A CLIMATOLOGY OF PERSISTENT HIGH RELATIVE HUMIDITY FOR THE LOWER PENINSULA OF MICHIGAN: IMPLICATIONS FOR HEALTH AND AGRICULTURE

By

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ABSTRACT

A CLIMATOLOGY OF PERSISTENT HIGH RELATIVE HUMIDITY FOR THE LOWER PENINSULA OF MICHIGAN: IMPLICATIONS FOR HEALTH AND AGRICULTURE

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High values of relative humidity have implications for many processes including human health, animal health and production, and crop disease. Despite its importance, little research has been completed about the persistence of high relative humidity. The goals of this study were to 1) create a baseline climatology of the persistence of high relative humidity (HRH), defined as ≥ 60%, and extremely high relative humidity (EHRH), defined as ≥ 85%, for the Lower Peninsula of Michigan and 2) examine, using persistent EHRH events as a surrogate for leaf wetness duration, the frequency of favorable environmental conditions for apple scab and cherry leaf spot, major crop diseases in the state. Results demonstrate that although overall persistent relative humidity events often occur throughout the state, their frequency appears to be decreasing with time. Temporal trends in the frequency of favorable environmental conditions for apple scab and cherry leaf spot vary by location and disease, but there is a general trend toward fewer occurrences of favorable environmental conditions. The climatological analyses provide Michigan stakeholders with essential information for long-term planning and management to mitigate and/or adapt to persistent high relative humidity and to assess future changes in persistent high relative humidity as expected with climate change.

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KEY TO ABBREVIATIONS

HRH	High Relative Humidity
EHRH	Extremely High Relative Humidity
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
NOAA	National Oceanic and Atmospheric Administration
TTF	Monroe Custer Airport
APN	Alpena County Regional Airport
DTW	Detroit Metropolitan Wayne County Airport
FNT	Bishop International Airport
GRR	Gerald R. Ford International Airport
LAN	Capital City Airport
MKG	Muskegon County Airport
TVC	Cherry Capital Airport
SAO	Surface Aviation Observation
METAR	Meteorological Terminal Aviation Routine Weather Report Code
GDU	Growing Degree Unit
BE	Baskerville-Emin

CHAPTER 1: INTRODUCTION TO THE RESEARCH

Climate has a powerful influence on local processes. Two principal climatic factors driving local pursuits include temperature and atmospheric moisture. Temperature determines when seasonally-specific activities can be undertaken and when life cycles of various animals and plants begin. Similarly, a common measure of atmospheric moisture, relative humidity, has implications for human health, as well as animal and plant production because relative humidity alters the effectiveness of physiological processes (Shi, Zhu, and Zheng 2013; West 2003; Bruzual et al. 2000). This can change the well-being or determine the likelihood of survival for certain organisms. Various relative humidity climatologies have been developed and trends in relative humidity have been found, however few studies have given attention to the persistence of relative humidity.

Since many of the effects relative humidity has on physical processes stem from continuous spells of high relative humidity, a climatology of persistent relative humidity events is vital in recognizing potential impacts on natural and anthropogenic processes. This is particularly relevant for the Lower Peninsula of Michigan, which is surrounded by freshwater lakes and includes many bodies of water within its boundaries, while agriculture comprises a large proportion of the state's economy and is responsible for many people's livelihoods. The goal of this thesis is to better understand the inter-annual, intra-annual, and spatial variations in the persistence of high relative humidity in the Lower Peninsula of Michigan. Two specific objectives are to: 1) develop a climatology for 1973-2017 of persistent high relative humidity events that is useful for planning and decision-making for a wide range of activities, and 2) evaluate the potential impacts of persistent high relative humidity on disease infection affecting apple and cherry, important perennial crops produced in Michigan. Addressing these objectives provides a valuable resource for people whose work is impacted by high relative humidity spells.

This thesis begins by introducing the motivation behind and objectives of the study. Chapter 2, which is about the climatology of persistent relative humidity in the Lower Peninsula of Michigan, first provides examples of the impacts of high relative humidity spells on various processes. The text then describes the data and methods used to create the climatology, examines and discusses results of analyses, and concludes by discussing the importance of having a baseline climatology of the persistence of high relative humidity. Chapter 3 assesses the impact of persistent high relative humidity on crop disease, first introducing the crops and primary diseases, then explaining the data and methods used to determine frequency of periods of favorable environmental conditions. The next section shows findings from analysis of crops' vulnerable stages and frequency of periods of favorable environmental conditions, along with the types of wetness duration and temperatures that most frequently caused in periods of favorable environmental conditions. The implications of the results, as well as study limitations and avenues for future work are addressed in the discussion section, while the conclusion reiterates the importance of a climatology of persistent relative humidity for assessing the frequency of relative humidity and temperature conditions conducive to apple scab and cherry leaf spot infection. Finally, the concluding chapter reviews the objectives, data and methods, main findings, limitations, and explores potential further work.

CHAPTER 2: A CLIMATOLOGY OF THE FREQUENCY AND DURATION OF HIGH RELATIVE HUMIDITY EVENTS FOR THE LOWER PENINSULA OF MICHIGAN

INTRODUCTION

A baseline climatology is essential for understanding historical variations and trends in climate parameters and for assessing future climate change. Relative humidity, the degree of air saturation (Brown and Degaetano 2013), is a common measure of atmospheric moisture. Although relative humidity impacts a wide range of phenomena, little research has been done on the persistence of high relative humidity and whether the frequency of high relative humidity spells has changed over time. As a result, this study aims to develop a baseline climatology of persistent high relative humidity for the Lower Peninsula of Michigan. Prolonged spells of high relative humidity can have significant effects on human health, animal welfare and production, and crop yield. The importance of these processes and activities in Michigan, combined with its location, make the state particularly vulnerable to impacts from persistent high atmospheric humidity.

Relative humidity is primarily impactful on human health when it is outside of a moderate range, defined as around 40-60% (Arundel et al. 1986). Although low relative humidity can negatively affect human health by potentially exacerbating asthma severity and causing dryness in eyes and mucous membranes (Arundel et al. 1986), the impacts of high relative humidity have received more attention. High relative humidity has direct effects on physiology when it co-occurs with high temperature, since evaporative cooling becomes less efficient in dispelling heat (Arundel et al. 1986). This can lead to heat-related illnesses, which account for an average of 658 fatalities in the United States annually (MMWR 2013). In general, the temperature at which heat-related human morbidity and mortality commonly occurs decreases with increasing relative humidity (Mora et al. 2017).

Long spells of high relative humidity are damaging to employees whose work requires them to be outside for extended periods of time, presenting an occupational health and safety concern for people in sectors like agriculture and construction (Schall et al. 2017). Hot and humid environments of temperatures above 30°C and relative humidity above 60% may cause heat strain, decreasing productivity and putting human health at risk from both heat-related illnesses and increased risk of occupational injury (Schall et al. 2017; Shi, Zhu, and Zheng 2013; Varghese et al. 2018). Changes in physiology are necessary to regulate body temperature when employees are doing physical labor in hot and humid environments (Shi, Zhu, and Zheng 2013). If these processes cannot perform efficiently, core temperature will increase. The worker will have a higher likelihood of suffering from a heat-related illness like heat stroke, heat exhaustion, or heat cramps, as well as potentially worsening or setting off preexisting medical conditions (Davis, McGregor, and Enfield 2016; Shi, Zhu, and Zheng 2013; Hancock and Vasmatzidis 1998). Additionally, a change in blood circulation leads to important organs receiving less blood, which can cause dizziness, fainting, fatigue, and reduced concentration (Varghese et al. 2018). Resultant impaired awareness, reasoning, and motor skills increase the chance of workplace injury (Park and Kim 2017).

Another risk to human health comes from the effect of relative humidity on carriers of vector-borne diseases, including mosquitoes that spread malaria and ticks that cause Lyme disease. Long spells of high relative humidity are indicative of epidemic risk, as malaria outbreaks commonly occur after prolonged periods of high relative humidity, with levels of 70-80% or greater, creating conditions conducive for transmission (Onori and Grab 1980). This is the result of a positive relationship between longevity of mosquitoes that transmit malaria and relative humidity (Clements 1963). Since the parasite must develop in the host, mosquito longevity is vital in disease transmission (Martens et al. 1995). Like mosquitoes, Blacklegged ticks, a species that carries Lyme disease, are sensitive to environmental conditions (Vail and Smith 1998). Vail (1998) demonstrates that tick activity is positively correlated with relative humidity, suggesting that the greater the humidity, the more active ticks will be. This implies that higher relative humidity has the potential to increase vector-borne disease prevalence.

Persistent relative humidity also impacts animal health and productivity. For example, high relative humidity in conjunction with high temperature leaves dairy cows struggling to maintain normal body temperatures since they rely on evaporative cooling (West 2003). When high relative humidity is sustained for long time periods, the cows overheat, instigating decreased feed intake, milk yield, milk production efficiency, and milk nutritional value (West 2003; Xiong et al. 2017). Broiler chickens provide another example of the impact of persistent high relative humidity on animal health. With persistent relative humidity of 63% or greater, broiler chickens experience complications in embryonic development, resulting in a larger number of late dead embryos (Bruzual et al. 2000). Additionally, bacteria and viruses that affect livestock have differing survival rates depending on atmospheric moisture conditions. One example is a common infection-causing bacteria among livestock called Pseudomonadaceae that experiences increased survival rates with air humidity of 85% or greater (Xiong et al. 2017). High relative humidity can also facilitate growth of fungi in both livestock bedding and feed, potentially leading animals to develop respiratory problems or consume harmful mycotoxins (Xiong et al. 2017).

Crops are susceptible to disease, which is partially controlled by environmental conditions, particularly temperature and moisture. Moist conditions facilitated by high relative humidity are conducive to fungal diseases that may harm a variety of crops (Bourke 1970). Most fungal diseases require free water to infect the crop, and persistence of high relative humidity has been shown to be an accurate estimator of leaf wetness (Sentelhas et al. 2008). Fusarium head blight is an example of a fungal disease that requires free water on crop canopies, which affects wheat and is caused by members of the *Fusarium graminearum* species complex (Wegulo et al. 2008). The pathogen's ability to infect the crop requires continuous periods of warm temperatures and high relative humidity (Vaughan 2016), although a range of critical temperatures and humidity levels for infection have been reported. For example, De Wolf et al. (2003) found that one of the best predictors of infection severity included the duration that temperature fell between 15-20°C when relative humidity was at least 90%. Temperature and moisture can indirectly endanger wheat by creating conditions favorable to other pathogens or pests like aphids that will weaken the crop, leaving it susceptible to infection (Vaughan 2016). The consequences of Fusarium head blight include decreased yields, poor grain quality, and potential health risks to humans and livestock from mycotoxin contamination. *Venturia inaequalis* is responsible for apple scab, another example of a disease that plagues agricultural yields and profits (Biggs and Tree 2009). Like with Fusarium head blight, temperature and leaf wetness duration are predictors of disease infection and severity (Jones et al. 1980). Apple scab results in heavy losses because the pathogen directly damages the fruit and defoliates the tree, increasing its susceptibility to frost damage (Biggs and Tree 2009).

The frequency, spatial variation, and temporal trends in persistent high relative humidity events have not yet been documented for the Lower Peninsula of Michigan, despite the potential large impacts of high relative humidity on human health, animal health and production, and crop production in the region. At least 150,000 people in the state have jobs that require outdoor work that puts them at risk of heat-related illness, while anyone living in the state may contract diseases from vectors like mosquitoes and ticks (Bureau of Labor Statistics 2017). Animal production is common in the state and makes an important contribution to the economy. For example, in 2016 dairy added $15.7 billion to Michigan's economy, while the state generated 6.2 million broiler chickens annually (Michigan Agriculture 2016). Crop production is an industry that is central to the welfare of the Lower Peninsula of Michigan's population and economy. Many of the crops grown in Michigan are susceptible to fungal infections including, as mentioned above, wheat, which has averaged an annual income of $238.31 million in recent years (USDA 2016) and apples which contributed $293.45 million in 2016 (USDA 2016).

To uphold health and production in Michigan, a state with unique geography and climate, having an awareness of typical weather behavior from historical data will be useful in planning and decision-making. The Lower Peninsula is in the northeast Midwest and is surrounded by Lake Michigan, Lake Huron, and Lake Erie. These lakes influence the climate in the region primarily by regulating temperature, increasing precipitation, and producing greater cloud cover (Scott and Huff 1996). Areas east and southeast of the Great Lakes have higher levels of water vapor compared to surrounding regions, originating from lake moisture retained in the atmosphere and from the transport of moist air masses from the Gulf of Mexico (Scott and Huff 1996; Danard and McMillan 1973).

