

Table 2.5: Post-harvest test of apples from misted and non-misted buds at St. Joseph, MI; weight, redness, starch, brix and firmness.

Year	Variety	Treatment	harvest date	Average weight (g)	Redness (%)	Starch (1-8)	Brix (%)	Firmness (lbs)
2013	Gala	Control	12-Sep	116.9	75.5	3	13.2	18.15
		Treatment 1	12-Sep	120.71	69	4	11.9	17.60
		Treatment 2	12-Sep	109.36	65.5	3	13.7	17.72
	Honey Crisp	Control	12-Sep	157.87	65.5	8	13.2	13.78
		Treatment 1	12-Sep	148.9	66	7	14.6	13.63
		Treatment 2	12-Sep	187.78	76	7	13.9	13.99
	Red Delicious	Control	12-Sep	113.84	93.5	6	13.1	16.45
		Treatment 1	12-Sep	105.29	96.5	4	12.7	16.145
		Treatment 2	12-Sep	119.64	93	4	12	15.91
2014	Gala	Control	14-Sep	126.5	97	5	11.84	17.92
		Treatment 1	14-Sep	124.74	96.5	6	11.4	16.93
		Treatment 2	14-Sep	113.64	93	4	10.56	18.3
	Honey Crisp	Control	14-Sep	196.3	56	4	15	14.065
		Treatment 1	14-Sep	189.6	45.5	3	13	14.56
		Treatment 2	14-Sep	203.12	46	3	13.8	13.97
	Red Delicious	Control	14-Sep	174.23	98.6	3	11.12	16.38
		Treatment 1	14-Sep	167.25	96	3	10.32	15.29
		Treatment 2	14-Sep	151.57	94	3	10.6	15.58
2015	Gala	Control	14-Sep	168.48	59.75	6	13.28	21.221
		Treatment	14-Sep	162.73	60.5	6	12.92	21.221
	Honey Crisp	Control	14-Sep	204.92	31	7	12.53	15.6875
		Treatment	14-Sep	206.225	16	6	12.14	16.87
	Red Delicious	Control	14-Sep	122.87	64	2	8.46	17.64
		Treatment	14-Sep	113.575	54.25	2	9.07	15.58

In 2013, sweet cherries were harvested on June 24 and July 5 for the post harvest test. However, in 2014 we only had one sample, all the fruits were harvested right after our first sampling date (July 1), which prevented us from getting next sample. The misted sweet cherry harvested on July 5 2013, and July 1 2014 had statistically lower (P value<0.05) value of the weight, size, and brix compared to sweet cherry from non-misted buds harvested on the same date. The size, weight, firmness and brix of sweet cherry are shown in table 2.6. The maturity of sweet cherry was delayed by a week in 2013 and 2014 but there was no difference in the maturity of sour cherry and apricot. And there was no evidence of disease and/or pathogen problems and/or a reduction in fruit size.

Table 2.6: Post-harvest test of sweet cherry from misted and non-misted buds at SWMREC; weight, brix, size and firmness.

year	variety	treatment	harvest date	weight (g)	brix (%)	size (mm)	firmness
2013	Skeena	Misted	June 24	6.16	11.6	24.6	446.86
		Non-misted	June 24	8.49	14.8	26.83	354.67
		Misted	July 5	10.2	18.08	28.64	401.63
		Non-misted	July 5	10.82	18.16	29.99	342.49
	Rainer	Misted	June 24	8.41	14.8	27.67	261.93
		Non-misted	June 24	10.58	17.2	29.74	231.33
		Misted	July 5	10.18	19	29.33	315.75
		Non-misted	July 5	12.31	19.7	29.45	265.01
2014	Skeena	Misted	July 1	7.96	17.42	26.57	412.65
		Non-misted	July 1	12.87	19.75	37.44	282.27
	Rainer	Misted	July 1	10.71	15.52	30.49	321.89
		Non-misted	July 1	11.62	18.52	37.84	239.67

4. Discussions

The use of SSCD system with micro sprayers along with advanced weather monitoring sensors and the mist application rate based on temperature and RH reduced the volume of water used to delay bloom in apple and cherry over the three growing seasons (2013-15). The misting via micro sprayers (ie SSCD) was sufficient to lower the temperature of buds because evaporation is higher with smaller drops as they have greater surface area relative to the volume (WSDA). Drop in bud temperature right after misting could be due to conduction. And continuous drop for next 4-5 minute could be due to latent heat loss. After a few minutes of mist application buds started gaining back the temperature; it depended on the air temperature, wind speed, and relative humidity. The evaporation and heat loss from the bud is influenced by the wind and net radiation (Landsberg et al. 1974) which was not included in the datalogger program. This indicated the heat lost in wet buds is driven by conduction, convection, latent and radiation. Drop in temperature slowed down the development of bud. The lower bud temperature of misted buds delayed all the phenological stages of misted buds compared to non-misted ones.

The SSCD system consumed a lower volume of water (1.158 L/min per tree) than reported in earlier studies. The rate of water application used by Anderson et al. (1975) was10 L/min per tree to achieve the delay of 18 days in apple bloom. Managing the misting interval based on ambient temperature and RH might have reduced the water use. Chesness et al. (1977) sprinkled 46 cm of water in 209.1 hours in the area of 0.0021 ha to protect peach from frost. Chesness et al. (1977) sprinkled the bud when the air temperature was above 7.22 ^{0}C with 1.25 minutes ON and OFF cycle to delay the peach bloom by 14 days. Hewett and Young (1980) sprinkled only during day time when the air temperature was more than 7 ^{0}C (1975) and 8 ^{0}C (1976) with 5 minutes ON and OFF cycle and got 6 days (in1975) and 18 days (in1976) of bloom delay in apple.

The days of bloom delay obtained in the apple at southwest and central Michigan was less than that reported by Anderson et al. (1975) in Utah, USA and Hewett and Young (1980) in 1976 in Otago, New Zealand. The difference could be due to a higher volume of water application in earlier studies, or different weather conditions. The spring weather of Utah is generally drier than in Michigan, causing a higher rate of evaporative cooling resulting more days of bloom delay. However, using higher volume of water did not always have a positive results for example Hewett and Young (1980) used a larger volume of water in 1975 compared to that in 1976, but achieved more days of delay in 1976. Despite the higher volume of mist application at Charlotte, MI we were not able to get more days of bloom delay in 2014 because of poor coverage caused by malfunctioning of a nozzle (plugged by the small coarse particle) and low water pressure (about 172 kPa). The higher volume of mist used did not delay the bloom by longer days at Hillsdale. The temperature recorded at the Hillsdale station was higher than in the other stations causing a higher rate of mist application. The area was windy, the mist was drifted by the wind majority of the time resulting in higher rate of evaporation due to convective transfer. Also, in sweet cherry at SWMREC higher volume of mist in 2014 (almost double of 2013) did not yield more days of delay than that achieved in 2013. At SWMREC and Traverse city, more days of bloom delay was achieved with a lower volume of misting than reported by Tsipouridis et al. (2006), who obtained 5-6 days of delay in the cherry bloom using sprinkler irrigation.

Though the number of days of bloom delay in apples was less than that reported in earlier studies, it might be sufficient to protect the buds from frost damage. In the last 25 years of bloom record from Peach ridge for McIntosh apple showed that the bloom date is getting earlier; around the first week of May (Phillip Schwallier personal communication). The probability of occurrence of freezing temperature is 50 % after the first week of May (May 3), 25 % after May 9 and 0 % after the last week of May (May 23) in the southwest Michigan. In the North West Michigan (Lower Peninsula) probability of occurrence of freezing temperature is 50 % after the third week of May and 0 % after the first week of July (Michigan State Climatologist Office, https://climate.geo.msu.edu/climate_mi/index.html). In that case, if the apple is in full bloom by the first week of May, 90% of flowers are killed once the temperature drops to -4 ^{0}C and 10% are killed with the drop of the temperature to -2 ^{0}C. In this study, non-misted apple buds were in full pink or first bloom on the first week of May where freezing temperature of -4 ^{0}C kills 90% of a flower. Misted buds were half inch green or tight cluster; temperature between -5 to -2 ^{0}C kills only 10% of buds (Michigan State University Extension). Thus delaying a bloom along with other phenological stages by a week could protect the buds/flowers from late spring frost by 50-75%.

The timing of mist application, ambient weather conditions and water quality are important to achieve effective days of bloom delay to protect buds from frost damage. The sweet cherry buds misted until May 15, 2013 (until 13 days after the full bloom of non-misted buds) did not have a flower. This could be because the soluble salt in the water formed a coated layer outside the buds limiting the reproductive development.

The spring seasons in 2013, 2014 and 2015 were different than those of previous years (2012). We did not have any freezing events after bud break. However, in about 2 and half hours of freezing temperature (=<-2 ^{0}C) in May 13, 2013 at Charlotte, 34 % of non-misted apple buds were killed, whereas the damage was only 16% in misted buds. At that time non-misted buds were at open cluster to king bloom and misted were at tight cluster, less vulnerable to temperature between -2 to 0 ^{0}C. Generally, evaporative cooling via misting decreases the bud temperature, causing slow development of buds because the physiological activities and bud development depend on bud temperature (Chesness et al. 1977). Besides, bloom delay by misting looks convincing as the bud sensitivity to the frost increases with its development, and slower development could protect it from major frost events.

Date of bloom is also influenced by GDD (Nesmith and Bridges, 1992), bud temperature (Hamer 1985), the end of endo-dormancy and variety of fruit because each can have a different chilling requirement. Misting slowed down the phenological development of buds. However, delay in bloom did not delay the maturity of fruits by an equal number of days; maturity of sweet cherry was delayed by a week and maturity of apple and sour cherry was not delayed. This is different than 10 days of delay in maturity of apple observed in semiarid Utah where bloom was delayed by 18 days (Anderson et al. 1975). The suitable weather condition in summer might have accelerated the development of fruits from misted buds.

5. Conclusions

For all three years, the mist was applied before bud break (assuming after the end of endo-dormancy) in apples and cherries, which resulted in bloom delays with no pathogen or fruit set problems. Mist application through the SSCD delayed the apple bloom by 4 to 9 days and cherries by a week to 11 days depending on the treatment and variety. The number of days delayed depended on the time of water application, whether it was started right after the end of endo-dormancy or some phenological stages after that. Keeping the buds in its dormant stage for a longer time reduces its vulnerability to spring freeze events. Also, delaying the development of each reproductive phenological stage protected them from frost damage. The SSCD system of mist application based on air temperature and relative humidity lowered the water use to achieve sufficient delay in bloom without any compromise in quality when compared to previous research (Stang et al. 1978, Collins 1977). This system is cost effective because growers could use the SSCD system used for pesticide, growth regulator, and foliar nutrient application, as well as mist-cooling, to improve fruit quality during the hot part of the summer.

The mist ON/OFF interval might be further improved by including the effect of net radiation, and wind speed, which could minimize the water use. And if possible water should be free of salt and iron, as it develops the separate layer outside the plant, repelling the pollinators.

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[Companies name are for introduction purpose]

CHAPTER 3:DEVELOPMENT AND APPLICATION OF A BUD TEMPERATURE SIMULATION MODEL

Abstract

Temperate fruit crops are prone to spring frost damage, the intensity of which depends on the intensity and duration of frost and the phenological stage of development. Flower buds are more susceptible to frost damage in later stages of their phenological development. Therefore, delaying the phenology could reduce their relative vulnerability to frost. One potential strategy to delay the phenology is the suppression of the bud temperature through evaporative cooling with the application of water as mist or sprinkler. In this study, a deterministic model was developed to estimate the impact of evaporative cooling on tree fruit bud temperatures and the potential for delaying reproductive phenology. The model was developed with several different sets of observational data taken from growth chamber, potted plant and field experiments in which water spray mist was applied to suppress bud temperatures. The model was calibrated using growth chamber data and validated using potted plant and field data. The simulated bud temperatures were in good agreement with observed bud temperature with an overall R- square of 0.94,0.88, 0.95 for three different sets of the experiment at HTRC, and 0.85, 0. 86 and 0.81 for field results from SWMREC, St. Joseph, Charlotte, MI respectively. The mean absolute difference was 0.65, 0.92, 0.75 for three different sets of the experiment at HTRC and 0.818, 0.97 and 1.4 for field results of SWMREC, St. Joseph, and Charlotte, MI respectively. Finally, the calibrated model was run with historical climate data (2006-2015) at three sites within major fruit growing areas of Michigan to examine how mist application might delay bloom and offer increased resilience to spring freeze events. At all three sites, misted buds up to bloom were cooler compared to non-misted buds by an average of 1.2 ºC per season which resulted in a

relative average decrease of 133 base 4ºC GDD (GDD calculated using bud temperature) prior to bloom of non-misted buds per season. Estimated water use associated with the misting was 130-350 mm per season per hectare in apple and 80-220 mm per season per hectare in sweet and sour cherry, which is significantly less than previous related efforts using conventional sprinkler-based irrigation. Maximum cooling and GDD reductions were observed in relatively warm springs such as 2012.Using a simple GDD-based phenology model and known freeze damage thresholds, bloom in the apple was delayed from 9- 22 days, and in sweet and sour cherry bloom was delayed from 7-21 days. That translated into relative decreases of damage of 10-60 % in apple and 45-100% in cherry for the misted buds. Results from the study suggest the potential for spray misting to reduce spring-freeze related damage risk in tree fruit production systems with limited amounts of water consumption.

1. Introduction

The production of tree fruit around the world is constrained by temperature extremes including spring freeze events (Flore 1994; Snyder and de Melo-Abreu 2005). Freeze injury damages the reproductive organs of fruit trees due to ice formation in tissues that ruptures the cell walls (Legave et al. 2013). Freeze injury in temperate fruit plants may occur in fall before dormancy, at mid-winter during dormancy, or in spring during bud development. During the spring season, damage risk generally increases with the stage of phenological development (Rodrigo 2000). The severity of injury depends both on the intensity and duration of sub-freezing temperatures (Rodrigo 2000). Due to recent temperature increases, the chilling requirements and heat accumulations for temperate fruit crops in several international production areas have been fulfilled earlier (Guédon and Legave 2008; Doi and Katano 2008), resulting in earlier flowering than usual. Reduction in yield due to spring frost is a primary climate-related constraint for temperate fruit crops (Flore 1994).

In the western Lower Peninsula of Michigan, many fruit crops including cherry, apple, apricots, and peaches are grown due to a favorable climate moderated by the Great Lakes (Andresen and Winkler 2009). Michigan is the leading state in sour cherry production and third in apple production among states in the USA (USDA/ NASS, Michigan field office 2014). However, recent warming during the winter and spring seasons have resulted in a decreases in Great Lakes ice cover and to an earlier onset of the spring growing season (Andresen et al. 2001; Andresen and Winkler 2009; Wang et al. 2012; Andresen et al. 2012). The warmer winter and spring temperatures have resulted in earlier phenological development of overwintering perennial crops; for example, Zavalloni et al. (2006) reported earlier phenological development of sour cherry in Michigan. Despite the increases of spring temperatures in Michigan in recent decades, the frequency and timing of spring freeze events have not changed (Andresen and Harman 1994; Winkler et al. 2013; Schultze et al. 2013), and fruit crops grown in the region remain prone to spring frost damage associated with air temperatures < -2 ^{0}C. Severe frost injury kills buds and light frost may degrade fruit quality (Eccel et al. 2009). The severity of bud injury depends on the stage of development, and the severity and duration of the critical air temperature. For example, when apple buds are at green tip, 90% of the buds are killed if the temperature drops to -12 ^{0}C for 30 minutes, however, at first pink stage, 90 % of buds are killed if the air temperature drops to -4 ^{0}C (apple - Washington State University, WSU EB0913).

During the past two decades, tree fruit production in the Great Lakes region was severely reduced by spring frosts in 2002 and 2012. In 2012, an unprecedented March heat wave brought tree fruit buds out of their dormant stage at least one month ahead of normal. The heat wave was followed by a series of freeze events during April that killed nearly all buds. Michigan's sour cherry production was reduced by 90 % and apple by 88 % compared to previous years resulting in major economic impacts the region's fruit industry (USDA 2013).

Protection of developing tree fruit buds from frost is an major and immediate industry need. There are several frost protection methods in practice across the region like wind machine, orchard heater, helicopter, water and so on. Among them, the application of water is an efficient and relatively environmentally-friendly method.

Sprinkler systems have been widely used in different parts of the world to directly protect plants from frost through the release of latent heat as water freezes on the plant tissue (Heinemann et al. 1992, Heisey et al.1994). Water was also used as the indirect method of frost protection with the evaporative cooling to delay the phenological development resulting in a relatively lower risk of freeze damage (Hewitt and Young, 1980; Anderson and Seeley, 1993). Similarly, water mist is commonly used to moderate the microclimate of enclosed greenhouses (Baille et al. 1994; Katsoulas et al. 2001) and reduce plant transpiration rates and vapor pressure deficits (Baille et al. 1994; Giacomelli et al. 1985).

A major potential drawback of the application of water for frost control is the amount of water needed. In the Hewitt and Young (1980) study, for example, more than 500 mm per season per ha (215062 gal/ac) of water was required in just one growing season. Such volumes of water may result in significant economic and environmental costs (Stang et al. 1978; Anderson and Seeley 1993). One promising water-related frost protection strategy involves the application of water-mist using a solid set canopy delivery system (SSCD), which are used to deliver precision spray applications in high density orchard production systems (Agnello and Landers 2006; Grieshop 2015). Such a system has the potential to provide effective evaporative cooling and indirect frost protection at a fraction of the water needed with conventional sprinkler-based irrigation. Given the need to better understand the potential for and physical limitations of such a strategy in frost protection in a variety of climates, the primary objective of this study is the development of a process-based simulation model of tree fruit bud temperature based on spray mist application.

2. Methods

In this study, we simulated the effect of mist droplet evaporation and evaporative cooling on tree fruit bud temperature with a heat transfer energy balance approach. The temperature of a fruit bud is largely dependent on a balance between radiation, convective, and conduction heat fluxes, and when wet, latent heat (Hamer 1986a). Such approaches have been utilized previously by Hamer (1986 b) and Barfield et al. (1981). However, the focus of these efforts was on sprinkler-based freeze protection. We considered bud temperature as:

$$\rho C_b \frac{dT}{dt} = \frac{1}{r}(LE + H + C + Rn\_a) \qquad \text{eq 1}$$

where:

T= bud temperature (^{0}C)

t= time (s)

ρ= bud density (kg/m^3)

C_b=specific heat capacity of bud (J/kg C)

r= radius of bud (m)

LE= latent heat transfer (W/m^2)

H= convective heat transfer (W/m^2)

C=conductive heat transfer (W/m^2)

R_n_a= net radiation adjusted for bud geometry (W/m^2)

Latent heat flux was estimated following Gebremedhin and Wu (2001), who simulated the body temperature of a cow in a hot, dry environment:

$$LE = \lambda j \beta A \qquad \text{eq 2}$$

where:

LE= Latent heat flux (KJ/s) which will be changed to W/m^2

β=defined wet area of bud surface (%)

λ=Latent heat of vaporization (KJ/kg of water)

A=area of bud (m^2)

and j, the mass flux transfer between the bud and the atmosphere is:

$$j = (C_b - C_a)h_m \qquad \text{eq 3}$$

where:

j=mass flux between bud and atmosphere (Kg/ m^2 s)

C_b=water vapor concentration of bud (Kg/m^3)

C_a=water vapor concentration of air (Kg/m^3)

h_m= mass transfer coefficient, (m/s)

Convective heat transfer was estimated following Barfield et al. (1981) and Gebremedhin and Wu (2001). Convective heat transfer is dependent on bud and air temperature and wind speed:

$$H = h_c(T_a - T_b) \qquad \text{eq 4}$$

Where:

H= convective heat flux (W/m^2)

T_a= air temperature (deg K)

T_b=bud temperature (deg K)

and h_c, the convective heat transfer coefficient is:

$$h_c = NuK / D \qquad \text{eq 5}$$

where:

h_c= convective heat transfer coefficient (W/m^2 C)

Nu= Nusselt number

K= thermal conductivity (W/ m C)

D= diameter of bud (m)

Conductive heat transfer was based on the differences between bud and applied water temperatures as:

$$C = m_b C_b (T_w - T_b) \qquad \text{eq 6}$$

where:

C=conductive heat transfer (W/m^2)

m_b=mass of the bud (kg)

C_b = specific heat capacity of the bud (J/Kg K)

T_w=temperature of water (K)

The last component of the energy balance was radiative heat transfer, which is given as:

$$R_n\_a = \alpha R_n \qquad \text{eq 7}$$

where:

R_n_a= net radiation adjusted for bud geometry and surface area of bud (W/m^2)

R_n= observed net radiation on a horizontal surface (W/m^2)

α= albedo of bud

The adjusted net radiation absorbed by the bud was dependent on the orientation and shape of the bud.

2.1 Model assumptions and formulations

The heat transfer model was written in the Fortran programming Language (FORTRAN 90) and compiled using GNU compiler. It requires a large number of coefficients and parameters unique to tree fruit buds, many of which were unknown. As a result, many were derived from empirical observations in a series of experiments in laboratory, growth chamber, and field settings. The model assumes a one minute (60s) time step.

2.1.1 Bud Geometry and Thermodynamic Properties

Bud geometry and thermodynamic properties were based on the empirical observations of a large number of swollen apple buds randomly selected from the field. The same selected buds were used to estimate the total water holding capacity at saturation. The weight of the buds was measured when dry and then re-weighed after the buds had been immersed in the water overnight. The average bud dry weight was 0.00576 g and the bud diameter was 3.4 mm, which was close to that obtained by Hamer (1986a). The diameter of buds were measured after soaking it in water for 24 hours and the total water content was estimated to be 63 % in full saturation. By using the volume and weight, the density of bud was estimated to be 560 kg/m^3.

The thermal conductivity of water is 0.58 W/ m C and dry wood is 0.17 W/ m C at 25 ^{0}C. The lab observations of bud volume indicated a water content of more than 40 %. It was assumed that the dry matter composition of the bud is similar to wood. Using a weighted average, the thermal conductivity of a bud was estimated as 0.38 W/ m C. The bud specific heat capacity was estimated with a number of buds in a growth chamber following the methodology of Glass and Zelinka (2010). The specific heat capacity of the bud was estimated to be 2160 J/Kg C when the bud temperature was 10 ^{0}C.

For modeling purposes, the geometric shape of the bud was assumed to be hemispheric and representative of tree fruit buds in general (Figure 3.1). Buds were considered to be one solid layer. Based on observations of buds misted by hand in a laboratory setting, water depth following a spray was considered to be 0.3 mm. Due to surface tension on the bud and in some cases the presence of small hairs, the water area coverage on the buds was found to vary greatly, ranging from 25% in a field setting to almost 100 % in a controlled lab environment with no wind. For nearly all model simulations, the water area coverage was assumed to be 25%, distributed across all areas of the bud and the water depth in the bud after misting was assumed to be 0.2 mm.

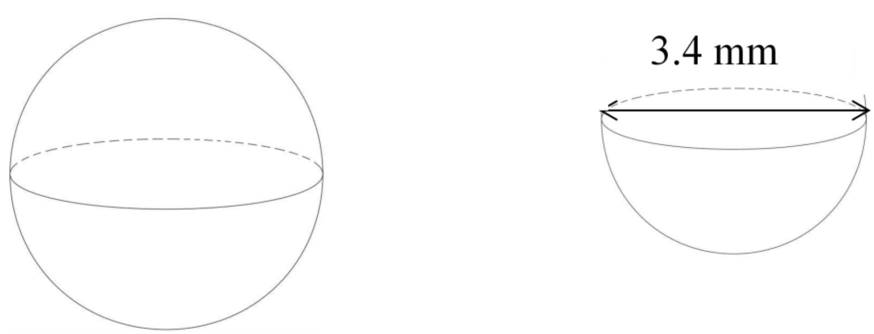

Figure 3.1: Bud geometry.

The reflectivity of the bud was estimated from a series of observations on buds on a sunny and mild day at East Lansing, MI in May of 2015. The observations were taken with and without mist under full and no shade treatments. All the four component of solar radiation and net radiation and both the air and bud temperature was measured. The albedo was estimated using incoming and outgoing solar radiation and air and bud temperature. A surface area correction and geometric correction based on Lambert's law were applied due to the shape, orientation, and surface area of the bud. The surface area correction was 0.5 and the geometric shape correction was 0.7 which assumes an average zenith angle of 45º. The reflectivity was thus estimated using the albedo and surface and geometric correction. The reflectivity of the a wet bud was found to be 0.248 and dry bud to be 0.0317 and these values were used in all subsequent model simulations.

Conductive heat transfer was based on differences between observed water and air temperatures. Observed water temperatures were found to vary in some cases depending on the source of water (ground vs. surface) and the length of irrigation pipe needed to reach the treated plots. In the cases of high variability, prescribed input water temperature was varied on a diurnal basis to reflect the observed temperatures. In the growth chamber experiment, the bud temperature dropped down right after misting if the bud temperature was more than water temperature and rose up right after misting if the bud temperature was less than water temperature. So, all conductive heat transfer was assumed to have occurred in the one minute period after misting.

2.2 Lab and field studies

With the set of tree fruit bud-specific coefficients and parameters, a set of controlled simulation experiments was run with the model to examine performance under idealized and outdoor field settings. Four different sets of experiments were conducted with cut twigs containing several buds; three in a growth chamber (apple-Cortland and Red Delicious, sweet cherry- Skeena and Rainer), and a fourth in an outdoor setting (sour cherry- Montmorency) at the Horticultural Demonstration Garden of Michigan State University, East Lasing, MI. The twigs were kept in the cooler (3- 4 ^{0}C) and taken out as per the requirement. Two separate model validation studies were conducted, the first was carried out with the buds of potted apple trees (apple- Cotland) at Horticulture Teaching and Research Center (HTRC), Holt, MI in fall 2014. A second, comprehensive study was carried out in a research orchard for Sweet cherry (Skeena and Rainer) at Southwest Michigan Research and Extension Center (SWMREC) at Benton Harbor, and in a commercial apple orchards at St Joseph, MI on Honey Crisp, Red Delicious and Gala and at Charlotte, MI on Honey Crisp. The experiments included:

2.2.1 Latent heat transfer

This experiment was carried out in the growth chamber at Department of Horticulture, MSU on January 2015. The temperature and relative humidity (RH) within a growth chamber were set to 20 ^{0}C and 55 %, respectively. Water mist at a temperature between 9.8 to 10.2 ^{0}C was manually sprayed on the buds with a handheld spray bottle. Three wetting and drying cycles, each approximately one hour long, were performed with a single soaking mist performed at the top of each hour followed by drying. This study was used to validate only the latent and conductive heat transfer equations. The water coverage on the bud from the mist application was assumed to be 100 % and the wind speed was considered to be 0.1m/s. The air temperature and RH was measured using HMP 60, temperature and relative humidity probe and bud, air and water temperature was measured using type E-chromium constantan thermocouples (Campbell Sci Inc.). The thermocouple was inserted in the bud from the base of bud, just adjacent to its connection to the stem.

2.2.2 Convective heat transfer

This experiment was carried out in the growth chamber at Department of Horticulture, MSU on March 2015. This study was carried out to see how quickly (non-misted) bud temperatures rise and fall when suddenly exposed to a prescribed step change in ambient temperature, in this case a move to or from growth chamber to room temperature and vice versa. The growth chamber temperature and RH were set to 10 ^{0}C and 65 % respectively. The room temperature during the period was 21-22 ^{0}C and RH was 20-23 %. Artificial wind (speeds of 2.3 and 2.7 m/s) was generated using a tabletop fan. Like in convective heat transfer, the air temperature and RH was measured using HMP 60, temperature and relative humidity probe and bud, air and water temperature was measured using type E-Nickel chromium constantan thermocouples (Campbell Sci Inc.). Wind speed was measured by SM-18 Hand-Held Wind Meter (SkyMate, Inc., Reston, VA). This study was used to validate the convective heat transfer segment of the model. This study was used to validate only the convective heat transfer equation.

2.2.3 Combined latent and convective heat transfer

This experiment was also carried out in the growth chamber at Department of Horticulture, MSU on May 2015. The growth chamber temperature and RH were set to 20 ^{0}C and 60 % respectively. A tabletop fan was used to generate the wind speeds of 1m/s, 1.8m/s, 2.5m/s, and 3.3m/s. Water spray mist at a temperature of 10-12 ^{0}C was sprayed on the buds at a one hour frequency and an assumed areal coverage on the bud of 50 % and conduction heat transfer was assumed for first two minutes as bud temperature dropped right after misting. the air temperature and RH was measured using HMP 60, temperature and relative humidity probe and bud, air and water temperature was measured using type E- Nickel chromium constantan thermocouples (Campbell Sci Inc.). Wind speed was measured by SM-18 Hand-Held Wind Meter (SkyMate, Inc., Reston, VA).

2.2.4 Latent, convective and radiative heat transfer

This study was carried out in an outdoor environment at the MSU Horticulture Demonstration Garden in East Lansing, Michigan State University on a mild, sunny day (May 29, 2015). The study was performed under four different conditions, each with two different replication; mist with shade, mist without shade, no mist and shade, and no mist without shade. A piece of opaque brown cardboard 5mm thick was used to provide shading to the cut twigs and buds. Water temperature of 10-12 ^{0}C was sprayed in mist form on the buds every 50 minutes. Air and bud temperature, relative humidity, wind speed and all four components (incoming and outgoing shortwave, incoming and outgoing long wave radiation) of radiation and net radiation were measured. Air temperature and RH was measured by HMP 60, temperature and relative humidity probe (Campbell Sci. Inc.). All four components of net radiation (incoming and outgoing shortwave, incoming and outgoing longwave) and net radiation was measured using a Kipp and Zonen pyrgeometer (Campbell Sci. Inc.). The wind speed was measured using a Cup anemometer (Campbell Sci. Inc.), and the bud and water temperature was measured using a type E- Nickle chromium constantan thermocouples (Campbell Sci Inc.). This study was done to validate the equations for all four components of heat transfer.

2.2.5 Potted tree and field validation studies

Three different sets of potted tree experiments were carried out during the fall season (August-September 2014) at the MSU Horticultural Teaching and Research Center (HTRC) in Holt, MI. In each experiment, dormant potted trees (Cortland apple) were brought out of a controlled cool environment into an outdoor setting. Water mist was applied to half of the trees and bud temperatures were measured on both misted and non-misted buds until the non-misted buds reached bloom. Air and bud temperatures, wind speed, and all four components of net radiation (incoming and outgoing shortwave, incoming and outgoing longwave) were measured with an automated datalogger like in outdoor environment study at the MSU Horticulture Demonstration Garden in East Lansing. Three different sets of experiment was carried out; set 1, set 2 and set 3.