Relative humidity is reported at a small number of locations compared to other climate parameters such as temperature and precipitation, and observational quality has been variable throughout the past century. However some studies suggest that average annual relative humidity may have increased slightly—0.5-2.0%—throughout the past few decades in the Midwestern United States (Brown and Degaetano 2013; Dai 2006). At the same time, for most of the contiguous United States, there appears to be a drying trend (Brown and Degaetano 2013).

Currently, there is insufficient evidence to support a strong positive or negative trend in average relative humidity in Michigan. Furthermore, no previous study has been found that investigates the intra-annual and inter-annual variability and temporal trends of persistent high relative humidity events for Michigan or elsewhere. This climatology is focused on the Lower Peninsula of Michigan and its main economic sectors, however similar studies targeted toward local industries in other study regions would be beneficial to the communities there. An improved understanding of the climatology of persistent spells of high relative humidity is necessary to combat negative impacts to human health, animal welfare and production, and agriculture, as well as to provide a baseline for evaluating future changes in the persistence of high relative humidity.

The goal of this research is to provide a climatology of persistent high relative humidity that is useful for a wide range of applications. This study aims first to understand the spatial patterns in persistent high relative humidity, second to analyze temporal trends in persistent high relative humidity, and third to explore the co-occurrence of various temperatures with long spells of high relative humidity in the Lower Peninsula of Michigan.

DATA AND METHODS

Selection of relative humidity thresholds

To ensure the climatology's usefulness for a wide range of applications, 2 relative humidity thresholds were used to characterize persistent relative humidity. The first is high relative humidity (HRH), defined as greater than or equal to 60%, and the second is extremely high relative humidity (EHRH), defined as greater than or equal to 85%. The HRH threshold corresponds with humidity levels reported as impacting human health (Arundel et al. 1986; Mora et al. 2017; Schall et al. 2017; Shi, Zhu, and Zheng 2013; Varghese et al. 2018; Hancock and

Vasmatzidis 1998), animal health (West 2003; XIONG et al. 2017; Bruzual et al. 2000), and promoting vector-borne diseases (Onori and Grab 1980; Clements 1963; Martens et al. 1995; Vail and Smith 1998), whereas the EHRH threshold corresponds with the relative humidity levels associated with leaf wetness and fungal crop disease (Sentelhas et al. 2008; Rowlandson et al. 2015). The choice of 85% for EHRH was based on the successful modelling of leaf wetness duration at Elora, Ontario (Sentelhas et al. 2008). Elora is located approximately 150 miles east of the eastern border of Michigan and has a similar climate, suggesting that this relative humidity threshold can be effectively used for estimating leaf wetness duration in the study area.

Temperature and humidity observations

Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) station data were downloaded from the National Centers for Environmental Information Integrated Surface Database (Smith, Lott, and Vose 2011) for 53 stations in the Lower Peninsula of Michigan and 1 station in Indiana, which was used as a neighbor for the Benton Harbor, Michigan station. These data were the only data available that provided the weather variables, record length, temporal scale, and station density appropriate for the study. Data obtained were hourly observations of temperature, dewpoint temperature, and relative humidity by station.

As with all climate datasets, potential limitations and inhomogeneities of the ASOS and AWOS observations need to be considered, along with other inconsistencies including early records with observations only every 3 hours, changes in instrumentation, and shifts in data recording procedure. As a first step, duplicate observations and erroneous data—extreme values greater than 6.0 standard deviations from the mean—were removed. Next, the percent of missing temperature and humidity observations for each station was calculated, and a quality check was completed using NOAA quality codes. These codes indicate whether the observation is rated as passed gross limits check, passed all quality control checks, suspect, or erroneous, along with various codes that indicate the origin of the observation (NCDC, n.d.). 7 stations had less than 10% missing observations over a 45-year period from 1973-2017, and are referred to below as "long-term" stations. Inspection of the record lengths and time series for the remaining stations indicated that 2003-2017 was the most recent period of time with the largest number of stations that have overlapping records and the fewest missing observations. Only those stations with less than 10% missing values during 2003-2007 were retained, with the exception of 1 station, Monroe/Custer (TTF). This station was located in a data-void portion of the study area and had approximately 15% missing observations embedded within longer periods of continuous observations. See Figure 2.1 for the locations of the 36 stations included in the analysis.

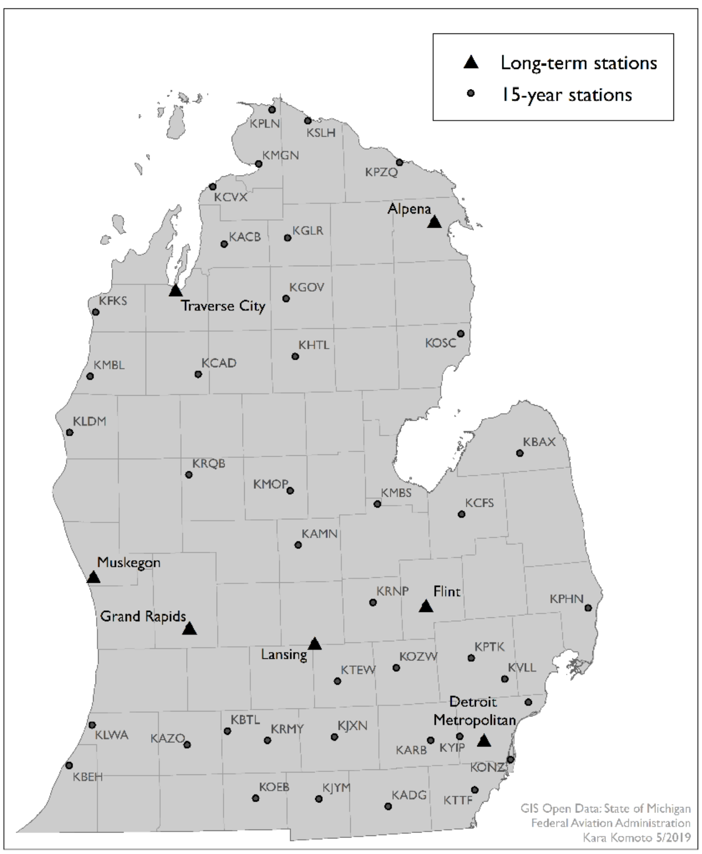


Figure 2.1. AWOS/ASOS stations in Lower Peninsula of Michigan used in analysis.

To estimate the persistence of high humidity events it was necessary to fill in hours with missing relative humidity observations. A two-step process was used to accomplish this. Since the long-term stations only took synoptic observations every 3 hours early in their records, the first step involved averaging for instances where only 1 or 2 hours were missing. The average of the hour before the missing value(s) and the hour after the missing value(s) was taken and added to the dataset in place of the missing values. Because of the large diurnal variation in relative humidity, missing blocks longer than 2 hours were filled in using a second technique, which required filling in blocks of missing values with data from neighboring stations under the assumption that nearby stations are affected by the same air masses and thus have comparable levels of relative humidity. Surrounding stations were iterated through by closest proximity until the hourly time series for a station was serially complete (see Table 2.1 for the portion of missing values that were filled in from averaging and from surrounding stations).

Table 2.1. Proportion of data filled by averaging and surrounding station data.

Stations	Orig. obs.	Average	Surrounding stations	Stations	Orig. obs.	Average	Surrounding stations
ACB	97.87%	0.87%	1.22%	**JYM**	97.08%	1.43%	1.45%
ADG	97.74%	0.58%	1.62%	**LAN**	99.46%	0.36%	0.06%
AMN	93.92%	2.03%	4.01%	**LDM**	98.19%	0.66%	1.15%
APN	99.87%	0.02%	0.08%	**MBL**	93.41%	1.37%	5.23%
ARB	97.33%	0.82%	1.79%	**MBS**	94.59%	1.46%	3.94%
AZO	98.38%	0.86%	0.73%	**MKG**	99.08%	0.28%	0.50%
BAX	97.39%	1.15%	1.43%	**MOP**	98.38%	0.84%	0.79%
BEH	96.17%	1.38%	1.79%	**OEB**	98.03%	0.92%	1.01%
BTL	97.41%	1.01%	1.54%	**ONZ**	97.39%	1.01%	1.56%
CAD	98.85%	0.61%	0.53%	**OZW**	98.37%	0.56%	1.05%
CVX	98.43%	0.62%	0.94%	**PHN**	96.90%	1.18%	1.92%
DET	95.01%	0.56%	4.20%	**PLN**	98.68%	1.03%	0.25%
DTW	99.78%	0.10%	0.01%	**PTK**	92.01%	0.78%	7.20%
FNT	99.33%	0.51%	0.05%	**RMY**	96.91%	1.31%	1.76%
GLR	97.69%	1.28%	1.01%	**TTF**	84.11%	1.41%	14.44%
GRR	99.80%	0.03%	0.08%	**TVC**	98.20%	0.99%	0.57%
HTL	97.66%	1.87%	0.41%	**VLL**	98.98%	0.59%	0.42%
JXN	99.32%	0.07%	0.59%	**YIP**	97.40%	1.08%	1.29%

Definition of relative humidity spells

HRH and EHRH spells were defined as 2 or more consecutive hours with relative humidity ≥60% and ≥85%, respectively. The length and start dates of all HRH and EHRH spells at each of the 36 stations were found for the period 2003-2017 and additionally for 1973-2017 for the 7 long-term stations. The maximum and minimum hourly temperature during each spell were also recorded. The HRH and EHRH spells were categorized by biweeks (14-day periods beginning January 1), based on their start date, in order to investigate intra-annual variations in the occurrence of persistent high relative humidity.

Spatial variations in the probability of EHRH and HRH spells

The probability of EHRH and HRH spells exceeding durations of 9, 12, 15, 18, 24, 36, 48 and 72 hours was estimated by biweek at each of the 36 stations. Durations were chosen by determining the spell lengths that were both applicable to human activities and had variation in probabilities, since shorter and longer spell lengths resulted in mainly 1.00 or 0.00 values. Probability is defined as the proportion of years during 2003-2017 with at least 1 occurrence of a HRH or EHRH spell exceeding the specified duration during a particular biweek. To explore spatial variation in the estimated probabilities, ordinary kriging—a method that uses spatial variation measures to estimate values between sampled locations—was employed using the 36 15-year stations (Oliver, Webster, and Gerrard 1989). To achieve better estimates at short distances, variogram model fitting was completed by eye and trial and error rather than automatically to avoid fitting to the entire variogram (Oliver, Webster, and Gerrard 1989). For kriging, the average distance between stations was approximately 35 kilometers, leading to an interpolation grid of 15-kilometer resolution. The farthest distance used in kriging was 100 kilometers, while the number of nearest neighbors was 8. This method was implemented because it uses local neighborhood estimation and provides standard error estimates for predictions allowing potential interpretation of interpolated value validity.

Temporal trends in EHRH and HRH spells

To examine long-term trends in the frequency of EHRH and HRH spells, stations with a record of at least 45 years were used—Alpena (APN), Detroit Metropolitan (DTW), Flint (FNT), Grand Rapids (GRR), Lansing (LAN), Muskegon (MKG), and Traverse City (TVC) (Figure 2.1). Trend analysis can be affected by inhomogeneities in a time series. As summarized by Brown and DeGaetano (2013), 3 known sources of potential inhomogeneity for the relative humidity time series for observation stations in the United States are the switch in the 1980s from dial hygrothermometers with a lithium chloride absorption sensor to chilled mirror hygrothermometers, the move in the mid-1990s to a chilled mirror sensor with a modified aspirator, and the replacement in the mid-2000s of the hygrothermometers with the Vaisla Inc. solid state relative humidity sensor. Prior to the implementation of the Vaisla Inc. sensors, relative humidity was calculated from temperature and dewpoint temperature measurements. Thus, the relative humidity measurements were potentially subject to inhomogeneities from both the temperature and dewpoint times series. The Vaisla Inc. sensor, on the other hand, directly measures relative humidity (dewpoint is calculated). To assess potential bias introduced by the change in sensors on the interpretation of the temporal trends in the relative humidity spells, 4 tests—the standard normal homogeneity test (SNHT), the Buishand range test, the Pettitt test, and the Von Neumann ratio test—were applied to annual averages of temperature, dewpoint temperature, and relative humidity based on Wijngaard et al (2003). The SNHT, Buishand, and Pettitt tests find the year when the break occurred, while the Von Neumann ratio test only determines whether the data are randomly distributed or not (Wijngaard, Klein Tank, and Können 2003). Based on these tests, the records are rated either useful, doubtful, or suspect, with useful having 0-1 significant break, doubtful having 2 significant breaks, and suspect having 3-4 significant breaks (Wijngaard, Klein Tank, and Können 2003).