First set of experiment (set 1) was carried out in the fall (Aug 17- Aug 23) of 2014. Water temperature was measured in different time of the day, water temperature was cooler in the morning and warmer in the afternoon and evening. Thus, the average water temperature was used for the modeling propose. For the day time (1100-2000) temperature of mist was considered to be 22 ^{0}C and during other hours it was considered to be 19 ^{0}C.

Second sets (set 2) of experiment was carried out from August 28 to September 6 2014. Similarly in set 1, the temperature of mist was considered 22 ^{0}C during day time hours (1100 to 2000) and was considered 19 ^{0}C during other hours.

The last set of experiment (set 3) was conducted from late September to early October (Sept 26-Oct 2) 2014. The water temperature in the morning and day time was fairly constant, with the average water temperature of 14.8 ^{0}C. The water temperature was considered 14.8 ^{0}C for the modeling propose.

The field validation experiment was conducted on commercial apple (Honeycrisp, Red Delicious and Gala) orchards at St. Joseph and Honeycrisp orchrd at Charlotte, MI during the spring of 2014 and in a sweet cherry orchard (Ranier) at SWMREC during the spring of 2014. Bud temperatures were measured on apple (Honeycrisp) and sweet cherry (Ranier). At SWMREC, the sweet cherry plants were under a 3m tall plastic tunnel (Haygrove, Inc., Mount Joy, PA). At St. Joseph, Charlotte, and SWMREC air and bud temperature and relative humidity were measured with HMP 60, temperature and relative humidity probe (Campbell Sci. Inc.) and bud temperature was measured using type E- Nickle chromium constantan thermocouples (Campbell Sci. Inc.) and data was continuously processed and recorded by CR 1000 datalogger (Campbell Sci. Inc.). Shortwave solar radiation and wind speed data were obtained from nearby weather stations of the EnviroWeather Information System (https://enviroweather.msu.edu/). For both potted tree and orchard studies, water mist was applied via SSCD system for a 1 minute spray duration, with the frequency between misting dependent on the ambient air temperature and relative humidity (summarized in Chapter 2, Table 2.1 for year 2014 and 2015). In field, each tree was misted by 2 emitters one on top of the canopy and one/half on each side and in potted each tree was misted by 1 emitter on the top of the canopy. The discharge rate of each emitter was 0.579 lpm at 275.79 kPa (40 psi). Air temperature and relative humidity were measured using HMP 60 temperature and relative humidity probe (Campbell Sci. Inc.), respectively. The water temperature of 10 ^{0}C was used, it is the average value of water temperature measured at different time of the day in the field.

The phenology of the misted and non-misted apple and sweet cherry buds were recorded based on visual observations twice a week. The phenological stages were also simulated for both the misted and non-misted apple and sweet cherry buds. Average GDD_{Tbud4} totals from April 1 at St. Joseph and April 9 at SWMREC for various stages of development for apple and sweet cherry were calculated based on the phenological observations, 2006-2015. The phenological stages of development for each crop were estimated based on the averaged summed GDD_{Tbud4} totals. In the field study, the mist was applied from April 1 at St. Joseph (apple-Red delicious buds) and April 9 (Sweet cherry-Skeena) at SWMREC. A similar condition was mimic in the model, the mist was applied from April 1until full bloom of apple and April 9 until first bloom of sweet cherry to simulate the misted bud temperature at St. Joseph and SWMREC respectively.

3. Results and Discussions

Both the simulated and observed bud temperature followed the similar pattern of change and were comparable in magnitude majority of the time. However, the simulated and observed bud temperatures behaved differently during higher wind speed and lower RH causing under-prediction. Upon the satisfactory performance of the model during validation processes in the growth chamber, potted tree and field study the model was applied to the long-term weather data from three different fruit growing locations of Michigan (Southwest, West central and Northwest) to estimate the delay in phenology by misting.

3.1 Growth chamber and garden study

3.1.1 Latent heat transfer

Simulations of latent heat transfer in the growth chamber were generally close to observed values, although the simulated temperature values after misting tended to return to the original temperatures more quickly than the observed values. With an ambient air temperature of 20 ^{0}C and relative humidity of 55%, there was an immediate drop of bud temperature right after misting, much of which appears to be due to conductive losses associated with the near 10 ºC water mist. The bud temperature remained fairly constant or rose slightly until the water was completely evaporated from the bud (Figure 3.2, 3.3). The bud temperature increased after the end of evaporation, and the simulated bud first returned to the original temperature (temperature before misting) in 66, 60 and 56 minutes for sets 1, 2 and 3 respectively. Whereas, the observed bud regained the original temperature in 71, 80 and 67 minutes for sets 1, 2 and 3 respectively. The mean differences between observed and simulated bud temperatures were 0.3, -1, and 0.9 ^{0}C for sets 1, 2 and 3 respectively. Likewise, mean absolute differences were 0.8, 1.1and 0.9 ^{0}C for sets 1, 2 and 3 respectively. In set 2, the model underestimated the bud temperature, whereas in set 1 and set 3, the model slightly overestimated the bud temperature. The r^2 between simulated and observed bud temperatures for set 1 was 0.81, set 2 was 0.8 and set 3 was 0.91 suggesting the comparable results.

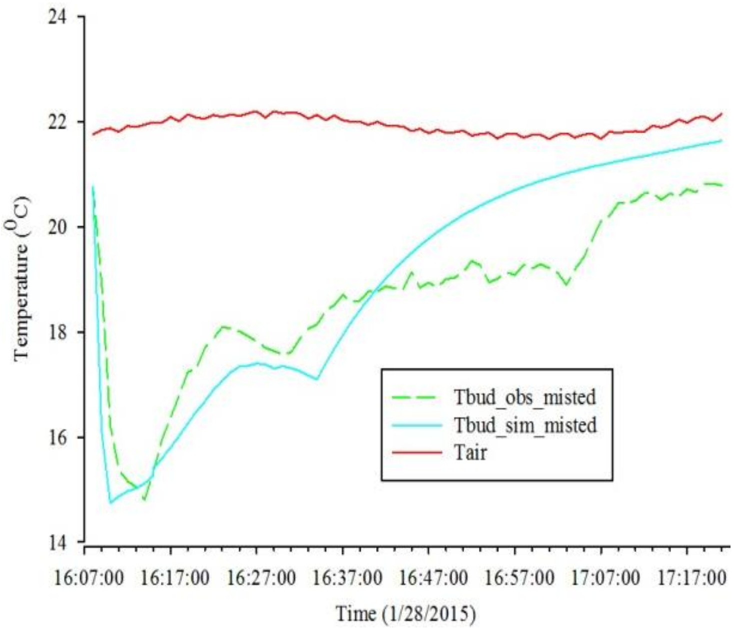

Figure 3.2: Observed and simulated misted bud and air temperatures from growth chamber study (January 2015) set 1.The temperature of the water mist was 10.2 ^{0}C.

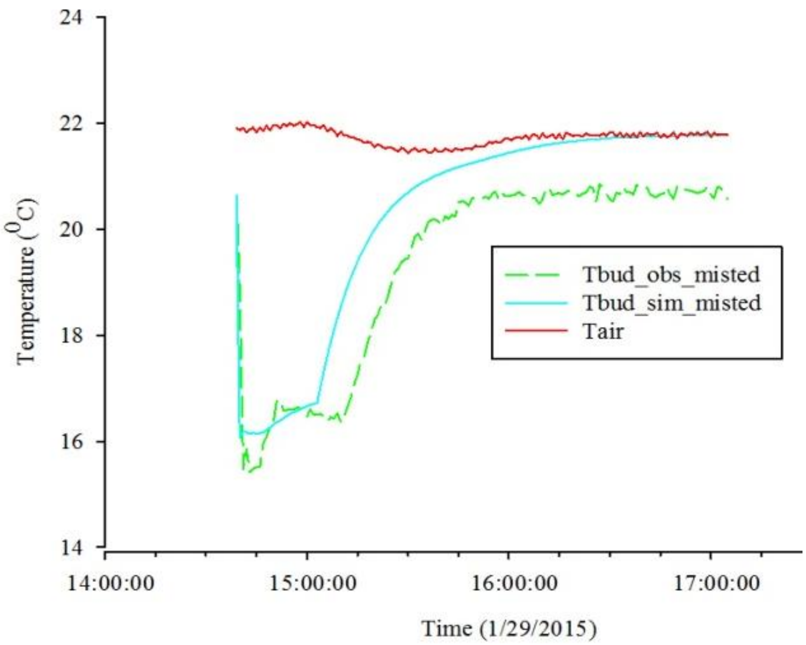

Figure 3.3: Observed and simulated misted bud and air temperatures from growth chamber study (January 2015) set 1(a) and set 3 (b).The temperature of the water mist was 10.2 ^{0}C.t

3.1.2 Convective heat transfer

The model simulated bud temperatures were in excellent agreement with observed temperatures in periods of step warming and cooling with wind speeds of 2.3 m/s (Figure 3.4) and 2.7 m/s. They required similar times to cool down when transferred from room temperature (21-22 ^{0}C) to a 10 ^{0}C growth chamber and warm up when the procedure was reversed. In the growth chamber both simulated and observed bud took 5-6 minutes to reach the stable temperature and when moved from the growth chamber back to room temperature the buds took 10-12 minutes to reach the stable temperature. The mean absolute difference between observed and model simulated bud temperature during drying cycle with wind speed 2.3 m/s was 0.1 ^{0}C and for wind speed 2.7 m/s was 0.2 ^{0}C. The mean absolute difference of cooling cycle with wind speed 2.3 m/s was 0.1 ^{0}C and for wind speed 2.7 m/s was 0.1 ^{0}C.

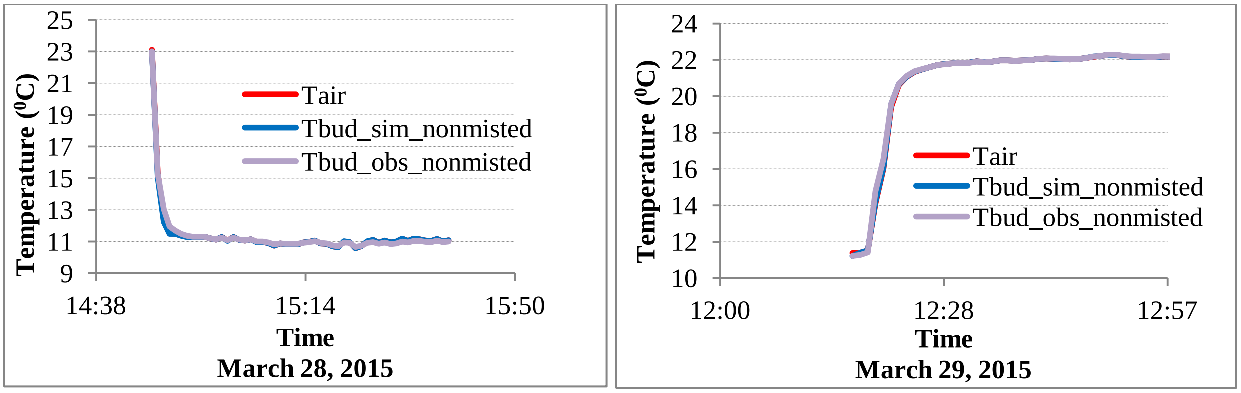

Figure 3.4: Observed and simulated non-misted bud and air temperatures from growth chamber study (March 2015) to examine convective heat exchange and step temperature changes. The wind speed was a constant 2.3 m/s.

3.1.3 Latent and convective heat transfer

While the model simulated bud temperatures tended to generally follow the observed values, the model tended to underestimate bud temperatures, especially during the dry down period of the wetting cycle. This pattern was more significant at lower wind speeds (Figures 3.5 and 3.6). The mean absolute differences between observed and simulated bud temperatures across the trials were 1.2, 0.76, 0.59, 0.85 for wind speed of 1, 1.8, 2, 3.3 m/s, respectively. Similar to the latent heat transfer trials, bud temperatures did not return to their original values until all water was evaporated from the bud. For the simulated bud temperatures, the rate of temperature increase after wetting was more rapid with higher wind speeds (Figure 3.5).

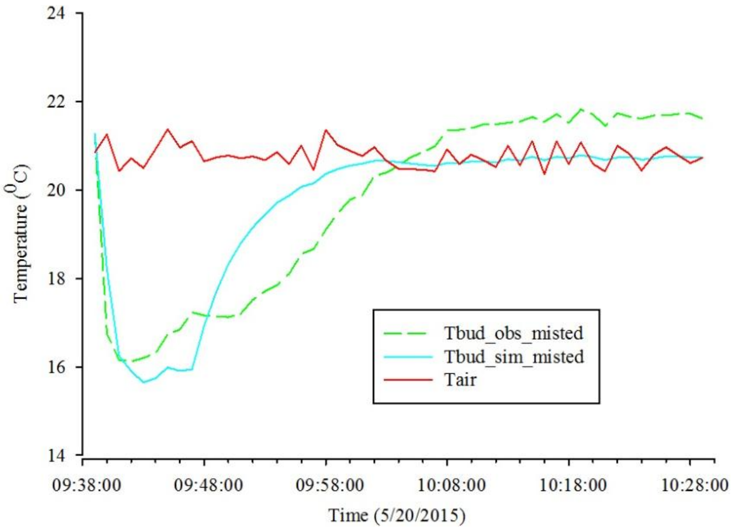

Figure 3.5: Observed and simulated misted bud and air temperatures in the growth chamber study (May 2015) with relative humidity of 55 % and wind speed of 3.3 m/s.

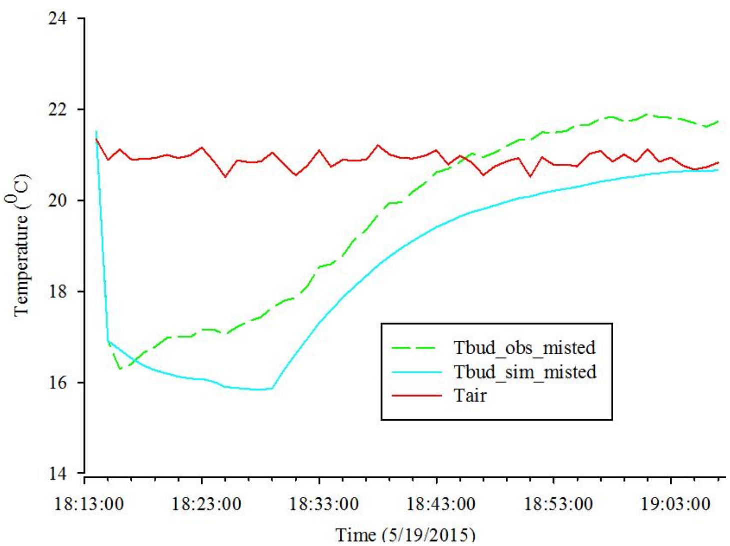

Figure 3.6: Observed and simulated misted bud and air temperatures in the growth chamber study (May 2015) with relative humidity of 55 % and wind speed of 2.0 m/s.

In terms of the bud drying cycle, evaporation on the model simulated buds tended to be longer than the observed buds (Table 3.1). As a result, the time to return to the original bud temperature was on average 11 minutes longer for the model simulated values.

Table 3.1: Time of evaporation of the misted water along with the time required to regain the original bud temperature from growth chamber study on May 2015.