Surprisingly, considering the change in the mid-2000s from being directly measured to calculated, all of the dewpoint time series were judged to be useful (Table 2.2). However, a breakpoint in 1996 or 1997 was identified in the temperature time series for the majority of the stations, which likely corresponds to the introduction of the replacement hygrothermometer. Furthermore, in July 1996 the Meteorological Terminal Aviation Routine Weather Report (METAR) code replaced the prior Surface Aviation Observation (SAO) code (Diamond 1996). This included a transition in temperature and dewpoint fields to degrees Celsius. Of the relative humidity time series at the 7 stations, 2 were classified as useful—Alpena and Flint; 1 as doubtful—Traverse City; and 4 as suspect—Detroit Metropolitan, Grand Rapids, Lansing, and Muskegon. Most of the breakpoints occurred in 2004 which corresponds to the introduction of the Vaisla Inc. relative humidity sensor. These homogeneity tests indicate that trends in the frequency of HRH and EHRH spells should be interpreted cautiously, although the 2004 breakpoint should have a smaller influence on occurrence of relative humidity spells in contrast to annual and seasonal averages of relative humidity.

Table 2.2 Results of 4 homogeneity tests and data reliability classification. NS is for tests that were not significant and S represents a significant test followed by the year where the break was found.

TEMPERATURE	APN	DTW	FNT	GRR	LAN	MKG	TVC
Buishand	NS	S - 1997	NS	S - 1997	S - 1997	S - 1997	S - 1996
Pettitt	S - 1997	S - 1989	S - 1997	S - 1997	S - 1997	S - 1997	S - 1996
SNHT	NS	S -1985	NS	S - 1997	S - 1997	S - 1997	NS
Von Neumann	NS	S	NS	NS	NS	S	S
Classification	Useful	Suspect	Useful	Suspect	Suspect	Suspect	Doubtful

DEWPOINT	APN	DTW	FNT	GRR	LAN	MKG	TVC
Buishand	NS	NS	NS	NS	NS	NS	NS
Pettitt	NS	NS	NS	NS	NS	S - 1997	NS
SNHT	NS	NS	NS	NS	NS	NS	NS
Von Neumann	NS	S	NS	NS	NS	NS	NS
Classification	Useful	Useful	Useful	Useful	Useful	Useful	Useful

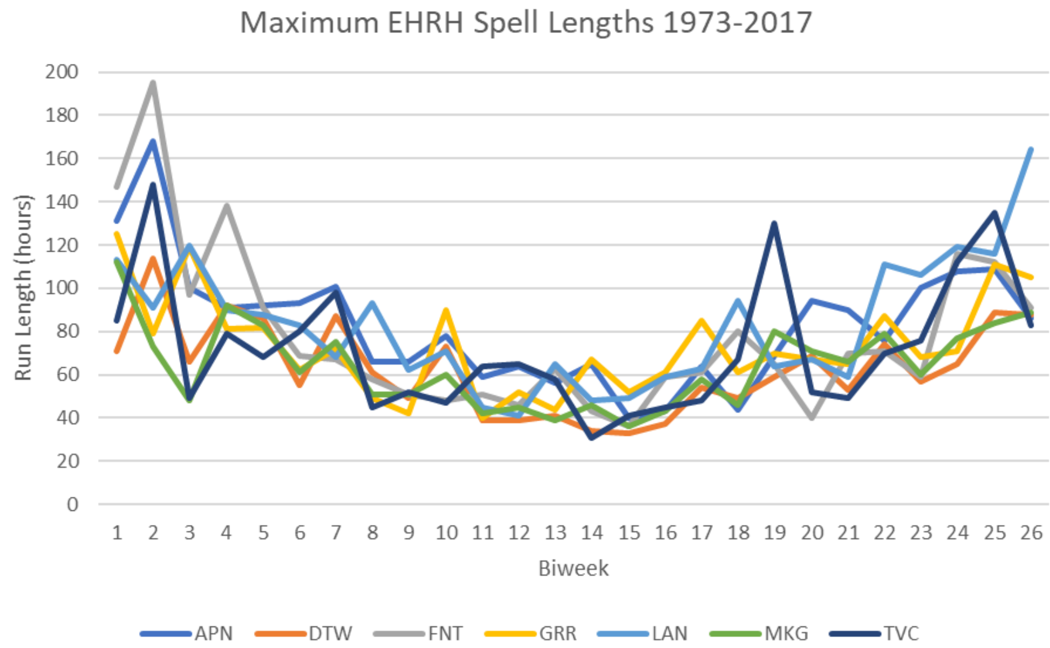
RELATIVE HUMIDITY	APN	DTW	FNT	GRR	LAN	MKG	TVC
Buishand	NS	NS	S - 2004	S - 2004	S - 2001	S - 2004	NS
Pettitt	NS	S - 2004	S - 2004	S - 2004	S - 2001	S - 2004	S - 2004
SNHT	NS	S - 2004	S - 2006	S - 2004	S - 2004	S -2004	S - 2004
Von Neumann	NS	NS	S	S	S	S	S
Classification	Useful	Doubtful	Suspect	Suspect	Suspect	Suspect	Suspect

Linear and polynomial regression analyses were run on the same stations with an alpha level of 0.10 to test for trends in the percent chance that relative humidity exceeding 85% would be continuous for hour lengths 12, 24, and 36 for each biweek of the year, while hour lengths 36, 48, and 72 were used for relative humidity exceeding 60%. Both linear and polynomial regressions were completed since most plots displayed either a linear or polynomial pattern. To determine the direction of the trend, first the results from the polynomial regression were considered. If the polynomial test was statistically significant, this result was used, unless it was clear that the function was strongly linear. If the polynomial regression trend was not significant, then the significant linear regression result was used. If neither test was significant, the biweek and station combination was classified as not significant. If greater than 90% of the values were the same, a trend was not calculated and the trend result for the biweek and station combination was labelled as not applicable. A correction was not used for the alpha level to compensate for doing multiple tests, creating potential for some significant trends to have occurred by chance.

RESULTS

Maximum Spell Length

The maximum spell length plots display the longest recorded EHRH or HRH run that began in each biweek in the 45-year records of the 7 long-term stations (Figure 2.2). The maximum spell length varies seasonally, with longer spells occurring during cooler biweeks and shorter EHRH events during warmer biweeks. Despite this seasonality, there is potential for long EHRH spells throughout the entire year. Even in early to midsummer, when the maximum spell lengths are shortest, all the long-term stations experienced at least 1 EHRH event of 36 hours or longer during 1973-2017 and several stations had maximum spell lengths of close to 60 hours.



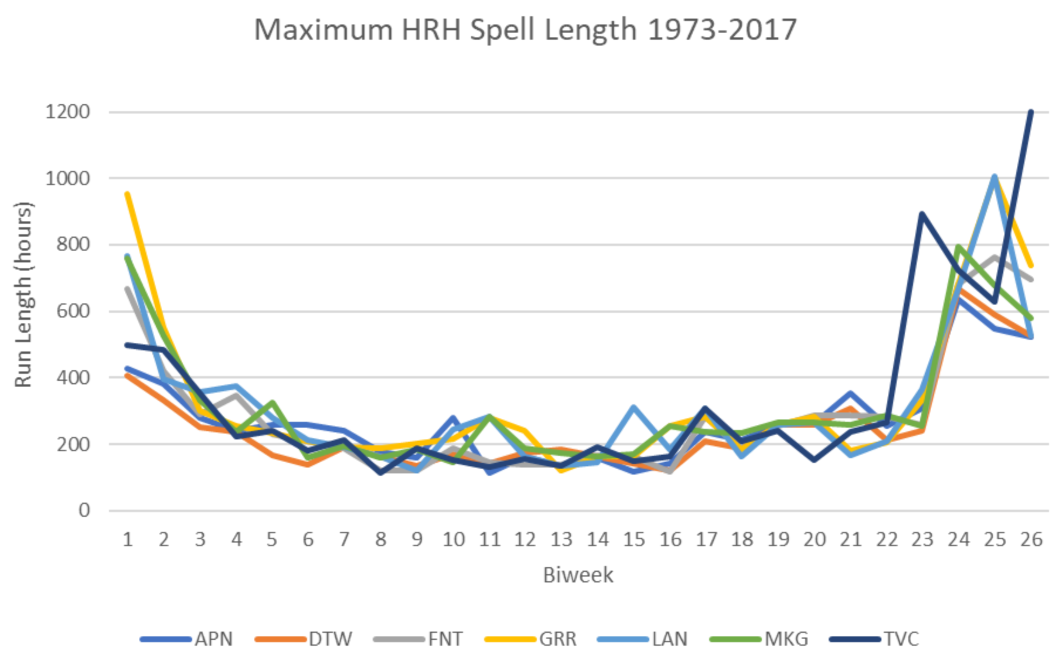


Figure 2.2. Maximum EHRH and HRH spell length at long-term stations, 1973-2017.

As expected given the lower humidity threshold, the maximum spell lengths for HRH events are considerably longer than those for EHRH events. During winter, biweeks 1-5 and 23-26, maximum length HRH events all fall above 200 hours, with many in biweeks 23-26 falling above 600 hours. During the remainder of the year, maximum run lengths are between 100 and 200 hours. There do not appear to be any consistent differences in either maximum EHRH or HRH events between the locations.

Spatial variations in the probability of EHRH and HRH spells

The spatial patterns in the probability of EHRH spells occurring in the Lower Peninsula of Michigan during biweeks 1-26 are presented for run lengths of 9, 12, 15, 18, 24, and 36 hours (Figure 2.3). As expected, the probability of experiencing an EHRH spell decreases as the length of the spell increases. Even in biweeks 1-3, when, as shown above, the maximum spell length is large, the probabilities decrease from almost 100% for spell lengths of ≥ 9 hours to around 50% for EHRH spells of ≥ 36 hours. Additionally, intra-annual variations are evident. For instance, in mid-February to early May (biweeks 4-9), the number of years with at least 1 EHRH event ≥ 9 hours remains around 80%, whereas the likelihood of experiencing EHRH events ≥ 24 hours decreases from 40-50% for biweeks 4-5 to only 0-30%, depending on location, during biweeks 8-9. In early May to late July (biweeks 10-15), EHRH spells ≥ 9 hours are still expected in at least 70% of all years, and EHRH spells ≥ 15 hours in at least 50% of all years. However, the probability of spells ≥ 24 hours drops to only 15%. As the season transitions from late July to mid-October (biweeks 16-21), the probability of experiencing a EHRH spell ≥ 9 hours in a given year increases to almost 100% across the Lower Peninsula, and that for EHRH spells > 24 hours increases to 50%. Some spatial variations are evident. For most biweeks and EHRH spells lengths, higher probabilities are apparent in the northern thumb and the central region of the

Lower Peninsula, with lower probabilities in the southern and southeastern portions of the study area.

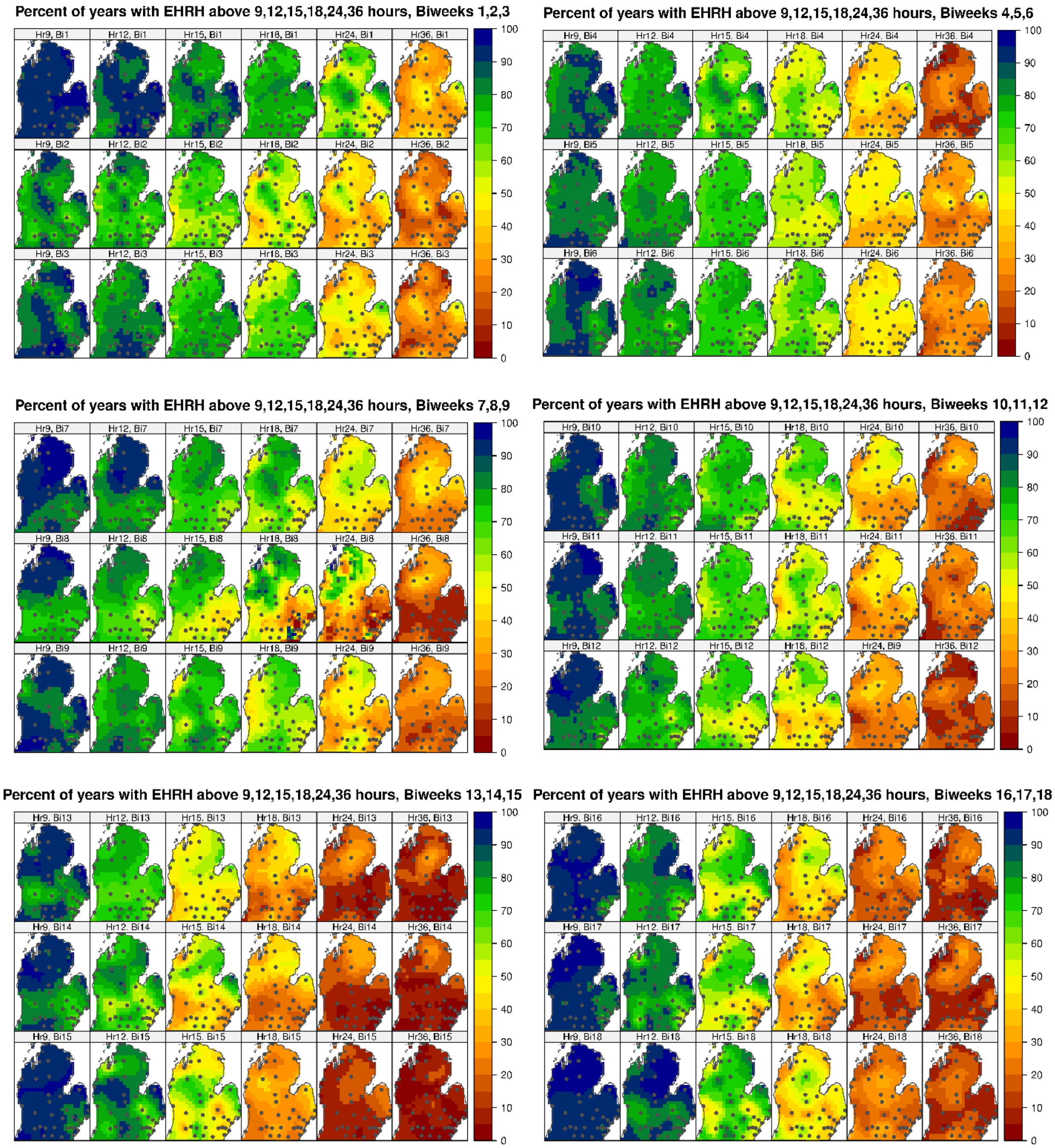
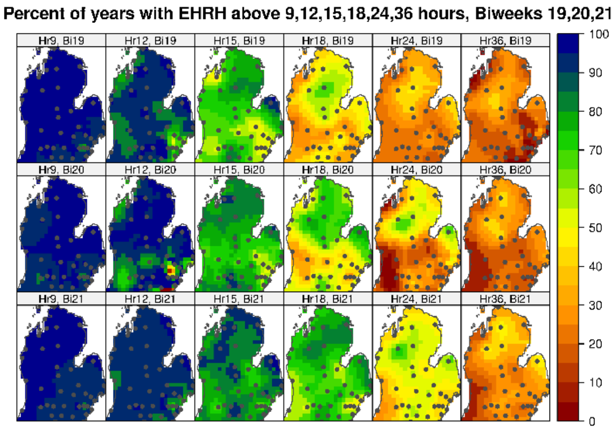
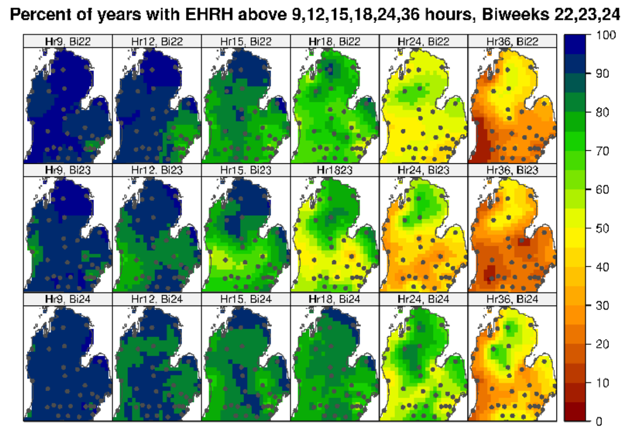
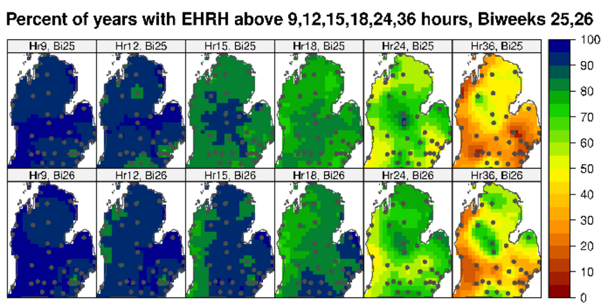


Figure 2.3. Spatial and intra-annual variation in the percentage of years during 2003-2017 with at least 1 EHRH event exceeding 9, 12, 15, 18, 24, and 36 hours during biweeks 1-26.

Figure 2.3 (cont'd)







Because, as shown earlier, the run lengths of HRH spells are longer than those of EHRH spells, spatial patterns are presented only for biweeks 4-21 and for run lengths of 15, 18, 24, 36, 48, and 72 hours (Figure 2.4). The kriged maps for the HRH spells display similar patterns as those for the EHRH maps, although the probabilities of longer spells are higher. For all biweekly periods, the probabilities of experiencing in a given year at least 1 occurrence of a HRH spell ≥ 12, ≥ 24, or ≥ 36 hours ranges from 70-100% across the Lower Peninsula. Intra-annual variations in the probability of HRH events with longer run lengths are evident. For example, the probabilities of HRH events ≥ 48 hours decrease from about 80% in biweek 4 to less than 40% in some parts of the Lower Peninsula in biweek 13, before increasing again to over 60% at most locations in biweek 25. HRH spells lengths ≥ 72 hours are relatively infrequent, with probabilities of 40% or lower in all biweekly periods and as low as 10% in portions of the Lower Peninsula during summer. In general, regardless of run length, higher probabilities are found in the north central, central, and northern thumb areas of the Lower Peninsula. There also appear to be higher probabilities along the western side of the Lower Peninsula, particularly for run lengths $\geq$ 48 and $\geq$ 72.

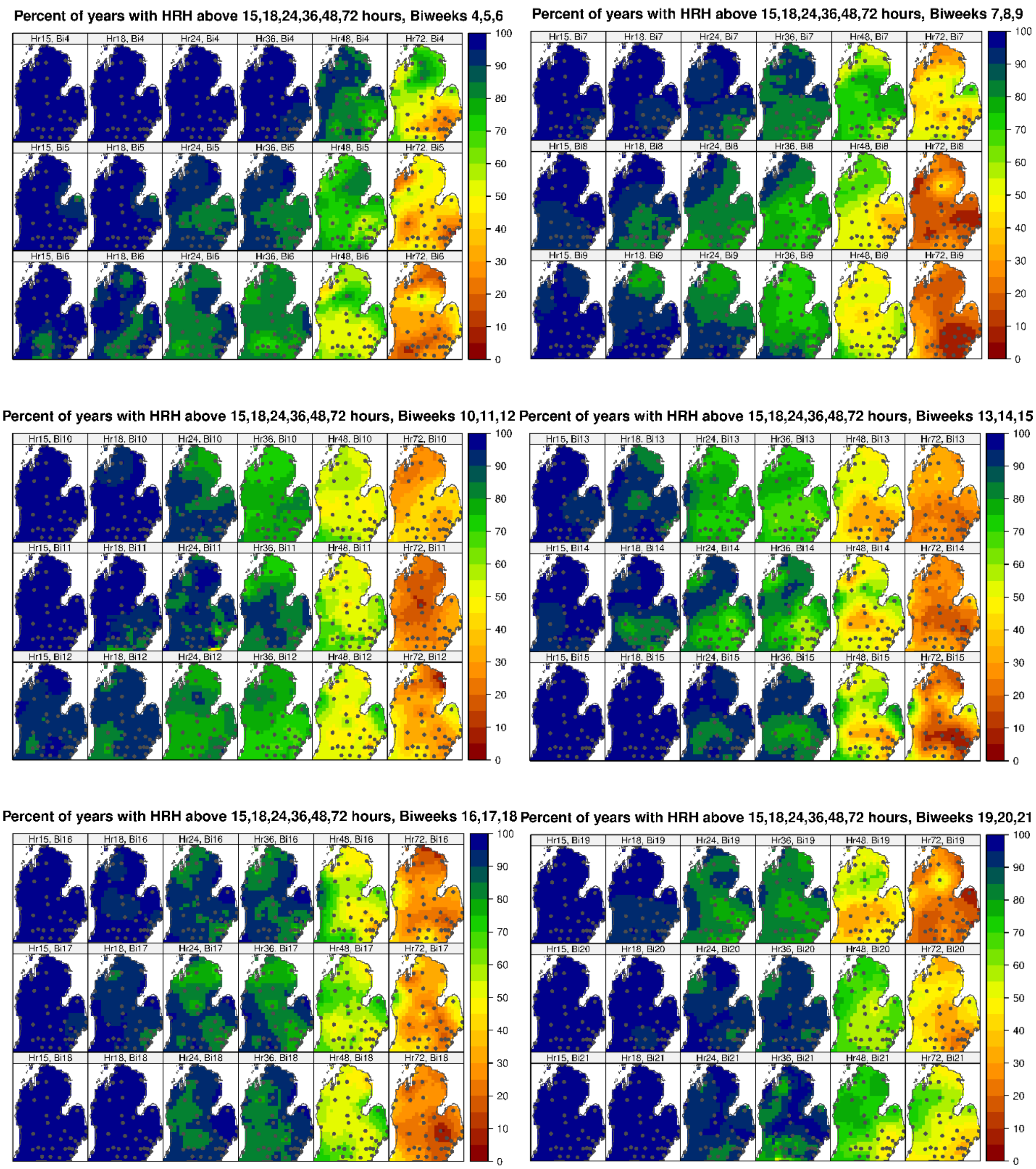


Figure 2.4. Spatial and intra-annual variation in the percentage of years during 2003-2017 with at least 1 HRH event exceeding 15, 18, 24, 36, 48, and 72 hours during biweeks 4-21.

Temporal trends in the probability of EHRH and HRH events

For the 7 long-term stations and each biweekly period, the percentage of years (i.e., probability) of EHRH spells ≥ 12, 24, and 36 hours was calculated for 15-year overlapping periods offset by 1 year (a total of 31 overlapping periods) to investigate temporal trends in the probability of EHRH events during 1973-2017. A 15-year overlapping period was selected to match the period length used for the spatial analysis above. Since the data displayed both linear and curvilinear tendencies, linear and polynomial regressions were run. Based on the protocol described in the methods, trend results of both types of regression were integrated into a single figure. A negative result indicates a linearly decreasing trend or a decreasing trend at the end of the 45-year period, while a positive result indicates a linearly increasing trend or an increasing trend toward the end of the 45-year period.

The trends for the majority of the station/biweek combinations for EHRH events ≥ 12 are negative, suggesting that EHRH events of this length have become less frequent during the study period, although during biweeks 6, 9, 10, 25, and 26 the trends at the majority of stations are positive (Figure 2.5). Trends could not be calculated for a number of the station/biweek combinations, as ≥ 12-hour runs occur frequently, resulting in frequencies of 100% for all of the 15-year overlapping periods. Negative trends also dominate for EHRH spells ≥ 24 hours, although several biweeks (6, 7, 10, 11, and 21) have predominantly positive trends. The northern stations (Alpena and Traverse City) display a larger number of biweeks with positive trends compared to the other locations. For EHRH spells ≥36 hours, significant positive trends in probability are observed for biweeks 10 and 11. The trends are mainly negative for the remainder of the year, although somewhat more biweekly periods at Traverse City and Alpena have positive trends compared to elsewhere. As with the EHRH events ≥ 12, a number of trends could not be calculated, as ≥ 36-hour runs are relatively uncommon, resulting in probabilities of 0% for all the overlapping periods for some of the station/biweek combinations.