Assumed water coverage (%)	Wind speed (m/s)	Evaporation time (minutes)				Time to return to original bud temperature (minutes)				Water temperature (^{0}C)	
		observed		simulated		observed		simulated			
		Set 1	Set 2	Set 1	Set 2	Set 1	Set 2	Set 1	Set 2	Set 1	Set 2
50	1	19	21	24	28	54	57	66	N	12	10.3
50	1.8	11	13	15	16	26	53	54	56	13	10.2
50	2	12	12	14	14	50	41	54	54	10.2	10.2
50	3.3	9	8	10.5	9.25	43	30	51	51	12	13

N= did not return to the original temperature within 70 minutes after spray application

3.1.4 Latent, convective, radiation and conductive heat transfer

For this combination of fluxes, simulated bud temperatures were similar to observed temperatures. In set 1, with mist and no shade cover, the model over-cooled the bud temperature right after misting (Figure 3.7). However, in set 2 with the same combination the model under-cooled bud temperatures (Figure 3.8). The temperature of the water mist was 12 and 10.2 ^{0}C for sets 1 and set 2 respectively. The maximum difference between simulated and observed bud temperature in set 1 (1400-1500 hours) was -2.2 ^{0}C (underestimate) when the air temperature was 30.6 ^{0}C and relative humidity was 41%. Similarly, in set 2 (1600-1700 hours), the maximum difference was 2.9 ^{0}C, (overestimate) when the air temperature was 28.9 ^{0}C and relative humidity was 34 %. Similar to the growth chamber studies, bud temperatures started to rise after the end of evaporation and latent heat transfer. The simulated times of evaporation were 8 and 9 minutes for sets 1 and set 2 respectively versus 8 and 10 minutes for the observed buds. The simulated bud temperatures returned to their original values in 11 (set 1) and 14 (set 2) minutes respectively, compared to the observed times of 12 and 14 minutes. During the study period of set 1, net radiation was fairly constant at a high level, ranging from 680-730 W/m^2 and during set 2, it decreased to 400-450 W/m^2. The average wind speed during the experimental period was 1.2 m/s (ranges from 0.4-2.3 m/s) with an average Reynolds number of 327 in 41 minutes. The convective heat transfer term contributed minimally to the total energy due to the lower wind speeds. The average relative humidity was 38 % and the air temperature was between 26 and 30 ^{0}C. Overall agreement between the simulated and observed bud temperatures was good, with r^2 values of 0.93 for set 1 and 0.97 for set 2. Mean absolute differences between simulated and observed bud temperatures were 0.8 and 0.5 ^{0}C for sets 1 and 2 respectively with the mist and no shade setup.

As expected, the rate of evaporation was slower in buds with shade than that without shade. The mist evaporated 1-2 minutes earlier on average from buds without shade compared to those buds under shade. Also, misted shaded buds took a longer time (5 minutes more in average) to return to the original bud temperature compared to misted buds without shade.

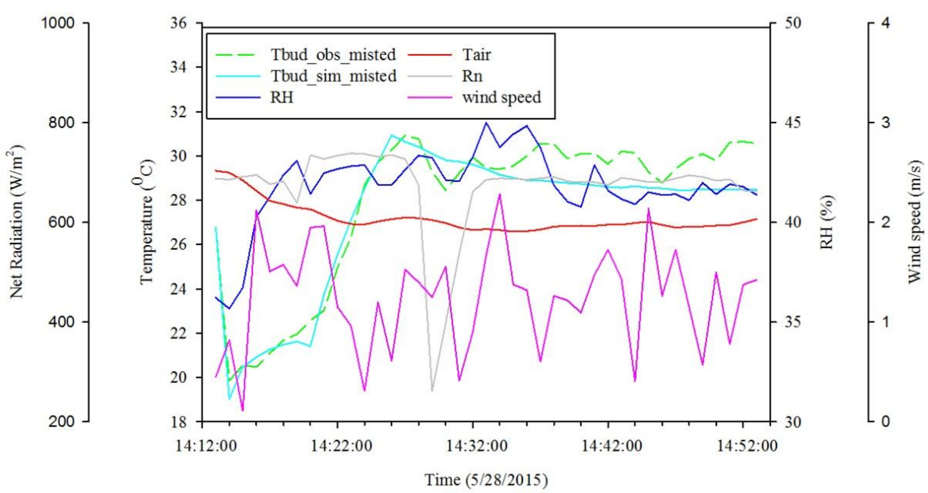

Figure 3.7: Simulated vs. observed misted bud and air temperatures in an outside study including net radiation on a mild and sunny day, May 28, 2015 at East Lansing MI.

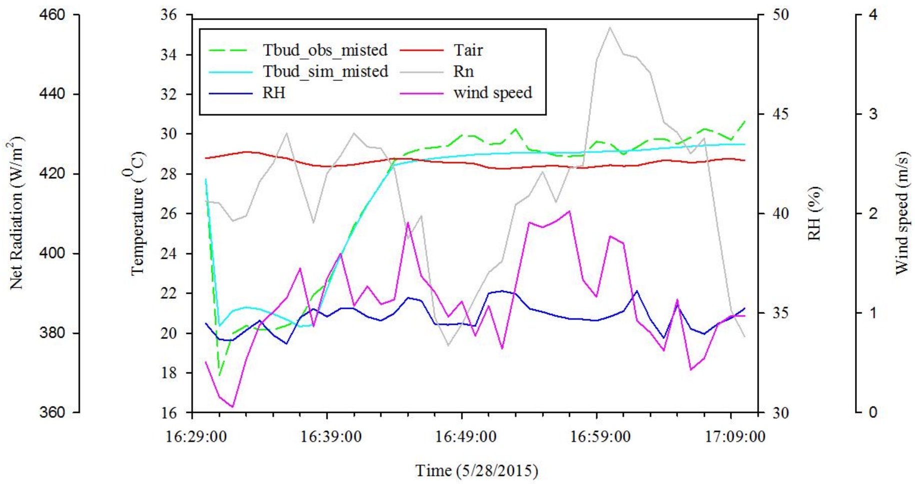

Figure 3.8: Simulated vs. observed misted bud and air temperatures in an outside study including net radiation on a mild and sunny day, May 28, 2015 at East Lansing MI.

3.2 Potted tree study

In this study, bud temperatures of potted trees approx. 1-1.5m in height and misted under an SSCD misting system were monitored. Daily and intra-daily (misting cycle) trends in simulated bud temperatures were similar to observed values, but differences varied in magnitude depending on weather conditions (Figure 3.9 and 3.11). The model tended to underestimate observed bud temperatures the majority of the time, with mean differences of -0.4 ºC, -0.2 ºC, and -0.3 ºC for sets 1, 2, and 3 respectively. Maximum differences were observed during higher wind speeds (> 4 m/s) when the observed bud temperatures were higher than simulated bud temperatures. Also, the model underestimated the bud temperature at lower values of RH (< 50%). However, when relative humidity was more than 85 %, differences between the observed and simulated bud temperatures were minimal, even at higher wind speeds. Also, the simulated and observed bud temperatures were comparable during morning and night time hours (1900-1000). As expected, the rate of evaporation was faster by 3 minutes when the RH was less than 50% compared to 60 % or greater RH for the same air temperature, wind speed and net solar radiation.

The mean absolute differences between observed and simulated bud temperatures for the set 1(7 days) was 0.6 ^{0}C, set 2 (10 days) was 0.8 ^{0}C and set 3 (7 days) was 0.7 ^{0}C and the r^2 value was greater than 0.85 (Table 3.2), indicating good performance of the model. The GDD totals derived from observed and simulated misted bud temperatures were not statistically different (Table 3.2).

Table 3.2: GDD, mean difference, and mean absolute values and R-square (r^2) between observed and simulated misted bud temperatures from potted tree study (Aug-Oct 2014) at HTRC, Holt, MI . GDDs were estimated from bud temperatures.

Sets	Days of observation	GDD		Observed and simulated bud temperature		
		Tbud_obs_ misted	Tbud_sim_ misted	Mean difference	Mean absolute difference	r^2
	days	^{0}C	^{0}C	^{0}C	^{0}C	
set 1	6	115.1	111.9	-0.4	0.6	0.94
set 2	10	159.7	156.3	-0.2	0.8	0.88
set 3	7	68.1	65.5	-0.3	0.7	0.95

Note-Tbud_obs_misted is observed misted bud temperature, Tbud_sim_misted is simulated misted bud temperature, Tair is air temperature

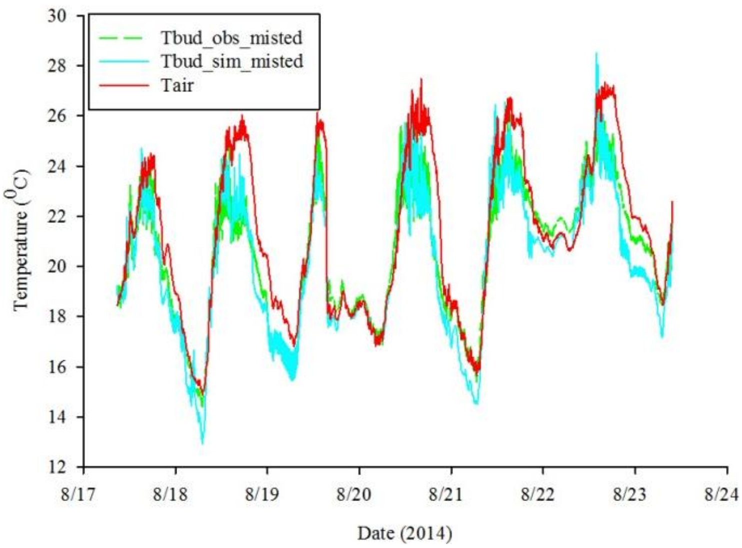

Figure 3.9: Simulated and observed misted bud and air temperatures, potted tree experiment from Aug 17- 23, 2014, HTRC, Holt, MI.

Time series plot of misting cycles and simulated versus observed bud temperatures during afternoon periods are given in Figures 3.10 and 3.11. A drop in bud temperature of approximately 1 ^{0}C occurs immediately after the initial misting. After misting, bud temperature followed water temperature, i.e. the bud temperature rose if the water temperature was higher than bud temperature, and vice versa (Figure 3.10, 3.11). The bud temperature continuously dropped down until after 4-5 minutes of misting. The later drop in bud temperature was likely due to latent heat loss. The difference between observed and simulated bud temperature was lower during minimal or no wind speed.

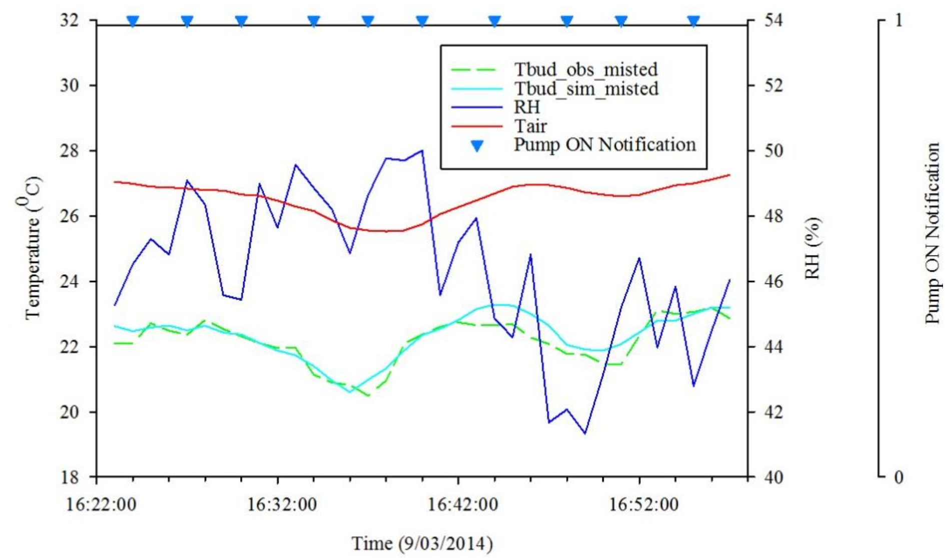

Figure 3.10: Simulated and observed misted bud temperature, air temperature, relative humidity and misted points of potted plant experiment, HTRC, Holt, MI on September 9, 2014. Wind speed ranged between 0.9 to 2.35 m/s.

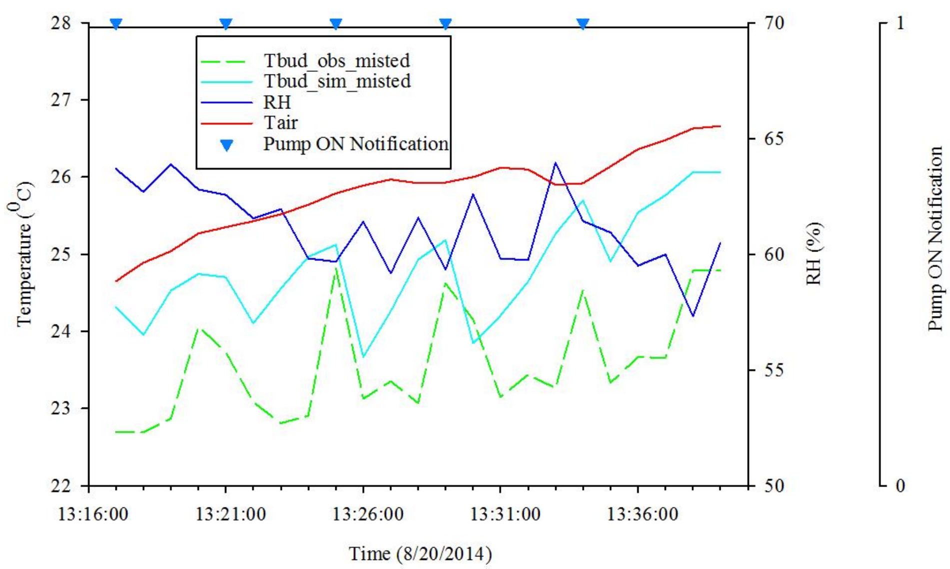

Figure 3.11: Simulated and observed misted bud temperature, air temperature, relative humidity and misted points of potted tree experiment, Holt, MI on August 20, 2014. Wind speed ranged between 0.1 to 2.8 m/s. net radiation ranged from 670 to 770 W/m ^{2}.

Latent heat loss contributed to a maximum of the heat loss followed by conduction. The latent heat loss ranged from -1 to -40 W/m^2 and conduction ranged from 2 to -8 W/m ^{2}. When water temperature was more than the bud temperature, conduction heat loss became the means of heat gain, increasing the bud temperature right after misting. However, the bud temperature dropped down later (1 minute after misting) due to latent heat loss. For similar air temperature and wind speed, latent heat loss was greater by 3- 7 W/m^2 at lower relative humidity (< 50 %) compared to higher relative humidity. Higher wind speed also enhances the rate of drying of the water droplets from the buds. The higher rates of evaporation with lower relative humidity and higher wind speed were also observed by Gebremedhin and Wu (2001) and Maia and Loureiro (2005) in their study of cooling dairy cows. Dry air can absorb a relatively larger volume of water, thus mass transfer is significantly greater in the dry environment resulting in higher rate of evaporation (Barrow and Pop (2006). Higher relative humidity reduces the vapor concentration gradient between bud and air and lowers the rate of evaporation. The rate of evaporation was slower at night likely due to an absence of solar radiation. According to Gebremedhin and Wu (2001), a greater rate of cooling could have been achieved with a higher level of wetness (ie higher spray rates).