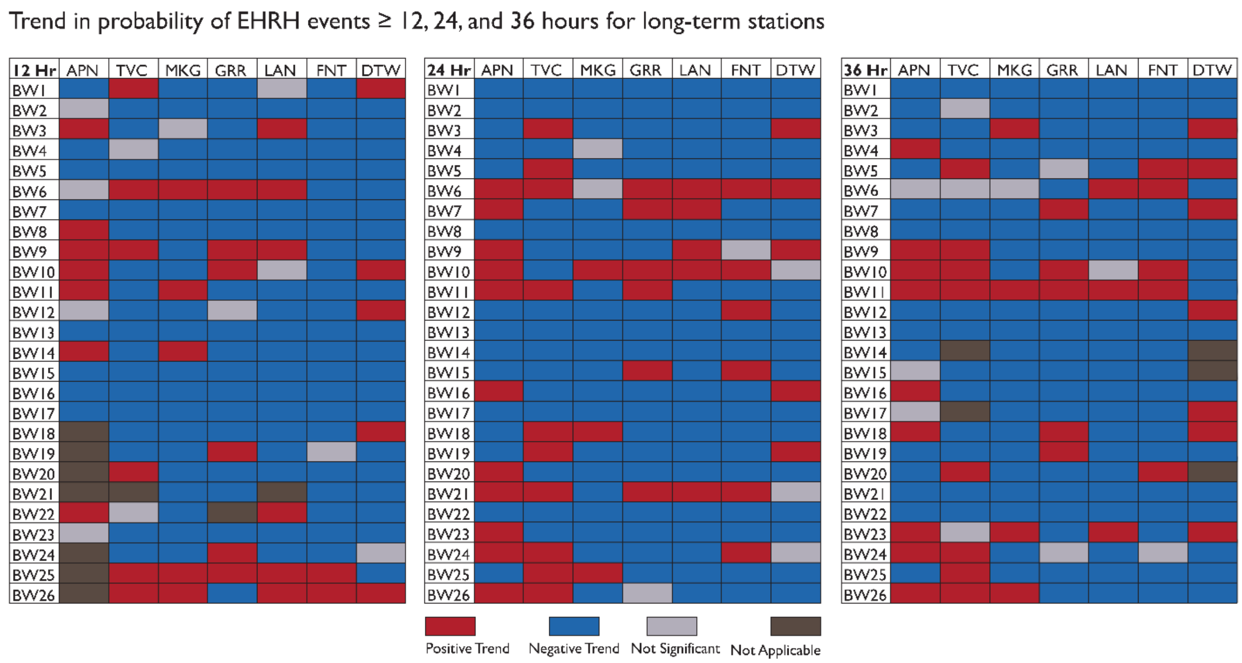


Figure 2.5. *Trends in the probability in a given year of experiencing EHRH events ≥12 hours, ≥24 hours, and ≥36 hours in length by biweek for the 7 long-term stations*. The stations are ordered generally from northwest to southeast. Blue blocks indicate significant negative trends from either polynomial or linear regression, red blocks significant positive trends from either type of regression, and light gray blocks insignificant trends for both polynomial and linear regression. Dark gray blocks are used for station/biweek combinations for which a trend could not be determined because the probabilities for over 90% of the overlapping periods were identical.

Trends were calculated for HRH events using the same process, but for longer spell lengths (≥ 36, ≥ 48, and ≥ 72 hours) (Figure 2.6). For HRH events of 36 hours or greater, there are slightly more negative trends, but the split between positive and negative trends is close to even, making patterns difficult to discern. Since observations of 60% relative humidity are common, 36-hour HRH runs occur frequently, resulting in a high number of uncalculated trends. Of the 7 stations, Grand Rapids has the greatest number of positive trends. The trends in HRH events ≥ 48 hours are also variable, although negative trends outnumber positive trends. Positive trends are most common in biweeks 1, 9-11, 24, and 25. Traverse City has the largest number of biweeks with positive trends in HRH events ≥ 48 hours. Most trends are negative for HRH spells ≥ 72 hours, although positive trends are evident for biweeks 1, 6, 7, 9, 10, 21, and 25, especially at Detroit.

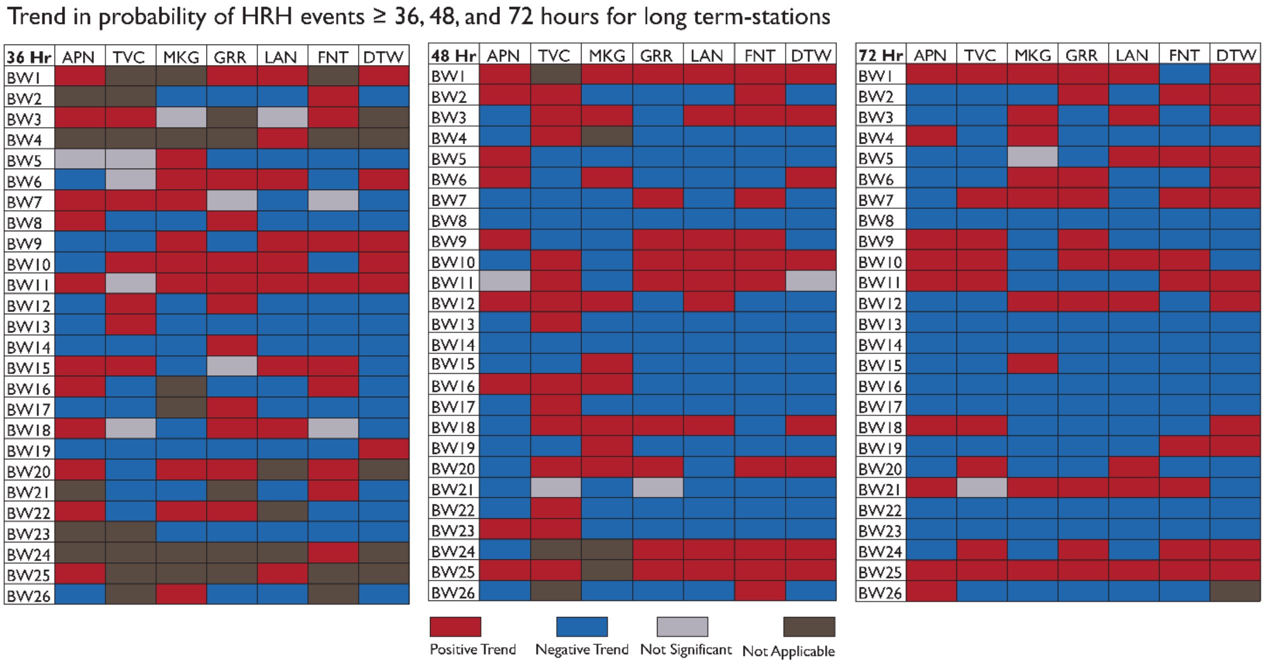


Figure 2.6. *Trends in the probability in a given year of experiencing HRH events ≥36 hours, ≥48 hours, and ≥72 hours in length by biweek for the 7 long-term stations.* The stations are ordered generally from northwest to south east. Blue blocks indicate significant negative trends from either polynomial or linear regression, red blocks significant positive trends from either type of regression, and light gray blocks insignificant trends for both polynomial and linear regression. Dark gray blocks are used for station/biweek combinations for which a trend could not be determined because the probabilities for over 90% of the overlapping periods were identical.

Temperature characteristics of HRH spells

Spells of high relative humidity are most impactful when the spell co-occurs with high temperatures, especially for HRH events as this humidity threshold is associated with human and animal health. To investigate the temperature characteristics of HRH spells, the frequency of maximum and minimum temperatures ≥ 0°C, ≥ 5°C, ≥ 10°C, ≥ 15°C, ≥ 20°C, ≥ 25°C, ≥ 30°C and ≥ 35°C were investigated for HRH event durations of ≥ 18, ≥ 24, ≥ 36, ≥ 48, ≥ 60, and ≥ 72 hours (Figure 2.7). These frequencies can be interpreted as the probability of experiencing a maximum or minimum temperature above a specified threshold, given that a HRH spell of a certain duration occurs.

In general, the maximum temperatures are somewhat cooler for those HRH events of shorter duration compared to events that span at least 24 hours, as shorter duration events are more likely to occur during the cooler portion of the day when relative humidity tends to be higher. In addition, the probabilities for the different temperature categories are alike across the 7 locations. For example, there is a high probability at all locations of temperatures ≥ 25°C during HRH spells occurring in the summer. During biweeks 12-19 there is a 60-100% chance of experiencing maximum temperatures ≥ 25°C at Muskegon and Grand Rapids for all run lengths except ≥ 24 hours, and for run lengths ≥ 48, ≥ 60, and ≥ 72 hours at Flint. Similarly, the probability of temperatures ≥ 25°C occurring with HRH spells ≥ 72 hours is greater than 80% at Grand Rapids during biweeks 16-18, and more than 60% at Traverse City during biweeks 14-18, at Lansing during biweeks 13-18, and at Detroit for the more extended period of biweeks 11-20. At Alpena probabilities between 55-80% are limited to biweeks 14-18.

As expected, probabilities for maximum temperatures ≥ 30°C are lower, but still present a hazard for workers whose occupations require rigorous physical activity outdoors for long periods of time. For example, at Flint the probability of experiencing a maximum temperature of ≥ 30°C is around 10% during biweeks 12-18 for HRH events with durations of ≥ 48, ≥ 60, and ≥ 72 hours and peaks at 20% during biweeks 12, 15, and 18. In contrast, at this time of year the probability of maximum temperatures ≥ 30°C during a HRH spell is only 5-15% at Alpena. The largest probabilities are observed for Detroit where maximum temperatures ≥ 30°C are observed with

HRH spells ≥ 72 hours during biweeks 12, 14, and 15, and at Lansing where probabilities reach 50% for HRH events ≥ 72 hours during biweek 14.

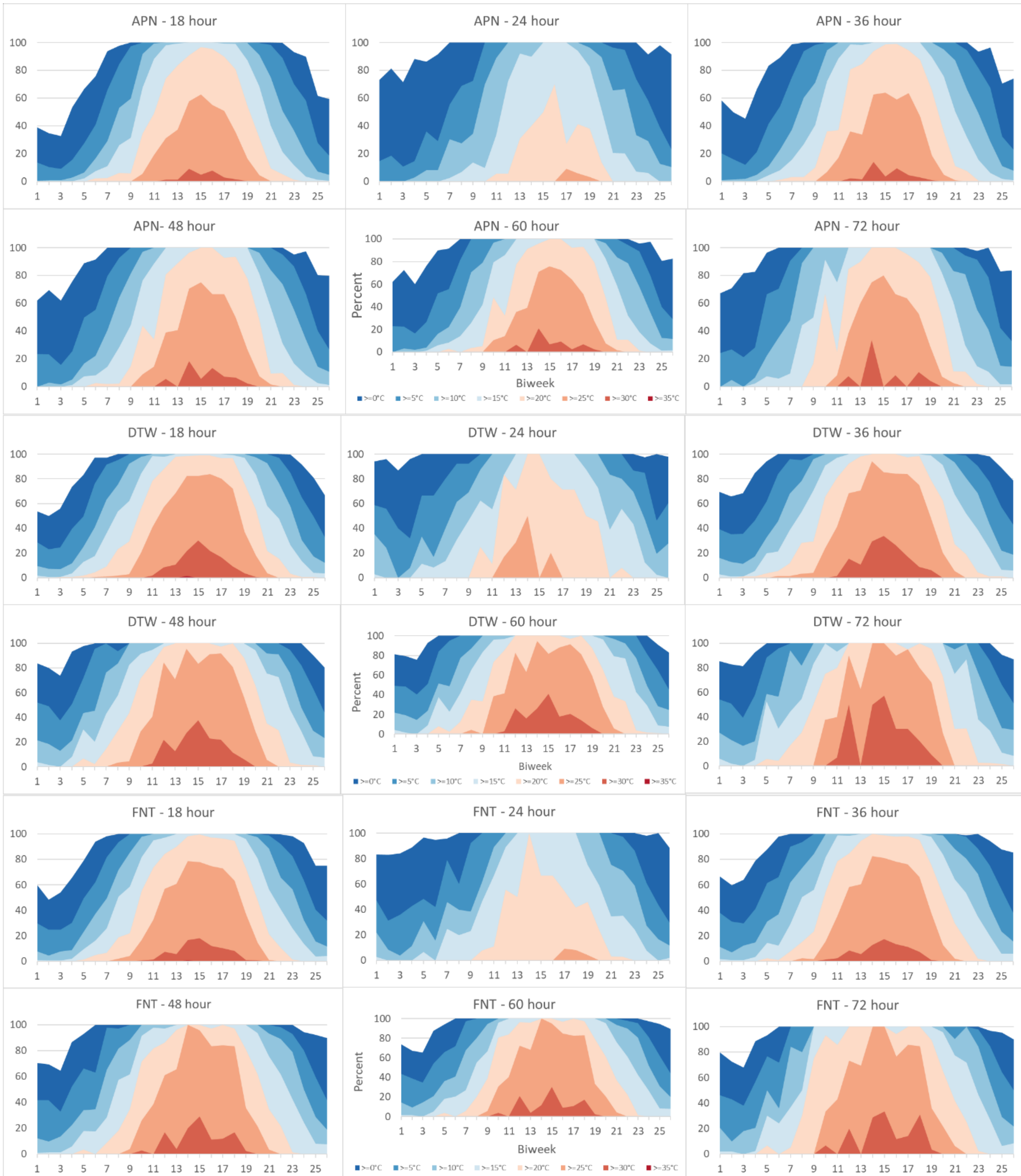
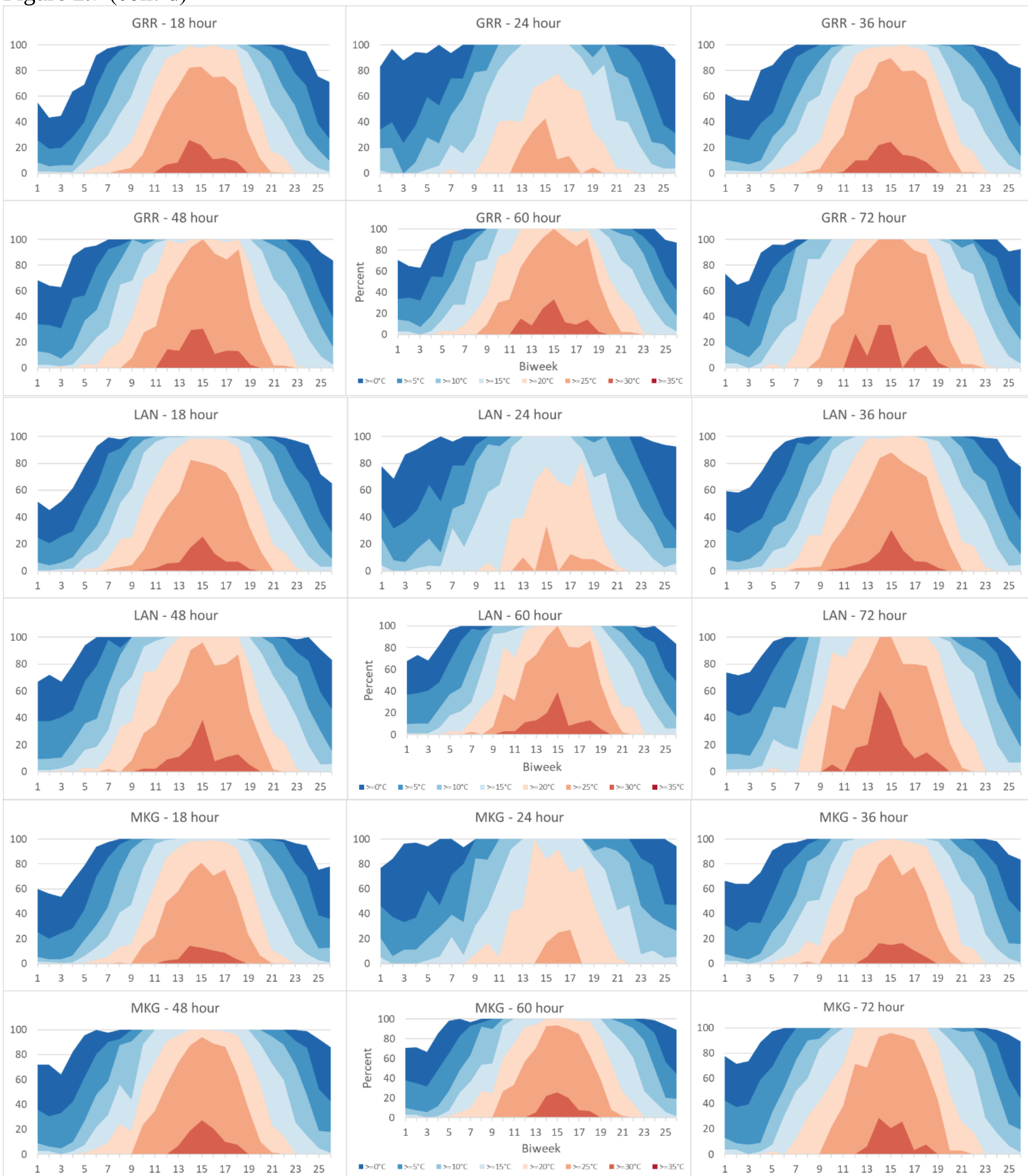