3.3 Field study in an orchard environment

In this phase of the project, the model was run to simulate the effects of misting in actual orchard environments at three locations during 2014. Overall model performance statistics are given in Tables 3.3 and 3.4. The mean difference between observed and simulated bud temperature of apple buds at St. Joseph was -0.2 ^{0}C and the mean absolute difference was 0.8 ^{0}C. Likewise, the mean absolute difference between observed and simulated bud temperature was 0.9 ^{0}C for sweet cherry (Table 3.3). The r^2 value between observed and simulated misted bud temperature was just above 0.8. Only at the Charlotte location, where we experienced malfunction of the mist application system, the mean absolute difference was greater than 1 ^{0}C

(Table 3.3). At this site, the emitters became clogged by sediment resulting in poor spray coverage and a reduced decrease in the bud temperature.

Most of the time, the simulated bud temperatures were close to the observed values, especially during periods of relatively low wind speeds (Figure 3.12) during evening. Some diurnal differences were noted. Maximum bud cooling relative to ambient air temperatures was achieved between 1200 to 1600 hours. During nighttime hours (2100 -0600), the model tended to overestimate bud temperatures (mean difference of 0.5 ^{0}C) compared to day time hours (mean difference of -0.3 ^{0}C) at SWMREC and St. Joseph, MI. However, in the case of sweet cherry under a partially- open plastic high tunnel at SWMREC, simulated bud temperature was greater than observed bud temperature during the period with higher wind speed. In this case, the simulation utilized wind speed data from a weather station which was likely less than the winds under the tunnel which could have resulted in a erroneously low convective heat exchange in the simulations. Also, leaves and branches could have influenced the net radiation to and from bud as described by Hamer (1985).

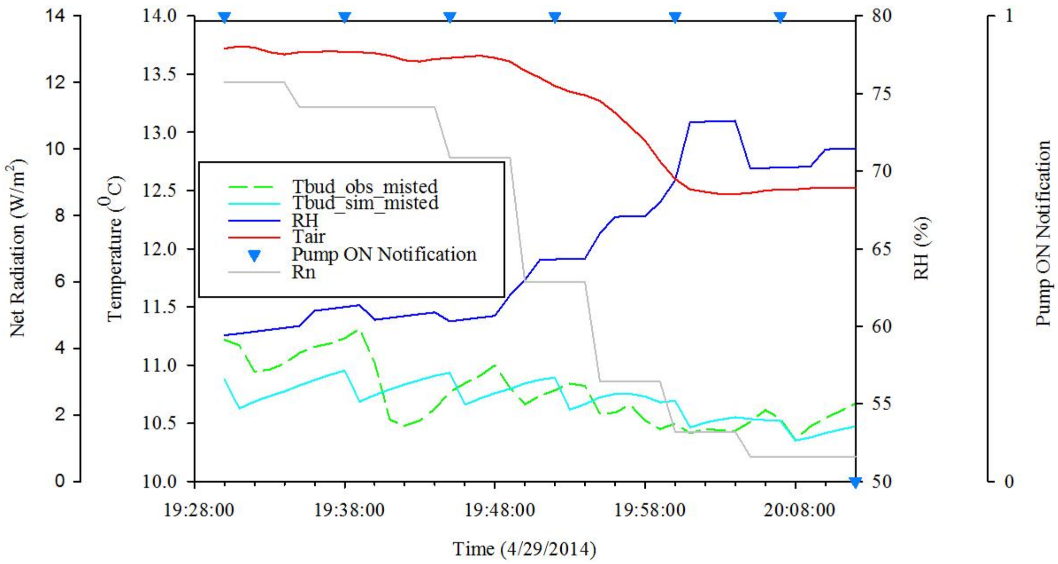

Figure 3.12: Simulated and observed misted bud temperature, air temperature, relative humidity and misted points of apple buds (Honey Crisp) at St. Joseph, MI on April 29, 2014. Wind speed was between 0.5 to 2.3 m/s.

There were additional wind-related impacts related to stronger winds. The most common was model under-prediction of bud temperature (and over-prediction of latent heat exchange). This effect is illustrated in Figure 3.13 for a midday through mid-afternoon period in the St. Joseph apple orchard. Between approximately 13:30 and 14:15 the simulated bud temperature was more than 2º cooler than the observed temperature. That was most likely due to winds increasing from 5 to 7 m/s which caused the mist spray to drift and miss the intended bud targets below, a factor not accounted for in the model. Similarly, the model also under-predicted bud temperatures from 12:00 to 12:25, but at lower wind speeds than observed later that day. An investigation of wind direction indicated that winds during the day shifted from the southeast to the northwest and at the time of under-prediction were blowing more parallel to the orchard rows (and once again creating a spray drift problem). Thus, the performance of the model may be sensitive to wind direction, topography, and orientation of the orchard. Similar issues with wind direction and evaporation of water droplets was also noted by Edling (1985).

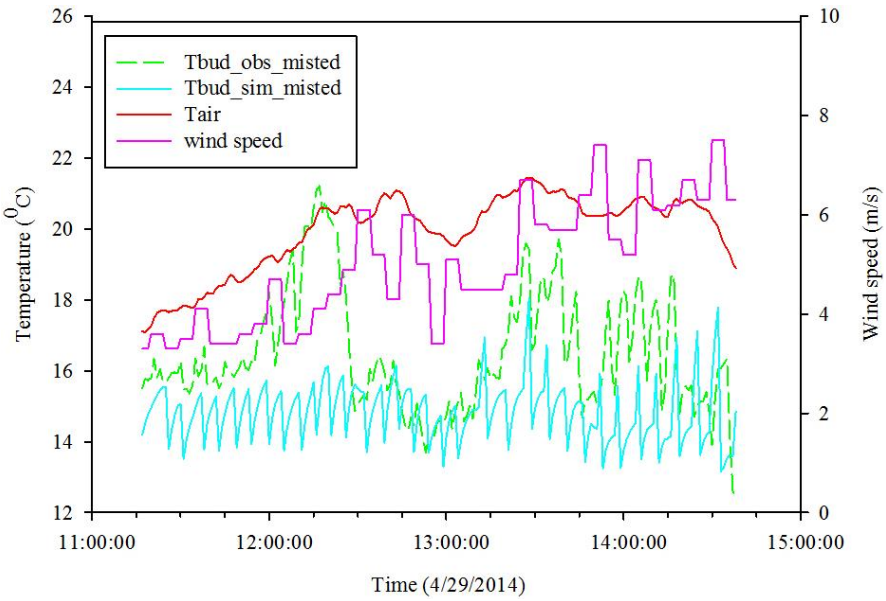

Figure 3.13: Simulated and observed misted bud temperature, air temperature, and wind speed at St. Joseph, MI on April 29, 2014. Relative humidity was between 35 to 65%.

Also, the interception of water by vegetation in the vicinity of the buds may affect the wetness of buds and potential bud temperature cooling in the field conditions since some of the water may not make contact with the buds. This effect would be most pronounced during the latter part of the vegetative growth cycle after new leaves and stems emerge. However, interception of spray by vegetation was not accounted for in the model which assumed complete saturation after each misting cycle. In his frost control-related simulation model, Hamer (1986 a) added an interception factor to estimate the reduction of water reaching the buds. However, estimating the interception is difficult because the rate of interception varies across growth stages and may be different with location and orientation of the bud.

Table 3.3 : GDD, mean differences, mean absolute differences and r^2 between observed and simulated misted bud temperature at St. Joseph, SWMREC, Charlotte, MI from April-May 2014. GDD of bud was estimated from bud temperature.

				GDD		Observed and simulated bud temperature		
Station	Fruit	Dates	Days of observation	Tbud_obs_ misted	Tbud_sim_ misted	Mean difference	Mean absolute difference	r^2
			days	^{0}C	^{0}C	^{0}C	^{0}C	
St. Joseph	Apple	4/26-5/4	9	36.9	35.3	-0.2	0.8	0.86
SWMREC	Sweet Cherry	4/21-5/2	12	47.1	48.8	0.2	0.9	0.85
Charlotte	Apple	5/4-5/8	5	33.1	30.8	-0.5	1.4	0.81

Base 4 ºC GDD totals calculated with simulated and observed misted bud temperature were comparable with no statistically significant differences. Based on these GDD totals, the observed reproductive bud phenology of the misted sweet cherry buds lagged by 2 days compared to simulated misted buds (Table 3.4). Simulated bloom date of non-misted sweet cherry bud was one day behind the observed bloom date of non-misted sweet cherry buds. Both the simulated and observed non-misted apple buds bloomed on the same day. Though the observed and simulated date of the green tip and tight cluster were comparable the observed misted buds of apple bloomed 4 days earlier than the simulated misted apple buds (Table 3.4). In general, the model tended to slightly overestimate the rate of bud cooling, resulting in slightly longer phenological delay of 5 days in the bloom date of apple and 4 days in sweet cherry compared to the observed bloom date.

Table 3.4: Simulated and observed phenological stages of apple (Red Delicious) and sweet cherry buds at St. Joseph and SWMREC, MI for 2014.

Location and fruits	Conditions	Misted bud			Non-misted bud			Total days of bloom delay
		Green tip	Tight cluster	bloom	Green tip	Tight cluster	bloom	days
St. Joseph, Apple-Red Delicious	Phenology from simulated bud temperature	5/2	5/13	5/29	4/16	4/28	5/16	13
	Observed phenology	5/4	5/12	5/25	*	4/30	5/16	9
SWMREC, Sweet cherry	Phenology from simulated bud temperature	5/6	5/10	5/19	4/23	4/29	5/7	12
	Observed phenology	5/4	5/8	5/17	4/24	4/29	5/8	9

*= No observation was made

3.4 Theoretical potential for spray misting as a frost protection strategy

Given satisfactory performance of the model in a number of settings, it was used to examine the potential benefits of spray misting for indirect frost control at three locations in major fruit-producing areas of western Lower Michigan during the 10-year period 2006-2015. The three locations were Southwest Michigan Research and Extension Center (SWMREC) near Benton Harbor in the southwestern corner of the state, Sparta in the West Central region, and the Northwest Michigan Horticulture Research Center (NWMHRC) near Traverse City in the Northwestern corner of the Lower Peninsula. Each year, the model was used to simulate misted bud temperatures for apple, sweet and sour cherry from March 1 until the date of first bloom for non-misted buds. In the simulation, misting was initiated whenever air temperatures reached a value of 4.4ºC or greater and RH was less than 90. The temperature of the mist water was assumed to be 10.0 ºC (similar to field study) and the misting interval of a single cycle was set at 4 to 12.5 minutes depending upon the air temperature and RH (summarized in Table 2.1 chapter 2, for year 2014 and 2015) and misting duration was 1 minute in all the cases. After simulated bud temperatures were obtained, base 4 ºC growing degree day totals were calculated with the bud temperatures to estimate crop phenology each season. Known critical temperature damage thresholds for the buds at given phenological stages were used along with observed air temperatures to estimate cold damage events. The simulations were run twice for each site, one with misting and one without, which provided an estimate of the relative impact of the spray mist applications to alter the frequency and severity of cold damage.

Five minute observations of air temperature, wind speed, and relative humidity (RH) and 1 hour observations of total solar radiation from each of the three sites were obtained from the Michigan State University Enviro-Weather information system (https://mawn.geo.msu.edu/) for the period 2006-2015. Given the 1 minute temporal resolution of the simulation model, the five minute values of air temperature, wind speed, and relative humidity (RH) were converted into one minute values by linear interpolation. Hourly values of net radiation were derived from the hourly values of air temperature, relative humidity, wind speed and solar radiation following Allen et. al (1998), and converted into 1-minute values assuming the same hourly value for each minute of that hour. In a comparison with observed values of net radiation taken from the Holt, MI 2014 potted tree studies, the estimated values of net radiation were in good general agreement with the observed values, especially during the daytime hours, but at night (2200 to 0500 hours) the model tended to overestimate net radiation by 32 W/m^2. The r^2 value between observed and simulated net radiation for the 8-day validation period was 0.98 with a mean absolute difference of 33 W/m^2.

Observations of phenological stages for the 2006-2015 study period were obtained from Michigan State University Extension personnel for the three study locations: Apple (Red Delicious) at SWMREC (Bill Shane), apple (MacIntosh) from Sparta (Philip Schwallier), apple

(Gala and Red Delicious) from NWMHRC (Bill Klein) and sweet and sour cherry from SWMREC and NWMHRS. Simulated phenology was obtained with accumulated GDD calculated from both misted and non-misted bud temperatures beginning each year on March 1st. Phenological GDD thresholds for the various stages of each crop were obtained as the average of the simulated non-misted bud temperature GDD totals at the various observed phenological stage over the 10-year study period. It was assumed that the GDD thresholds were the same for both non misted and misted buds.

Ten and ninety percent damage threshold temperatures for tree fruit at a number of phenological stages were obtained from a Washington state extension (WSU EB1128, WSU EB0913) and Michigan State Extension (MSU Research. Rpt. 220). Assuming a linear relationship between the damage and the critical freezing temperatures (Dennis and Howell, 1972), 50 % damage threshold temperatures of -3 ^{0}C was estimated for first pink to flower bloom stage for apple, first bloom to full bloom for sweet cherry, and popcorn to full bloom for sour cherry buds. In general, the damage threshold temperatures during vegetative phenological stages range from approximately -9.0 ºC in early stages to -2.0 ºC in later stages.

3.4.1 Results and discussions of application

The bud temperature patterns simulated by the model at the three study locations were very similar to those observed in the various field experiments. Simulated bud temperatures dropped after misting when the bud temperature was higher than the water temperature and rose if the bud temperature was less than water temperature. The maximum drop (5 ^{0}C) in simulated buds temperature was observed immediately after misting on a mild sunny day (May 21, 2012) at Sparta, MI when the air temperature was relative high (>20 ^{0}C) and RH was less than 50 % (Figure 3.14). Like the potted tree and field studies, buds took a longer time to return to their original temperatures in the misting cycle during relatively cool, humid, cloudy, and calm days, and at night. During warm and dry days the difference between the misted and non-misted bud temperatures was relatively greater. As expected, the rates of evaporation were greater during periods of relatively higher air temperatures, lower RH, higher wind speeds and sunny skies. For example, on a clear day (net radiation between 500-550 W/m^2) with an air temperature between 11-15 ^{0}C, RH less than 50 %, and wind speed between 7-8 m/s, the mist on the bud was evaporated in 6 minutes. Keeping all conditions the same with the absence of wind, the water evaporated in 8-9 minutes. With net radiation between 500-550 W/m^2 during the afternoon hours and an air temperature between 11-15 ^{0}C, wind speed between 7-8 m/s and RH greater than 60 %, the mist from bud evaporated in 10-11 minutes. However, at night time with the same air temperature (11-15 ^{0}C), wind speed (7-8 m/s) and RH (< 50 %), the mist was not completely evaporated before the next application (12 minutes).

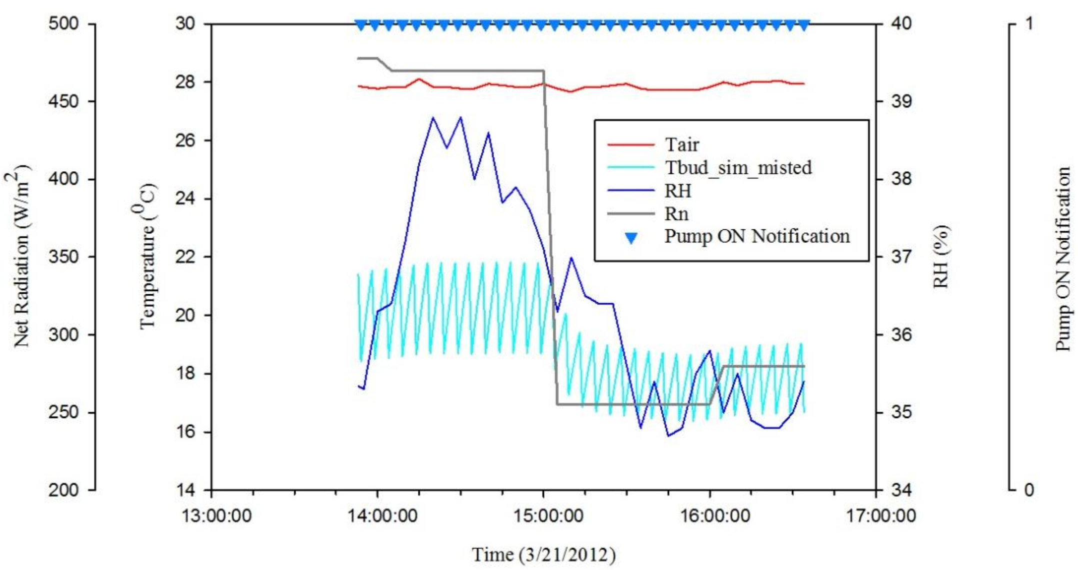

Figure 3.14: Simulated misted bud temperature, air temperature, relative humidity and misted points at Sparta, Michigan on May 21, 2012. Wind speed during the period was 2-4 m/s.

3.4.1.1 Diurnal cycle of cooling

Simulated bud temperatures averaged each hour across the three locations over the 10-year study period are given in Figure 3.15. Average rates of cooling were highest during afternoon hours (Figure 3.15) and lower in the morning, especially near sunrise. The maximum difference between misted and non-misted bud was from 1500 to 2000 hours, when misted bud temperatures were 5.2 to 5.4^{0}C cooler than non-misted buds. The almost complete lack of cooling near and just after sunrise (0800-0900) is likely associated with the typically high values of relative humidity and relatively low solar radiation and wind speeds at those hours and possibly even to condensation.

Misted bud temperatures during the day closely followed the diurnal trend of net radiation, with maximum values during the early afternoon (Figure 3.16). From the heat exchange terms in the model, latent heat flux was the largest source of energy loss and cooling over time, followed by conduction from the applied 10 ºC water. Convective heat transfer had the least influence on cooling. All the energy fluxes were small or near zero during nighttime hours between 2000 to 0800. During the daytime hours bud temperatures were always lower than the air temperature, therefore sensible heat flux was always positive. The loss from latent heat was greatest in the afternoon, typically averaging between -20 W/m^2 to -30 W/m^2. From 2000 to 0800 conduction was positive on average, adding heat to the bud.

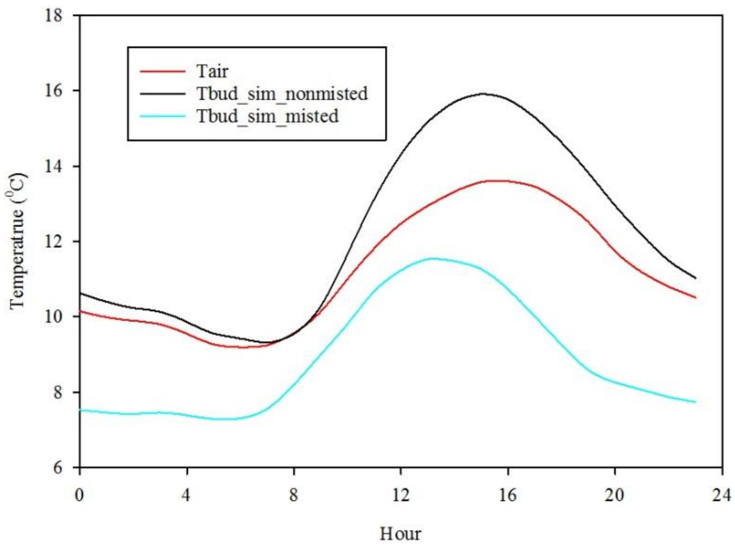

Figure 3.15: Diurnal variation of air and misted and non misted bud temperatures, averaged across the three location during the spring season (March, April, and May) for the 2006-2015 period. Averages are for hours with misting only (ie air temperature > 4.4^{0}C).

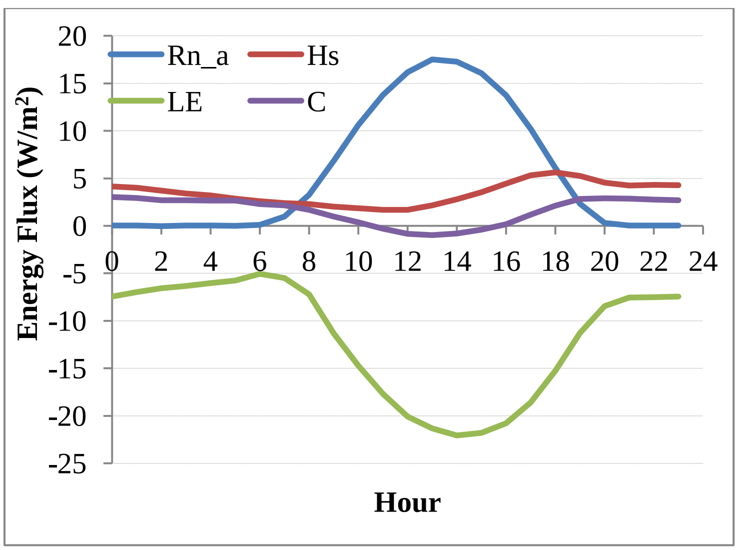

Figure 3.16: Diurnal variation of the four energy components, averaged across the three location during the spring season (March, April, and May) for the 2006-2015 period. Averages are for hours with misting only (ie air temperature > 4.4^{0}C).

3.4.1.2 Bud temperatures

Misting contributed to the cooling of buds during the spring seasons at all three locations during the ten years study period, and the misted temperatures were almost always lower than the non-misted bud temperatures. Considering only the period of time when the misting was taking place (air temperatures greater than 4.4 ^{0}C), maximum cooling was achieved during the months of April and May, except for the 2012 season (Table 3.5). The average monthly differences between misted and non-misted bud temperatures was -0.2 ^{0}C in March, -0.8 ^{0}C in April, and -2.0 ^{0}C in May. However, during the 2012 growing season, maximum cooling was obtained in March (-3.2 ^{0}C), which was associated with an unprecedented heat wave observed across Michigan and the Great Lakes region that month (Longstroth and Andresen, 2012). For the seasons as a whole, cooling was maximum in the warmer years such as 2012 compared to cooler years. In 2012, at SWMREC and Sparta, the average air temperature from mid-March to the first week of April was more than the applied water temperature (10 ^{0}C), and average RH was less than 70 % majority of the time. This condition contributed to some of the highest rates of evaporation and cooling during the 10-year period. Likewise, April 2010 was warmer than normal (Figure 3.17), leading to early phenological development. During most other years, air temperatures during March were relatively low and only 1-5 GDD_4 were obtained for the month. The table 3.5 and figure 3.17 shows only the time period when mist was applied (Tair > 4.44 ^{0}C), however if we including both mist and no mist period would decrease the average temperature of the season.

Table 3.5: Average monthly air, simulated misted and non-misted bud temperatures during the spring season (March 1 through last day of mist). Averages were calculated only for periods when misting took place (air temperature > 4.4 ^{0}C), at SWMREC, Sparta, and NWMHRC, 2006-2015.

		SWMREC			Sparta			NWMHRC		
year	month	Tair	Tbud_ sim_ misted	Tbud_ sim_non misted	Tair	Tbud_ sim_ misted	Tbud_ sim_non misted	Tair	Tbud_ sim_ misted	Tbud_ sim_non misted
		^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C	^{0}C
2006	March	10.4	8.8	11.3	10.4	9.2	11.4	9.7	8.0	11.3
	April	12.1	9.1	13.3	12.1	9.2	13.4	11.6	8.8	13.4
	May	13.0	14.0	14.4	14.2	15.5	16.2	12.6	12.4	14.3
2007	March	11.5	8.5	12.4	11.5	8.8	12.6	9.7	7.8	10.8
	April	11.3	8.3	12.4	11.3	8.4	12.5	11.0	8.6	12.6
	May	14.8	14.6	16.3	12.6	9.3	14.1	13.5	10.9	15.9
2008	March	6.9	5.8	7.6	7.0	6.6	6.3	6.6	6.0	7.3
	April	12.7	9.0	14.0	13.0	9.3	12.0	12.1	8.8	13.8
	May	13.1	12.7	14.4	12.3	9.9	11.9	11.1	10.1	13.1
2009	March	10.2	7.0	11.2	9.3	6.6	10.4	8.2	6.3	9.7
	April	12.5	8.8	13.5	11.4	8.4	12.7	11.0	7.9	12.7
	May	14.2	14.3	15.5	13.2	10.2	14.8	13.3	11.2	15.2
2010	March	10.0	7.6	11.0	9.3	7.9	10.8	9.4	8.2	11.4
	April	13.6	10.0	14.7	12.7	9.3	14.1	12.6	9.3	14.4
	May	No misting on May						16.4	13.5	18.2
2011	March	8.6	6.5	9.3	8.1	7.5	9.7	7.8	8.5	10.1
	April	10.4	8.0	11.2	10.2	8.3	11.3	9.7	9.1	11.6
	May	14.4	13.2	15.6	13.8	10.5	15.3	12.6	10.2	14.3
2012	March	15.5	10.5	16.4	15.0	12.6	16.1	14.0	12.1	15.0
	April	9.58	8.7	11.23	10.5	12.3	12.4	10.0	12.5	11.9
	May	No misting on May						10.6	11.2	11.1
2013	March	8.5	6.1	9.4	6.4	7.1	8.4	6.4	5.2	7.9
	April	11.5	8.0	12.3	8.2	10.8	11.9	11.3	8.6	12.4
	May	16.5	14.2	17.7	11.3	16.3	17.8	14.7	11.0	16.4
2014	March	8.3	5.7	9.0	8.0	6.1	9.5	7.6	5.2	8.7
	April	11.4	7.1	12.3	10.4	7.2	11.5	8.9	6.3	9.9
	May	15.0	13.6	16.1	12.6	10.2	13.7	13.7	11.8	14.0
2015	March	8.9	6.3	10.0	7.9	6.4	9.5	8.0	6.1	9.4
	April	10.9	7.2	11.8	11.0	7.8	12.4	10.0	7.2	11.4
	May	15.7	15.1	16.9	16.0	12.2	17.0	14.6	11.3	15.9
Avera ge	March	9.9	10.4	10.8	9.4	10.8	10.7	8.5	9.7	9.4
	April	11.6	11.4	12.6	11.4	11.9	12.5	10.5	11.2	11.8
	May	14.2	13.0	15.5	13.6	12.9	15.0	12.2	12.1	13.6

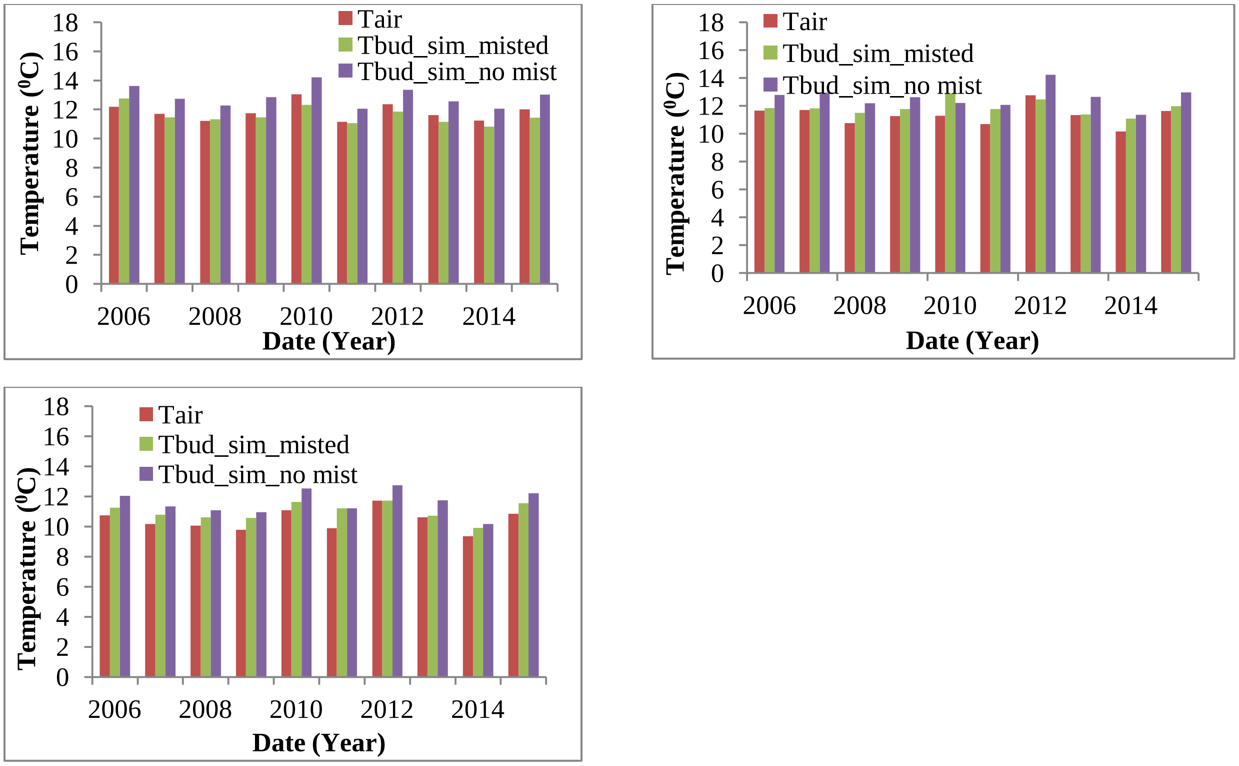

Figure 3.17: Seasonal (March - May) average air temperatures, and simulated misted and non-misted bud temperatures at a) SWMREC, b) Sparta, and c) NWMHRS, only for periods when misting took place (air temperature > 4.4 ^{0}C).

3.4.1.3 Bloom delay of apple and cherry buds

From the GDD-based estimated phenology each year, misting delayed the bloom of Red Delicious, Gala and McIntosh apple by 10 days or more at all three locations. The length of the bloom delay depended on the location and the weather condition and the timing of the misting. In general, any delay is potentially valuable, as the buds lose hardiness as soon as they begin to develop and are more susceptible to freeze damage (Rodrigo, 2000). The simulated misting delayed earlier phenological stages like green tip, half inch green, tight cluster, and pink open by more than a week compared to that of non-misted buds. Timing of the misting is important in achieving the required days of delay. Anderson et al. (1975) found mist application after the completion of endo-dormancy relatively more effective in delaying phenology. Also, applying the mist when the air temperature gets more than water temperature could be effective.