Figure 2.7. The probability of maximum temperatures exceeding ≥0°C, ≥5°,≥10°C, ≥15°C, ≥20°C, ≥25°C,≥30°C, and ≥35°C during HRH events with run lengths ≥18, ≥24, ≥36, ≥48,≥60, and ≥72 hours, by biweekly period for the 7 long-term stations.

Figure 2.7 (cont'd)



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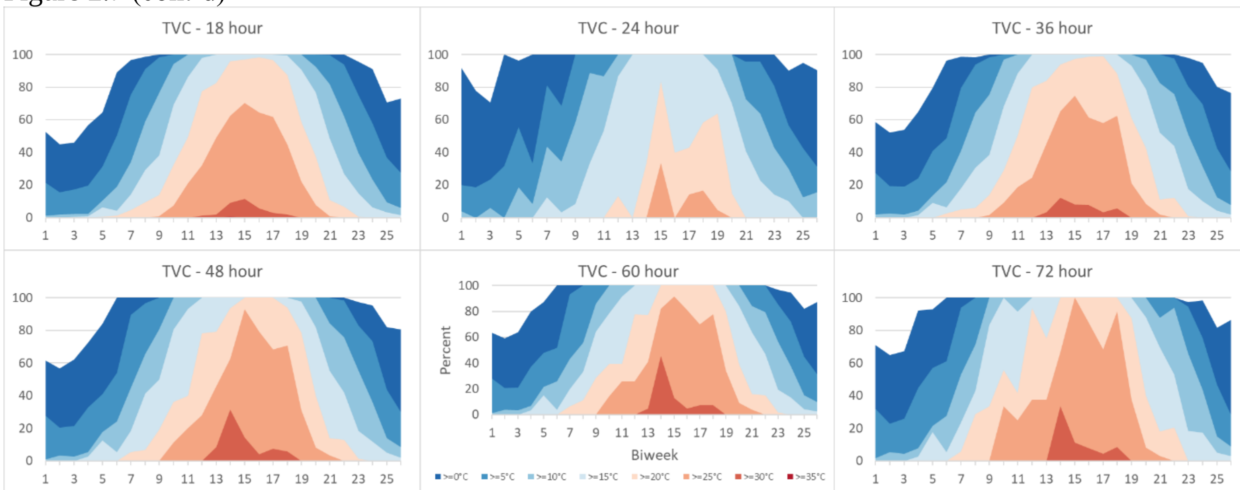


There is greater impact on health risk and cooling costs when the minimum temperature in addition to the maximum temperature is high. This is also important for livestock that are continuously exposed to outdoor temperatures. Focusing on minimum temperatures ≥ 20°C as an example, the highest probability of having temperatures above this threshold during a HRH event occurs during biweeks 13-17 at Detroit when there is a 30-40% chance that a minimum temperature of ≥ 20°C will co-occur with a HRH event, regardless of run length (Figure 2.8). In contrast, the probability at Alpena at this time of year is only around 5%. For both Grand Rapids and Muskegon the largest probability – 10-30% – of observing a minimum temperature ≥ 20°C with a HRH event occurs during biweeks 14-17, whereas at Lansing the probability is 10-20% for this time of year.

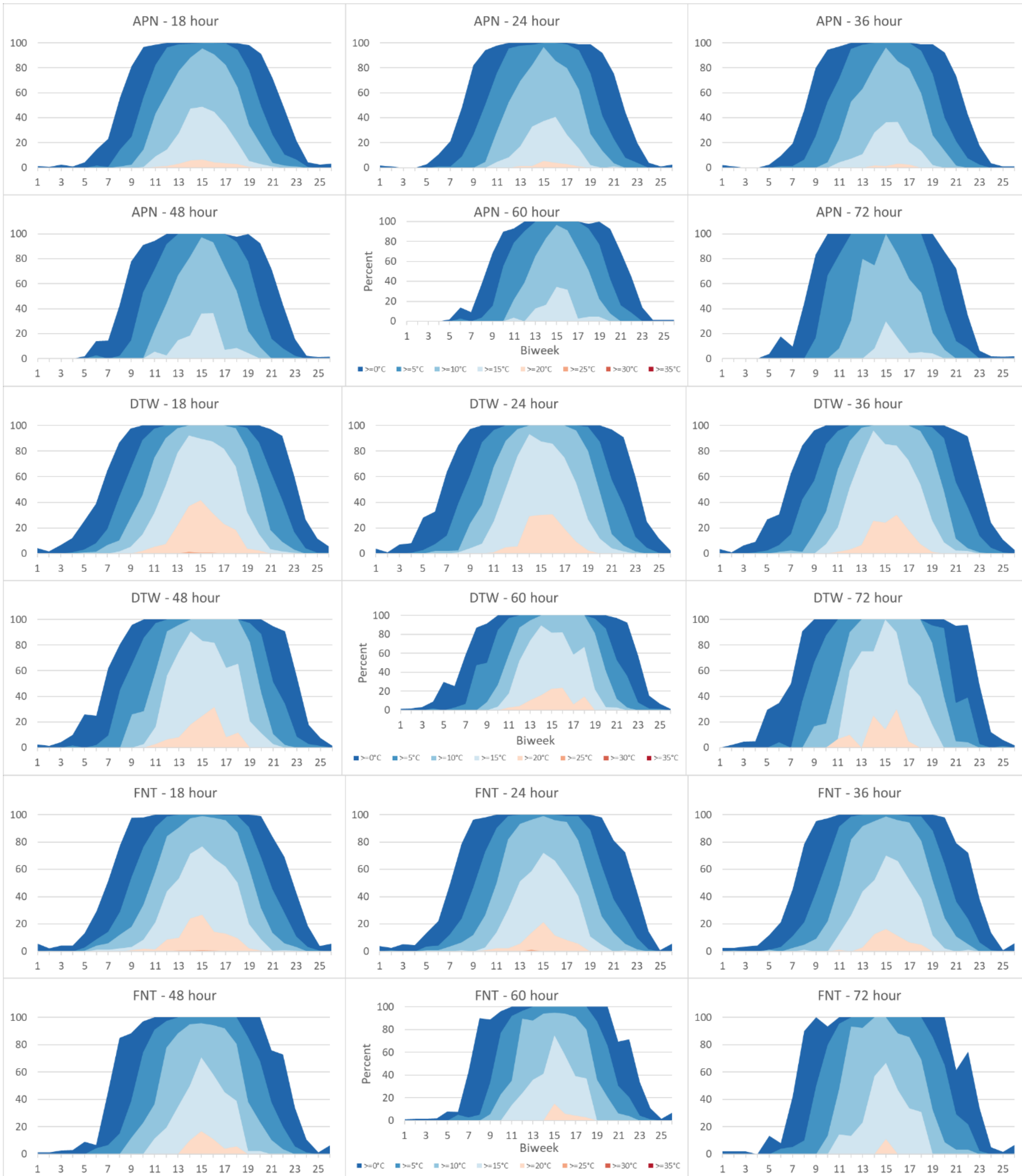
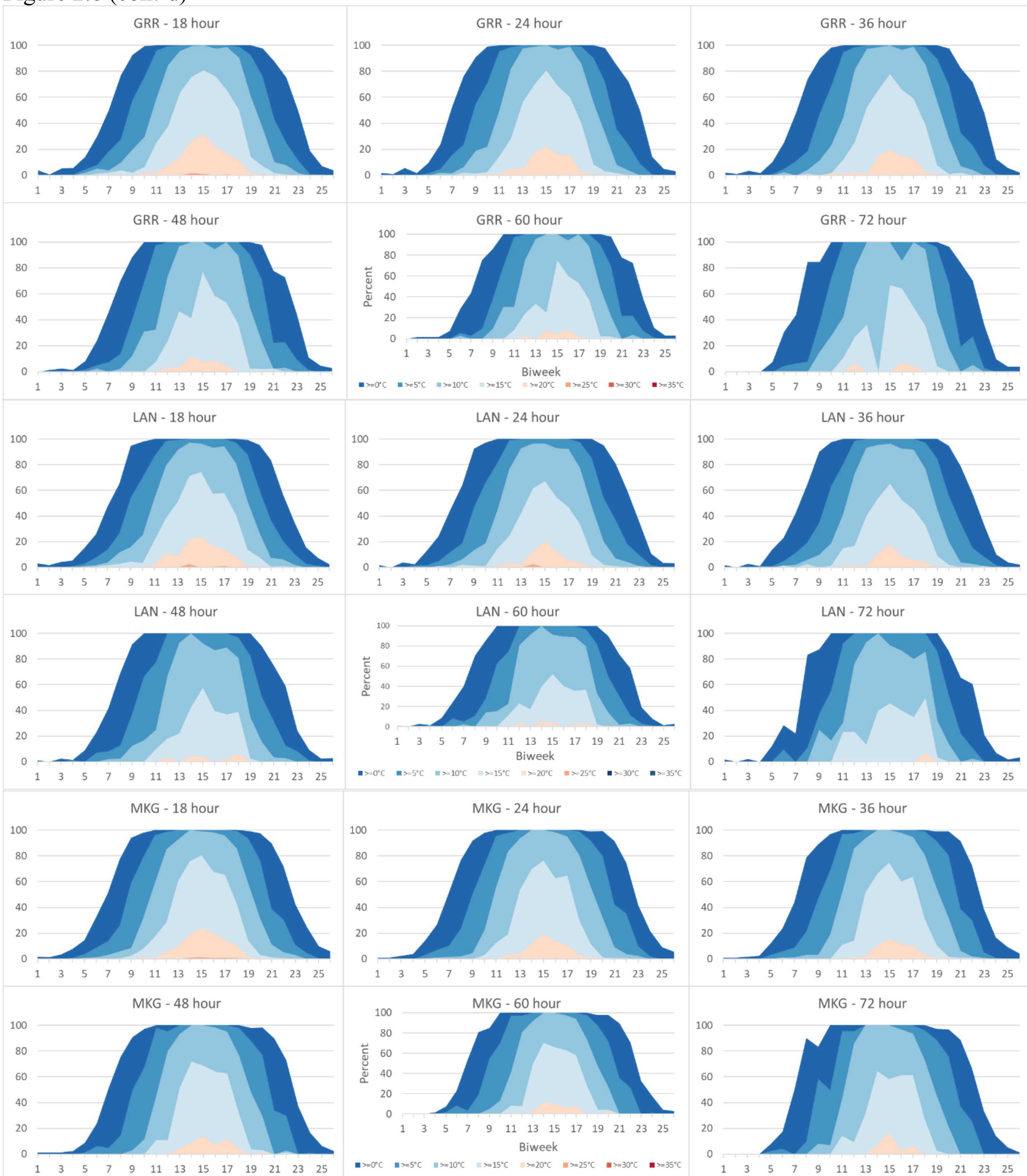


Figure 2.8. The probability of minimum temperatures exceeding ≥0°C, ≥5°,≥10°C, ≥15°C ,≥20°C, ≥25°C, ≥30°C, and ≥35°C during HRH events with run lengths ≥18, ≥24, ≥36, ≥48,≥60, and ≥72 hours, by biweekly period for the 7 long-term stations.