At SWMREC, misting delayed the apple bloom (Red Delicious) from 11 to 22 days compared to non-misted buds. At Sparta, misting delayed the apple bloom (MacIntosh) 9 to 21 days and at NWMHRS the apple bloom (Red Delicious and Gala) was delayed from 12 to 22 days compared to the non-misted buds (Table 3.6). In relatively warm years, the differences between bloom date of the misted and non misted treatment were larger. In 2012, for example, non-misted apple buds at the three locations bloomed more than 20 days earlier than the misted apple buds. Average delays for apples over the 10 year period were 14 days at SWMREC, 13 days at Sparta, and 15 days at NWMHRC.

Similar to the apple simulations, misting delayed the bloom of sour cherry (Montmorency) and sweet cherry by more than one week at SWMREC and NWMHRC. Water use depended on the weather condition and location, with relatively longer bloom delays in warmer springs such as 2010 and 2012. In 2012, both sweet and sour cherry blooms were delayed by 21 days at NWMHRC. In 2012, the sour cherry bloom was delayed by 17 days and sweet cherry bloom was delayed by 13 days at SWMREC. Despite the higher volume of water use, cherry bloom was delayed by only a few days during cooler springs (Figure 17) like 2009 and 2011 at SWMREC and 2007, 2011 and 2014 at NWMHRS (Table 3.7). In 2007, 2011 and 2014, non-misted buds bloomed 7-8 days earlier than misted buds at Northwest Michigan. Misted sweet and sour cherry buds also lagged more than one week behind non misted buds for other phenological stages including green tip, tight cluster, and white bud.

The average water required to delay the bloom of apple by more than 10 days was 15.6 ha-cm. Similarly, 12.5 ha-cm and 10 ha- cm of water was used to delay the bloom of sour cherry and sweet cherry by more than a week. Relatively warm springs like 2010 and 2012 corresponded to a reduced duration of water application and overall lower volume of water, even with relatively longer bloom delays. Conversely, the total duration of mist application was higher in cool springs like 2009, 2011, and 2014. At Sparta, the maximum volume of mist was applied in 2009 (17 ha-cm) and 2011 (16 ha-cm), and that delayed the apple bloom by 12 and 9 days respectively. The minimum volume of mist was applied in 2006 (13 ha-cm), which delayed the apple bloom by 13 days (Table 3.6). The mist was applied for relatively longer periods of time at NWMHRC compared to other two locations (Table 3.6). At that site, the volume (35 ha-cm) of mist applied in 2011 was twice that applied in any other year, and resulted in only 14 days of bloom delay between misted and non-misted treatments. Still, the simulated water needs in an SSCD-type system for this application were significantly less than that reported in earlier studies. Hewett and Young (1980) observed 6 days of bloom delay in apple achieved by applying 93 cm of water and 18 days of delay achieved by applying 48.8 cm of water over a 0.6 ha area. Similarly, Chesness et al. (1977) sprinkled 46 cm of water in an area of 0.0021 ha to delay bloom of peach by 14 days at Georgia. The rate of mist applied by Andreson et al. (1975) in Utah was to delay bloom was 10 L/min per tree which was 10 times more than the application rate by the simulated SSCD system (1.158 L/min per tree). Overall, the water used by Hewett and young (1980) was more than 4 times the water applied by SSCD system to delay apple bloom by more than a week.

According to Michigan State Climatologist's Office, the empirical probability of the occurrence of freezing minimum temperatures is 50 % after the first week of May (May 3) and and 0 % after the last week of May (May 23) in the vicinity of the SWMREC site in Southwest Michigan. At Sparta, it is the second week of May and the second week of June respectively. At the NWMHRC location in Northwestern Lower Michigan, the probability of occurrence of freezing temperature (0 ºC or less) is 50 % after the third week of May and 0 % after the first week of July (J. Andresen, personal communication). More comprehensive statistics on the last freezing temperatures of the spring season at the three study locations were obtained at https://climate.geo.msu.edu/climate_mi/index.html and were used to estimate the relative reductions in cold injury risk for apple associated with the delayed phenology. At SWMREC, the apple bloom was delayed by more than 10 days, which translates into a 75 % reduction in the expected frequency of freezing temperatures prior to the first pink and bloom stages relative to non misted buds. Likewise, misted sour and sweet cherry buds which bloomed more than 10 days after the non-misted buds would miss approximately 50 % of the expected freezing temperature events in a given season on average. At Sparta, the reduction in freeze frequency was 75 % prior to first pink and bloom and at NWMHRC the reduction was 50 %. It resulted in the potential reduction in the frequency of damaging freeze events by 50-75 %. These reductions are similar or greater to Chesness et al. (1977) who observed that 14 days of bloom delay on peaches reduced the probability of freeze damage by 50 %.

Table 3.6: Bloom dates of simulated misted and non-misted apple buds, along with days of bloom delay, the volume of mist applied, and the corresponding duration of mist application during the spring season, 2006-2015 at SWMREC, Sparta, NWMHRC, MI.

Location	Apple variety	year	Bloom date of non-misted buds	Estimated bloom date of misted buds	Total days of bloom delay	The volume of mist applied	Total duration of application in one season
			Date	Date	days	ha-cm	Hours
SWMREC	Red Delicious	2006	5/4/2006	5/18/2006	14	13	74
		2007	5/7/2007	5/18/2007	11	16	89
		2008	5/8/2008	5/26/2008	18	15	81
		2009	5/15/2009	5/26/2009	11	15	84
		2010	4/25/2010	5/14/2010	19	16	86
		2011	5/11/2011	5/25/2011	14	16	89
		2012	4/6/2012	4/28/2012	22	14	74
		2013	5/9/2013	5/20/2013	11	14	79
		2014	5/13/2014	5/27/2014	14	18	99
		2015	5/9/2015	5/21/2015	12	17	91
		Average			15	16	86
Sparta	McIntosh	2006	5/3/2006	5/16/2006	13	13	69
		2007	5/6/2007	5/16/2007	10	15	82
		2008	5/12/2008	5/27/2008	15	16	86
		2009	5/13/2009	5/25/2009	12	17	92
		2010	4/30/2010	5/17/2010	17	16	89
		2011	5/18/2011	5/28/2011	10	16	87
		2012	4/14/2012	5/5/2012	21	13	73
		2013	5/16/2013	5/27/2013	11	14	79
		2014	5/20/2014	5/29/2014	9	17	91
		2015	5/11/2015	5/25/2015	14	15	82
		Average			13	15	84
NWMHRC	Red Delicious and Gala	2006	5/8/2006	5/26/2006	18	15	80
		2007	5/11/2007	5/23/2007	12	14	78
		2008	5/19/2008	6/4/2008	16	14	79
		2009	5/18/2009	6/3/2009	16	22	121
		2010	4/30/2010	5/19/2010	19	16	87
		2011	5/23/2011	6/6/2011	14	35	175
		2012	4/23/2012	5/15/2012	22	14	79
		2013	5/20/2013	6/4/2013	15	13	74
		2014	5/27/2014	6/9/2014	13	15	81
		2015	5/18/2015	5/30/2015	12	15	83
		Average			15	18	97

Note- In Northwest, Gala and Red Delicious have the same date of phenological changes except for early pink, Red Delicious reached early pink stage 1-2 days before Gala.

Table 3.7: Bloom dates of simulated misted and non-misted sour and sweet cherry buds, along with days of bloom delay, the volume of mist applied, and the corresponding duration of mist application during the spring season, 2006-2015 at SWMREC, NWMHRC.

Location	Sour and sweet Cherry /Variety	year	Bloom date of non-misted buds	Estimated bloom date of misted buds	Total days of bloom delay	The volume of mist applied	Total duration of application in one season
			Date	Date	days	ha-cm	Hours
SWMREC	Sour Cherry Montmorency	2006	4/25/2006	5/5/2006	10	11	61
		2007	4/23/2007	5/4/2007	11	10	57
		2008	5/4/2008	5/14/2008	10	13	71
		2009	5/5/2009	5/13/2009	8	15	83
		2010	4/14/2010	4/30/2010	16	11	62
		2011	5/9/2011	5/17/2011	8	14	79
		2012	3/22/2012	4/8/2012	17	10	57
		2013	5/2/2013	5/16/2013	14	10	57
		2014	5/9/2014	5/21/2014	12	15	83
		2015	5/3/2015	5/13/2015	10	13	72
		Average			11.6	12.45	68.30
SWMREC	Sweet Cherry	2006	4/22/2006	4/29/2006	7	7	41
		2007	4/23/2007	5/4/2007	11	10	57
		2008	4/23/2008	5/5/2008	12	8	44
		2009	4/26/2009	5/6/2009	10	11	61
		2010	4/12/2010	4/27/2010	15	11	62
		2011	5/4/2011	5/11/2011	7	12	68
		2012	3/21/2012	4/3/2012	13	7	40
		2013	5/2/2013	5/10/2013	8	10	56
		2014	5/3/2014	5/12/2014	9	12	66
		2015	4/28/2015	5/8/2015	10	12	63
		Average			10.2	10.2	55.8
NWMHRC	Sour Cherry Montmorency	2006	5/1/2006	5/14/2006	13	11	62
		2007	5/7/2007	5/14/2007	7	12	67
		2008	5/12/2008	5/24/2008	12	11	60
		2009	5/11/2009	5/22/2009	11	16	87
		2010	4/23/2010	5/5/2010	12	13	70
		2011	5/16/2011	5/25/2011	9	22	120
		2012	4/13/2012	5/4/2012	21	11	62
		2013	5/13/2013	5/25/2013	12	9	51
		2014	5/25/2014	6/1/2014	7	12	65
		2015	5/11/2015	5/24/2015	13	12	64
		Average			11.7	12.9	70.8
NWMHRC	Sweet Cherry	2006	4/24/2006	5/4/2006	10	9	48
		2007	5/2/2007	5/9/2007	7	10	52
		2008	5/2/2008	5/15/2008	13	9	47
		2009	5/7/2009	5/15/2009	8	7	38
		2010	4/14/2010	4/29/2010	15	11	58
		2011	5/11/2011	5/21/2011	10	15	83
		2012	3/30/2012	4/20/2012	21	8	46
		2013	5/7/2013	5/17/2013	10	8	42
		2014	5/19/2014	5/27/2014	8	11	60
		2015	5/6/2015	5/17/2015	11	10	57
		Average			11.3	9.7	53

3.4.1.4 Freeze events and estimated damage

From the simulation results and the known cold injury thresholds, misted buds were found to have escaped most spring freeze events due to the delay in phenology associated with the reductions in bud temperature. At the SWMREC location, non-misted apple and cherry buds were exposed to freezing temperature (-2 ^{0}C) for more than 30 minutes on April 12 and 27, 2012, which could have damaged more than 20 % of unprotected apple (Table 3.8) and cherry buds (Table 3.9 and 3.10). At Sparta, the average air temperature of -3 ^{0}C was observed for more than 30 minutes on April 27, 2012, which could have damaged more than 50 % of the apple buds. At NWMHRS, a continuous freezing event (-4 ^{0}C) for more than 30 minutes on March 26, 2012 could have killed more than 45 % of non-misted apple (Gala and Red Delicious) buds which were at tight cluster (Table 3.8). And another freezing event (-2 ^{0}C) on April 12, 2012, could have killed an addition 10 percent of the remaining apple (Red Delicious) buds. Collectively, the two freeze events of March 26 and April 12 killed more than 55 % of non-misted sour cherry buds (Table 3.9) and more than 90 % of non-misted sweet cherry buds at NWMHRC (Table 3.10).

As described earlier, the 2012 spring season was exceptional in terms of climate, with a record breaking warm month of March (Longstroth and Andresen, 2012). Even with a bloom delay of 17 days in sour cherry and 13 days in sweet cherry that season at SWMREC, fruit buds faced post-bloom frost damage. More than 20 % of sour and sweet cherry flowers were estimated as killed in two different freezing events (Table 3.9, 3.10). 10 % of the misted apple buds (pink open stage) were killed at that location in the same events. At the other two locations, misted buds escaped the damaging freezing events corresponding to their phenological stages. Misting saved 100 percent of apple buds at Sparta and 100 % of apple and cherry buds at NWMHRS by delaying the phenology. The freeze event of 2008 killed more than 10% of non-misted apple and cherry buds at SWMREC whereas the misted buds were not damaged. In 2010, the freeze event of April 22 killed more than 10 % of non-misted apple (Red Delicious) and sweet and sour cherry buds at Northwest but the misted buds were protected as they lagged behind in the phenology (Table 3.9, 3.10). That resulted into relative decreases of damage of 10-60 % in apple and 45-100% in cherry for the misted buds. However, the damage to the non-misted buds could be more severe than estimated because the one half hour of exposure to the sub-freezing temperature (-2 ^{0}C) typically kills more than 10 % of apple and cherry flowers (Table 1.1, chapter 1), so the prolonged exposure to the same temperature for hours should increase the rate of damage.

Table 3.8: Freezing ((Temperature =<-2 ^{0}C) events after green tip of non-misted apple buds, duration of events, percentage of damage and the corresponding bud phenology of misted and non-misted apple buds.

Location and varieties of apple	Year	Date of freezing (Temperature =<-2 ^{0}C) events after green tip of non-misted buds	Duration of freeze events with temperatures:-2, -3, and -4 ^{0} C	Mean temperature during freeze events	Estimated damage on non-misted buds	Observed phenological stages of non-misted buds	Estimated damage on misted buds	Estimated phenological stages of misted buds
			minutes	^{0}C	%		%	
SWMREC Red Delicious	2007	4/4-4/10	more than 5 days	-4.1	0	Green tip	0	Swollen buds
		4/15	480,0,0	-2.1	0	Green tip	0	Swollen buds
	2008	4/30	305, 60,0	-2.6	10	Tight cluster	0	Green tip
	2009	3/28	360,0,0	-2.7	0	Green tip	0	Swollen buds
		3/30	260,0,0	-2.2	0	Green tip	0	Swollen buds
		4/8	154,0,0	-2.1	0	Green tip	0	Green tip
	2012	4/12	386, 15,0	-2.4	10	First pink	0	Green tip
		4/27	166,15,0	-2.3	10	Post Bloom	10	Pink open
	2014	4/14-4/16	2400	-2.9	0	Green tip	0	Swollen buds
Sparta, MacIntosh	2007	4/4-4/10	more than 5 days	-4.1	0	Green tip	0	Swollen buds
		4/14	467,0,0	-2.2	0	Green tip	0	Swollen buds
		4/15	240,0,0	-2.5	0	Green tip	0	Swollen buds
	2008	4/30	305,120,0	-2.5	0	Green tip	0	Swollen buds
	2009	4/23	340,0,0	-2.4	0	Green tip	0	Green tip
	2012	3/26	264,0,0	-2.2	0	Green tip	0	Green tip
		4/6	363,0,0	-2.2	10	First pink	0	Green tip
		4/27	194, 180,0	2.7	50	Full bloom	0	Green tip
		4/29	255,0,0	-2.2	10	Full bloom	0	Tight cluster
	2015	4/24	280,0,0	-2.6	0	Green Tip	0	Swollen buds
NWMHRC, Red Delicious and Gala	2010	4/22	480,0,0	-2.1	10	Early pink, RD	0	Green tip
	2012	3/26	389, 175, 100	-3.1	45	Tight cluster	0	Green tip
		4/12	478,0,0	-2.2	10	RD on early pink, No damage on Gala	0	Green tip
		4/17	790,0,0	-2.1	0	open cluster	0	Green tip
	2015	4/24	214, 60,0	-2.6	0	Green tip	0	

Table 3.9: Freezing ((Temperature =<-2 ^{0}C) events after green tip of non-misted sweet cherry buds, duration of events, percentage of damage and the corresponding bud phenology of misted and non-misted sweet cherry buds.

Location	Year	Date of freezing (air temperature =<-2 ^{0}C) events after green tip of non-misted buds	Duration of freeze events temperature (-2, -3, and -4 ^{0}C)	Mean temperature during freeze events	Estimated Damage on non-misted buds	Observed phenological stages of non-misted sweet cherry buds	Estimated damage on misted sweet cherry buds	Estimated phenological stages of misted sweet cherry buds
			minutes	^{0}C	%		%	
SWM REC	2007	4/15	480,0,0	-2.03	0	Green tip	0	Green tip
	2008	4/30	305, 60,0	-2.7	10	Post Bloom	0	Green tip
	2012	4/12	386, 15,0	-2.4	10	Post Bloom	10	Post Bloom
		4/27	166,15,0	-2.3	10	Post Bloom	10	Post Bloom
	2013	4/21	420,0,0	-2.4	0	Green tip	0	Green tip
	2014	4/14-4/16	2400	-2.9	0	Green tip	0	Swollen buds
NWM HRC	2010	4/22	480,0,0	-2.1	10	Post bloom	0	Tight cluster
	2012	3/26	389, 175, 100	-3.1	90	White bud/Popcorn	0	Swollen bud
		4/12	478,0,0	-2.2	10	Post bloom	0	Tight cluster
		4/17	790,0,0	-2.1	10	Post bloom	0	Tight cluster

Table 3.10: Freezing ((Temperature =<-2 ^{0}C) events after green tip of non-misted sour cherry buds, duration of events, percentage of damage and the corresponding bud phenology of misted and non-misted sour cherry buds.

Location	Year	Date of freezing (air temperature =<-2 ^{0}C) events after green tip of non-misted buds	Duration of freeze events temperature (-2, -3, and -4 ^{0} C)	Mean temperature during freeze events	Estimated damage on non-misted buds	Observed phenological stages of non-misted buds	Estimated damage on misted buds	Estimated phenological stages of misted buds
			minutes	^{0}C	%		%	
SWM REC	2007	4/15	480,0,0	-2.2	0	Bud burst	0	Bud burst
	2008	4/30	305, 60,0	-2.7	10	White bud	0	Green tip
	2012	4/12	386, 15,0	-2.4	10	Post Bloom	10	Post Bloom
		4/27	166,15,0	-2.3	10	Post Bloom	10	Post Bloom
	2013	4/21	420,0,0	-2.4	0	Bud burst	0	Swollen buds
NWM HRC	2010	4/22	2400	-2.1	10	First bloom	0	Tight cluster
	2012	3/26	480,0,0	-3.1	45	Bud burst	0	Swollen bud
		4/12	389, 175, 100	-2.2	10	First bloom	0	Green tip
		4/17	478,0,0	-2.1	10	Post bloom	0	Tight cluster

5. Conclusions

In this study, water in the form of a spray mist was applied to apple and cherry buds to delay the phonological development of buds using the SSCD system in a series of growth chamber, potted plant and field studies. The data from the growth chamber were used to calibrate and validate the model and data from potted plant and field were used to validate the model. The deterministic model developed in the study was then applied to estimate the bloom delay of apple and cherry over last 10 years at three locations in fruit growing regions of Michigan.

The model developed for the study was based on heat transfer theory. Simulated bud temperatures from the model were comparable to the observed bud temperatures. Also, simulated and observed timing and rates of evaporation of applied mist from the buds, a key element of the cooling process, were found to be in good general agreement. In the field validation study, the model was found to slightly underestimate bud temperature, which was likely due to canopy interception or wind drift of the applied spray in the field. Introducing a canopy interception and/or wind drift factor might improve the performance of the model.

The misting suppressed the bud temperature, resulting in the bloom delay of misted apple buds by more than 10 days and sweet cherry and sour cherry buds by more than a week compared to non-misted buds. However, the number of days of bloom delay and overall delay in phenology was likely influenced by the timing of mist and duration. Beginning mist applications early in the growing season only after air temperatures rise above the water temperature could reduce the amount of water needed for cooling.

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CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

Spring freeze events are a major climate-related threat to temperate fruit crops around the globe. The first chapter of this study reviewed different frost protection techniques practiced in research and commercial settings and their limitations. The second chapter described the results of a field study to examine the performance of misting at a number of orchard sites with the SSCD system. The primary conclusion was that the SSCD system can potentially reduce the risk of bud/ flower damage from spring frost by delaying phenological development. In addition, this system used less water than conventional methods practiced earlier without affecting fruit quality and quantity. The third chapter discussed the development, calibration, validation, and application of a deterministic model to estimate misted bud temperatures under a SSCD-type misting system. The model was found to satisfactorily simulate the bud temperatures and was used to examine the potential applicability of this technology over extended periods of time. Collectively, the results of the research suggest major potential for spray misting of buds as an effective method to delay phenology of buds and reduce the risk of frost.

1. Important findings

The second chapter was based on field observations of misted and non misted buds in apple orchards in southwest and central Michigan for three consecutive seasons. Similar studies were performed in a sweet cherry orchard and an apricot orchard in southwestern Michigan and a sour cherry orchard in northwestern Michigan for two consecutive seasons. Water mist was applied via the SSCD system to the apple buds after the end of endo-dormancy until the king (treatment 2) and full bloom (treatment 1) of the non-misted buds. Mist was applied after the end of endo- dormancy until full bloom in non-misted buds in sweet and sour cherry. Mist was applied from the popcorn stage until bloom in non-misted buds in apricot. Timing of the mist applications was based on ambient air temperature and relative humidity. The ON and OFF intervals for particular combinations of air temperature and relative humidity was determined by a growth chamber experiment. Also, it helped to identify the greatest relative rate of cooling with the least amount of water. The spray mist applied in the field study suppressed bud temperature and delayed phenological development of the buds using much less water than reported in earlier studies by Anderson et al. (1975) and Hewett and Young (1980). The apple bloom was delayed by 4-9 days depending on the treatment, location and weather condition with an average mist application of 15 ha-cm. The average delay in the sweet cherry bloom was 10 days with a mist application of 8 ha-cm. Misting also delayed the sour cherry bloom by a week and the apricot bloom by 5 days.

A deterministic model of bud temperature based on heat transfer theory was developed using the data from a series of growth chamber and outdoor-based studies. The model was validated using data collected in growth chamber, garden, potted plant, and field study trials under both misted and non misted conditions. The simulated and observed bud temperatures were generally in good agreement the majority of the time. However, the model was found to underestimate the temperature of misted buds at day times, likely due to higher wind speed and spray drift and interception of spray by the plant canopy. The time to evaporate the water and regain the original bud temperature (temperature before misting) were comparable between observed and simulated bud temperatures. Based on the satisfactory performance of the model (r^2 greater than 0.8 and a mean absolute difference of less than 1 ^{0}C), it was applied to simulate the bud temperature at three different locations in fruit growing areas of Michigan (SWMREC, Sparta and NWMHRC) for a 10 year period (2006-2015). From the simulations, the decrease in bud temperature from misting was found to be largely associated with evaporative cooling. The rate of evaporation was influenced by net radiation, air temperature, relative humidity, and wind speed. Higher net radiation and air temperature and lower relative humidity was found to enhance evaporation rates. Through the reductions in bud temperature, misting was found to delay apple bloom by 9-22 days as well as sour and sweet cherry bloom by 7 -21 days in the 10 years (2006-2015). Maximum cooling was obtained in relatively warmer years such as 2012 and cooling was minimum in the cooler years like 2007, 2009, 2011 and 2014. By delaying the bloom by a week or more, buds were less susceptible from frost injury. Moreover, by delaying the bloom by a week, the expected frequency of damage from the last killing frost of the season could be reduced by 75 %. The depth of applied mist in the simulations ranged from 13 ha-cm to 22 ha-cm for apple buds and 7 to 22 ha-cm for sweet and sour cherry. In 2012, a longer delay of bloom was obtained for apple and cherry buds with less volume of mist compared to that in other years. Even so, sour and sweet cherry buds were still damaged by frost during post bloom stages at SWMREC. However, at NWMHRC misted apple and cherry buds were projected to have survived late spring freeze events in 2010 and 2012 by delaying the phenology.

2. Implication of findings

Frost damage remains a major threat to temperate fruit, vegetable, and cereal crops. Fruit crops only bear flowers once per season, thus it is important and challenging to protect them from spring freezes. Use of water as a protective strategy is not new, as different researchers had used water in the past to protect buds from spring frost. Water applied by sprinklers when air temperatures drop below freezing is a common way to raise bud temperatures. This is the direct method of frost protection; the ice coating formed around the bud transfers heat to the bud through the latent heat of fusion as the water freezes. This system requires continuous water application and a potentially large discharge rate and volume of water. An alternative method is the indirect method of frost protection where water is applied in the form of mist to suppress bud temperatures and delay phenological development, reducing the relative risk of cold injury. This approach has been practiced in the past and while it delayed the bloom, it also used a lot of water. The higher water use may stretch existing water resources, increase production costs, cause ice nucleation in the buds and tree, as well as lead to nutrient leaching in the soil. This study modified the indirect method of mist application using the SSCD system with an automated mist application based on ambient air temperature and relative humidity. This system delayed the bloom by a week or more and reduced the volume of mist relative to previous studies. The magnitude of bloom delay obtained by simulation of the historical climate data demonstrated that the SSCD system has major potential for use as a frost protection strategy for tree fruit production in Michigan. Though the initial installation cost is expensive, it may be cost effective and cheaper than using any traditional frost protection method in the long term. Growers can be cost efficient by using the same system for pesticides, fertilizer application and irrigation.

3. Constraints and limitations

Weather conditions during the three years of field study proved to be a major constraint. While weather was different each year, no abnormally warm spring temperatures were observed (such as in 2012). Although the misting delayed the bloom by a week or more, only one significant freeze event was recorded at any of the sites after bud break to observe if the delay truly protected the buds. This occurred on May 13, 2013, when one freeze event (-2 0C) lasted for 2 hours after bud break, for which misting reduced the bud damage by 50%. In this case, 34 % of non-misted buds (at pink stage) were killed compared to only 16 % of misted buds that were slightly behind at tight cluster.

Another constraint of this study was the identification of a suitable start and end date for the spray mist applications. Ideally, misting should not be started until the end of endo-dormancy or later in the spring season. By starting earlier in the season, misting increased the bud temperatures (through conductive exchange associated with the water temperature) and increased the volume of water used, but delayed bloom only minimally. On the other hand, later starts may lead to a potential reduction in phenological delay and overall reduce the effectiveness of the methodology. As the bud develops, it loses its resilience to freezing temperatures; dormant flower buds are less vulnerable to low temperatures than buds at advanced stages of development. Also, the time to end the mist applications is equally important. If misting is terminated too early, the magnitude of the phenological delay is reduced. However, if the sprays continue too long, the mist could distract pollinators and the misted buds may not be pollinated. In this study, mist was applied after the end of endo-dormancy until the bloom of non-misted buds. Mist was applied for a similar duration by Anderson et al. (1975). Also, applying mist when the bud temperature is greater than the water temperature could be effective. If mist was applied when bud temperature was less than water temperature, it added only to the water volume without any contribution to cooling. For example, in all three locations if mist was applied when the bud temperature was less than water temperature, the mist warmed the bud instead of cooling it.

Another limitation in this study was the availability of weather data. Net solar radiation is not observed operationally and wind speed may vary significantly over an area due to microclimatic factors. For this study, solar radiation and wind speed measured at nearby MAWN network station sites were used. The resolution of the solar radiation was hourly and the temporal resolution of air temperature, relative humidity and wind speed was every five minutes. Net radiation was estimated following Allen et al. (1998). Later, the net radiation and all the weather parameters were interpolated to one-minute resolution to use in the model.

Water quality and temperature was another constraint. Clean, sediment-, and salt-free water is required. Sediment or any other coarse materials in the water has a high chance of blocking the emitters. At Charlotte, MI, the emitters were blocked several times by sediment, and the emitters either stopped misting or the discharge was reduced. This resulted in reduced or no cooling of the buds. A filter was used to remove any coarse materials from the water, which improves the performance of mist later. Salt in the water may leave deposits on the buds, potentially distracting pollinators. The temperature of the water plays a significant role in the cooling of the bud. Water cooler than bud drops the bud temperature by conductive exchange, whereas warmer water raises the bud temperature. To achieve maximum cooling, cooler water should be applied frequently for shorter duration. In the potted tree experiment, water temperature was from a surface source and warmer (19 ^{0}C at night and 22 ^{0}C during the day) than air temperature majority of the time. This increased the bud temperature immediately after misting, and the drop in bud temperature due to evaporative cooling was also reduced. Also, in the simulation of historical bud temperatures, increases in bud temperature were observed immediately after misting when the water temperature was greater than bud temperature (in this case, with ambient air temperatures between 4-10 ºC).

Windy conditions were another constraint of the study. Misting had reduced or even no effect in cooling of buds during windy periods when the wind speed was greater than 4m/s. Wind caused the mist to drift before it reached the buds. In some drift events at Hillsdale, MI the problem was significant enough to result lower rate of cooling. Similar conditions were observed occasionally at the St. Joseph, Charlotte, SWMREC and HTRC experiment sites.

Some other constraints in the model were water content of the bud and probable instrument error. Water content of the bud was assumed constant for all phenological stages of bud (green tip, tight cluster, open cluster and flower); however, it might change with different phenological stages of the bud. Also, in each cycle of mist application wetness area of the bud might change in every minutes but the model assumed it constant until all the water was evaporated. The thermocouples were inserted to the buds from the base just adjacent to its connection to the branches/twigs. The thermocouples were stuck to the twigs and held in the buds by duck tape such that it did not get displaced or come out, but that might have caused loading error in the reading of thermocouple which was not considered in the model.

4. Future research and potential improvement

The results of this study suggest that the misting via the SSCD system is a promising method for delaying the phenology and protecting tree fruit buds from frost while also using limited amount of water. Though this system used less volume of water than reported in earlier studies, there is potential for greater reduction in water use by modifying the automated mist application system. In this study, the ON/OFF interval of the pump for misting was based on ambient air temperature and relative humidity. However, our study (simulation results) showed the influence of wind speed and net radiation in the cooling of bud and evaporation of mist from the bud. Therefore, adding these variables to the spray criteria to control the ON/OFF interval of the pump could improve the performance of the system by 5-12 % depending on whether only the wind is added or net radiation is added or both are added.

In this study, mist was sometimes applied before water was completely evaporated from the bud in the previous spray cycle. In that case, the mist did not completely cool the buds, but instead increased water usage. Therefore, using a wetness sensor in the bud environment to help determine when the previous mist application had completely evaporated from the bud could improve the performance of the system.

The coverage of the mist application could be improved by spraying at the top of the canopy using revolving emitters. Also, adding additional laterals with emitters partially inside the tree canopy might be an effective way to increase spray coverage, especially during later portions of the season when the trees have leaves.

The performance of the developed model can be improved by further refining thermal conductivity and other related thermodynamic characteristics of the buds, introducing a canopy interception factor and a better understanding of the net radiation balance of the bud. Some portion of the mist is intercepted by branches and leaves before it reaches the buds. Introducing the interception factor in the model could help to better estimate the actual volume of mist received by the buds. Likewise, the net radiation of the bud is influenced by canopy shading, its orientation, and shape.

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