Figure 2.8 (cont'd)



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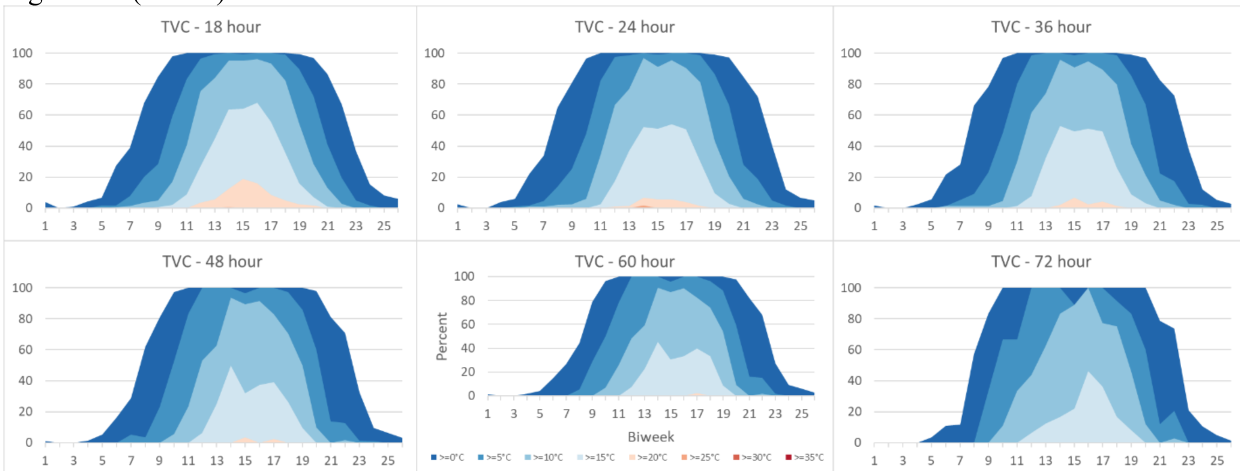

DISCUSSION AND CONCLUSIONS

The climatology presented above is likely the first that documents the spatial and temporal variations of spells of high relative humidity. Unlike previous studies, which have focused on annual, seasonal, or monthly averages of relative humidity, this climatology uses a smaller temporal scale and hourly relative humidity observations. These data were used to identify continuous spells of EHRH and HRH ranging from 6 hours to 3 days in length. The climatology provides relevant and useful information for a multitude of activities and processes that are impacted by persistent spells of high relative humidity. The climatology also includes the probability of a humidity spell that occurs with maximum and minimum temperatures exceeding critical temperature thresholds, as the impact of high relative humidity depends on accompanying high temperatures. An important potential use of the climatology is as a baseline to evaluate future changes in the frequency and character of high relative humidity spells. The major findings of the climatology are:

- Persistent spells of ≥ 85% relative humidity (EHRH events) and ≥ 60% relative humidity (HRH events) are common in the Lower Peninsula of Michigan. For all biweekly periods, EHRH events ≥ 9 hours and ≥ 12 hours in length occurred during more than 80% of all years from 1973-2017. Although longer EHRH events are less common, the probability of experiencing a spell length ≥ 15 hours is approximately 50% during most biweekly periods and that for spell lengths ≥ 24 hours is approximately 40% during the cool season. The chances of experiencing EHRH runs long enough to facilitate crop disease, vector-borne illness, and fungus growth in materials are substantial.

- Typical spell lengths are longer for HRH events given the lower humidity threshold, with probabilities of HRH spells ≥ 15 and ≥ 18 hours exceeding 80% and those of HRH spells ≥ 24 and ≥ 36 hours exceeding 85%, regardless of time of year.
- Spatial variations in the probability of EHRH and HRH events are modest, although probabilities of EHRH and HRH spells of any length are generally larger in the central and northern portions of the Lower Peninsula.
- The long-term trends in the frequency of EHRH and HRH events suggest a decrease in frequency during 1973-2017 for most biweekly periods and at most stations, although positive trends are evident at several stations during late spring/early summer and again in autumn, and positive trends are more likely to be observed at the 2 northern stations (Alpena and Traverse City).
- Maximum temperatures during HRH runs are often ≥ 20°C or higher during the summer, and for the majority of the year temperatures reached 15°C during at least 30% of HRH spells. These temperatures can be conducive to fungal disease infection, mosquito and tick activity and longevity, and fungus growth in livestock bedding and fodder.
- The probability of a HRH spell occurring in the summer months being accompanied by a maximum temperature ≥ 30°C, the temperature threshold considered a threat for heat-related illness, is 15-30% at most locations. If the temperature threshold is decreased to ≥

25°C, the likelihood of occurrence during summer increases substantially to approximately 50% for most HRH spell lengths. Also, at most locations, summertime HRH events have a 10-30% probability of being accompanied by temperatures that do not fall below 20°C, potentially impacting animal health and production.

- The maximum observed EHRH and HRH run lengths during 1973-2017 are substantial, even for the biweekly periods during summer. Summertime EHRH maximum run lengths exceed 30 hours, whereas summertime HRH maximum run lengths exceed 100 hours.

The study results also contribute to a more complete understanding of the complex climatology of relative humidity in Michigan. Previous findings regarding projected changes in annual, seasonal, and monthly averages of relative humidity have been contradictory. Brown and DeGaetano (2013), using 3 stations from Michigan, Traverse City, Grand Rapids, and Saginaw (near Flint), found that trends in annual and seasonal average relative humidity during 1930-2010 were insignificant for all stations except for a significant negative trend at Traverse City in spring and a significant positive trend at Grand Rapids in summer. When the longer period was broken into 2 subperiods, 1947-1979 and 1980-2010, none of the 3 stations had significant trends for either time period. Gaffen and Ross (1999) found significant positive trends at Detroit, Flint, Grand Rapids, Lansing, and Muskegon for all seasons except fall. In contrast, the findings presented here suggest significant negative trends in the frequency of HRH and EHRH spells in summer and a positive trend in spring and autumn, the opposite of the patterns observed by Gaffen and Ross (1999) and Brown and DeGaetano (2013). These contradictory findings imply that trends in the frequency of spells of high relative humidity cannot be inferred from trends in annual and seasonal average relative humidity.

Interpretation and application of the climatology of high relative humidity spells should take into consideration two important limitations of the analysis regarding data availability and data quality: 1) time series of hourly relative humidity are available for a small number of stations, the record length for most stations is limited, and the spatial coverage of the stations is uneven with only a few stations in the central northern portion of the Lower Peninsula and in Michigan's thumb area, and 2) potential heterogeneities in the relative humidity time series introduced by changes in instrumentation, observing practices, and station locations. One avenue of future work is to integrate observations from the ASOS/AWOS stations with observations from more recently established meteorological mesonetworks to improve spatial coverage.

CHAPTER 3: TEMPORAL AND SPATIAL VARIABILITY IN THE ENVIRONMENTAL CONDITIONS FAVORABLE FOR APPLE SCAB AND CHERRY LEAF SPOT INFECTION IN THE LOWER PENINSULA OF MICHIGAN

INTRODUCTION

Crop disease poses a threat to food production, the sustainability of livelihoods, and animal and human health. Many factors and processes contribute to the occurrence of crop disease. The fundamental disease triangle, thought to have been initially published by Stevens in 1960 (Horsfall and Dimond 1960; Francl 2001), serves as a helpful framework to conceptualize the contributors to plant disease (Figure 3.1). The figure suggests that for a biotic agent to cause disease in a plant, 3 factors must interact, a host, a pathogen, and an environment favorable for infection, each of which are located on the vertices of the triangle (Francl 2001). Since the factors rely on each other's presence, disease does not occur when 1 of these 3 causal agents is absent (Francl 2001).

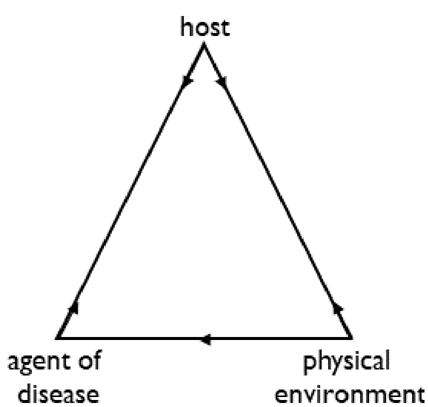

Figure 3.1 The fundamental disease triangle (Bourke 1970).

This study emphasizes the environmental component of the triangle. Without favorable environmental conditions, the pathogen does not pose a threat to the host. The goal is to identify the frequency of favorable environmental conditions for crop disease occurrence in the Lower

Peninsula of Michigan, specifically for apple scab and cherry leaf spot, which have large negative impacts on fruit production.

Agriculture is highly important to the Lower Peninsula of Michigan's population and economy. Michigan apples and cherries make a significant contribution to the nation's fruit supply, as well as bolster the state's economy. In 2016 apple production resulted in sales of $293.450 million, while sweet and tart cherry combined to generate $71.975 million for Michigan (USDA 2012). The average annual income for apple and cherry from the past 8 years has been $177.140 million and $64.802 million respectively (USDA 2012). These important crops are susceptible to disease, which poses a significant threat to the food security of consumers and the economic well-being of the state and growers. To minimize losses to disease, an understanding of the temporal and spatial variations in the frequency and persistence of favorable environmental conditions for infection is necessary to support long-term planning and decision-making.

Apple and cherry production in Michigan

Apples are a popular fruit for production and consumption in Michigan, which ranks third in the United States for apple production (Michigan Apple Committee 2018). Several varieties of apple are grown, including Fuji, Gala, Golden Delicious, Honeycrisp, Ida Red, and McIntosh (Michigan Apple Committee 2018). Apple production is spread throughout the state (Figure 3.2), with the highest production occurring in the west, including Kent, Oceana, Ottawa, Van Buren, and Berrien counties (USDA 2012). Apple trees begin flowering in the spring around mid-May and fruit start growing after pollination and fertilization (NW MI Horitcultural Research Center 2016, Lakso and Goffinet 2013). Harvesting dates vary depending on apple variety and environmental conditions—in Michigan most apples are picked from late-August to late-September.

The unique geography of Michigan's west coast, an area known as the fruit belt, presents an environment well-suited to the growth of tart and sweet cherry. High cherry-yielding counties include Leelanau, Oceana, Grand Traverse, Antrim, and Mason, all of which are located in the northwestern region of the state (USDA 2012). The state produces approximately 75% and 20% of the nation's tart and sweet cherry supply respectively, while serving as the largest producer of Montmorency tart cherries (Michigan Agriculture 2016). Historically, cherries in Michigan start to bloom around late April to early May (NW MI Horticultural Research Center 2016). Like apples, cherries grow from the flower of the plant into fruit after blossoming. Tart cherries can be harvested and consumed starting around late July and are available throughout the year as processed goods (Michigan Agriculture 2016).

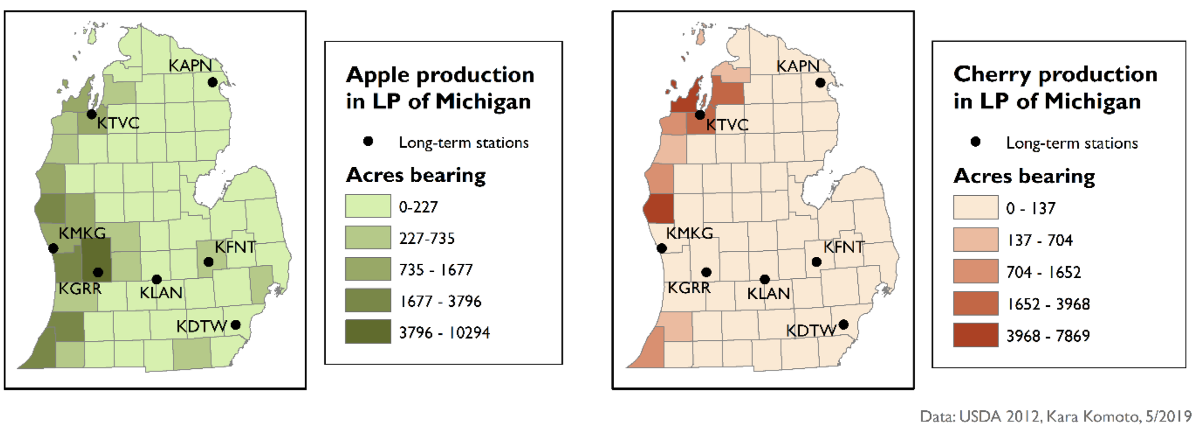

Figure 3.2. Acres bearing apple and cherry in the Lower Peninsula of Michigan (USDA 2012).

Crop diseases affecting apple and cherry production in Michigan

Apple scab poses a significant threat to fruit production in Michigan. The disease occurs when the fungus *Venturia inaequalis* releases spores from infected leaf litter. If these spores are released during periods with specific temperatures and leaf wetness duration they can cause primary apple scab infection (Hartman, Parisi, and Bautrais 1999; Michigan State Extension, n.d.). During primary infection the disease creates brown lesions on the foliage, blossoms, and fruit of the plant, which serve as sources of inoculum—conidia—for secondary infection later in the season. Since apple scab can impact leaves, blossoms, and fruit, the disease can be problematic throughout the entire growing season, defined as March through September (Michigan State Extension, n.d.). Disease incidence increases with longer durations of leaf wetness within a 9-28°C temperature range (Hartman et al. 1999; MacHardy and Gadoury 1989). The fewest hours of wetness required for apple scab to occur is 9 hours at approximately 17°C (Michigan State Extension, n.d.). If these conditions occur and inoculum infects the plant, the disease damages fruit and negatively affects foliage health, making the tree more susceptible to other diseases and pests (Gauthier 2018).

Cherry leaf spot is caused by the fungus *Blumeriella jaapii* (Wilcox 1993). Previously infected leaves become fungus-infested leaf litter that eventually releases spores in the spring when temperatures reach at least 16°C (Wilcox 1993). These spores infect cherry trees through leaf stomates, requiring the underside of the trees' leaves to be exposed as well as a prolonged period of leaf wetness (Wilcox 1993). The underside of leaves become uncovered around petal fall, the beginning of the period during which the tree can become diseased (Wilcox 1993). Cherry leaf spot can instigate primary and secondary infection, with secondary infection causing more severe damage as a result of prior weakening of the plant from the first infection cycle (Wilcox 1993). The disease creates brown lesions on cherry stems and lesions on leaves that become holes, eventually making leaves turn yellow and fall off (Michigan State Extension, n.d.). Cherry tree foliage is vulnerable to this disease beginning with the petal fall stage and ending 2-3 weeks after harvest (Wilcox 1993). If severe, cherry leaf spot can result in rapid defoliation, which reduces the tree's hardiness to cold weather and frosts during winter (Wilcox 1993). This is harmful to the tree's health and could eventually lead to decreased yields and poor crop quality (Wilcox 1993).

Leaf wetness duration models

One of the most infection-enabling factors involved in crop disease is leaf wetness since most pathogens require free water to infect, colonize, or sporulate (Huber and Gillespie 1992). Leaf wetness duration is the amount of time free water is continuously present on crop canopies. Natural leaf wetness occurs when crop canopies catch and retain rainwater or when dew forms on leaves, while anthropogenic leaf wetness results from irrigation (Rowlandson et al. 2015).

Leaf wetness is not a common nor standardized measurement. Therefore, leaf wetness must be estimated from models, particularly for use in crop disease simulations (Rowlandson et al. 2015). Many different leaf wetness estimation models exist. For example, empirical models are based on statistical associations, physical models focus on energy balance, and hybrid empirical and physical models integrate both methods (Rowlandson et al. 2015). Empirical models are relatively simple and employ quantitative methods to find statistical relationships between climatological variables and leaf wetness duration (Sentelhas et al. 2008). These models are designed to require few, common input variables that are accessible from most weather stations (Rowlandson et al. 2015). However, these models are more suited for use in the region where developed, since model variables match the location's characteristics (Huber and Gillespie 1992). In contrast, physical models focus on the physics of dew formation and dissipation, allowing them to be more generalizable and useful for all locations (Rowlandson et al. 2015). A disadvantage of physical models is that they require many input variables, the majority of which are not observed at weather stations and are unavailable for most locations (Rowlandson et al. 2015). Hybrid models share this disadvantage, since many have a substantial physical model component, requiring a large number of observed and generated variables (Rowlandson et al. 2015).

The rigor of data requirements make physical and hybrid model use impractical, while empirical models are more accessible and have performed as well as physical models (Rao, Gillespie, and Schaafsma 1998).

Objectives

The purpose of this chapter is to assess temporal and spatial variations in the occurrence of environmental conditions conducive to apple scab and cherry leaf spot infection. The focus on the environmental portion of the fundamental disease triangle considers temperature and relative humidity. The produced climatology is preconditioned on the estimated occurrence of growth stages sensitive to crop disease and can serve as a valuable resource for long-term planning and decision-making. Spatial and temporal variability in the timing of crop growth stages sensitive to disease are examined in relation to the co-occurrence of ambient air temperatures promoting disease infection and high relative humidity, which is used as an empirical model of leaf wetness. These results will be used to analyze long-term trends in favorable environmental conditions affecting crop disease incidence in Michigan.

METHODS

Climate observing stations

Temperature and relative humidity observations for 7 stations from the Automated Surface Observing System (ASOS) network were downloaded from the National Center for Environmental Information Integrated Surface Dataset (Smith, Lott, and Vose 2011). The stations were selected based on their long-term records and a low number of missing observations. The study period of 1973-2017 was selected for the analysis based on the completeness of the data record (see Chapter 2 for more information). 3 of the stations (Traverse City, Muskegon, and Grand Rapids) are located within or close to the primary fruit production belt of western Michigan. The additional stations (Alpena, Lansing, Flint, and Detroit) were included since apple production for farmers' markets and personal consumption occurs statewide. These additional stations also provide a reference for comparing risk of favorable environmental conditions for crop disease for the stations within the fruit production region.

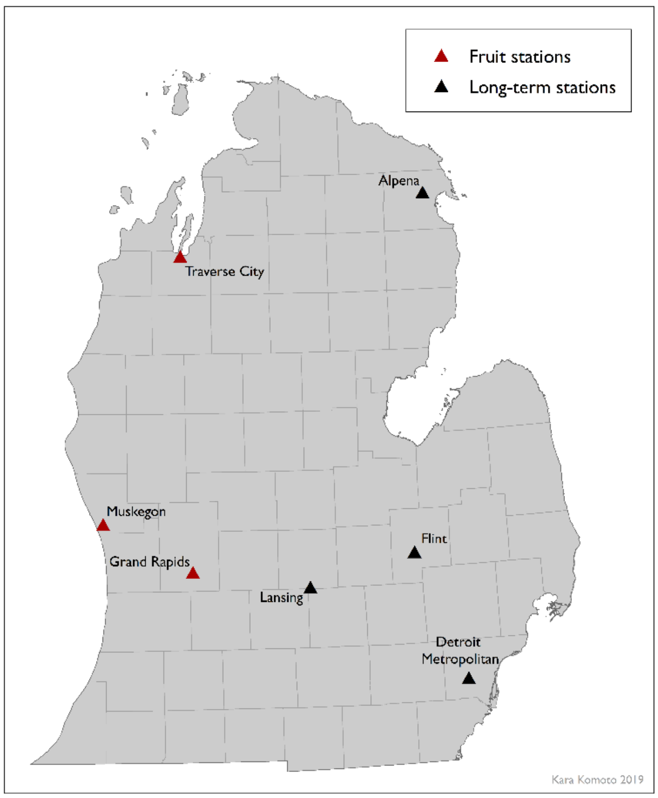

Figure 3.3 7 long-term ASOS stations used in analysis.

Relative humidity threshold for leaf wetness

An empirical model for estimating leaf wetness duration was employed. Relative humidity greater than 85% was used as a proxy for leaf wetness, based on the prior research of Sentelhas et al. (2008). They found that a relative humidity threshold of 85% was successful in modelling leaf wetness duration for Elora, Ontario, located approximately 150 miles east of Michigan and at a latitude of 43.684 degrees north, which is within the bounds of the state's latitudes. Climates between these places are similar, suggesting that the relative humidity threshold for Elora can be effectively used for estimating leaf wetness duration in the study area.

Growing degree units and vulnerable periods

Estimating plant phenology during the growing season is a challenge because the rate of plant growth changes depending on meteorological conditions, primarily temperature (Miller, Lanier, and Brandt, n.d.). Since weather is variable, using calendar dates to estimate crop growth is not an accurate method. A commonly used alternative technique is calculating growing degree units (GDUs), which are units of measurement based on temperature that can be associated with particular stages of crop growth (Miller, Lanier, and Brandt, n.d.). Various plants begin development at different temperatures, defined as their base temperature (Miller, Lanier, and Brandt, n.d.) and there are several techniques for calculating GDUs. To find GDUs for cherry and apple development, the Baskerville-Emin (BE) method was used (Baskerville and Emin 2019). This method is preferred to the averaging method when daily minimum temperature is below the crop's base temperature (Nugent, n.d.). The BE technique simulates diurnal temperature cycles by using daily maximum and minimum temperatures and a sine curve to estimate the area both below the curve and above the base temperature (Baskerville and Emin 2019; Nugent, n.d.). These daily heat estimates are accumulated as the season progresses. The crop's phenology can be estimated by referencing which stage is associated with the accrued number of GDUs and the Julian day on which it reached this threshold (See Table 3.1 for Julian day reference dates).

Table 3.1. Julian day associated with month start.

Month	Julian Day	Month	Julian Day
January	1	July	182
February	32	August	213
March	60	September	244
April	91	October	274
May	121	November	305
June	152	December	335

A literature review was conducted to determine each crop's base temperature, along with the appropriate growth stages and the corresponding GDUs during which they would be susceptible to their respective diseases (Table 3.2). The base temperature for apple was 5°C (Carisse, Jobin, and Bourgeois 2011), while cherry begins development at 4°C (Zavalloni, Andresen, and Flore 2006). Using these base temperatures, the BE method was used to accumulate GDUs to estimate when crop growth stages susceptible to disease occurred. Each crop had a start to its vulnerable period and an end to its vulnerable period, which were determined by the growth stages during which the disease can infect the plant. The number of growing degree units associated with these stages of development were identified, then for each year the Julian day when the appropriate GDU for the vulnerable stage beginning and end were found. If the crop was susceptible to disease through harvest, the Julian day associated with the typical harvest date was used as the end of the vulnerable period.

For apple scab, 2 vulnerable periods were considered, primary scab infection and overall scab infection, which includes primary infection and the potential subsequent secondary infection. The vulnerable stage for primary infection starts when green tissue emerges at green tip—20 GDU—(Carisse, Jobin, and Bourgeois 2011; TFREC, n.d.), while 2 thresholds were used for the end of the vulnerable stage based on primary and secondary infection. The end of the vulnerable stage is petal fall—165 GDU—for primary infection (Carisse, Jobin, and Bourgeois 2011;

TFREC, n.d.) and harvest—Julian 258—for secondary infection (Carisse, Jobin, and Bourgeois 2011; George Sundin, Personal communication, March 27, 2019). The chosen harvest date for apple was September 15, which is a compromise between 2018 harvest date estimates for the previously mentioned popular varieties grown in the state (Michigan Apple Committee 2018). For cherry, the vulnerable stage begins at petal fall—181 GDU—(Wilcox 1993) and continues to until the end of July—Julian 220—for every year, which is when tart cherries are typically harvested in Michigan (Wilcox 1993; Zavalloni, Andresen, and Flore 2006; George Sundin, Personal communication, March 27, 2019).

Using GDUs and the chosen growth stages, the Julian days during which the crops would be susceptible to disease infection were estimated for each year from 1973-2017. The average length, start date, and end date of the vulnerable period were found for each station, along with the earliest and latest Julian day on which the vulnerable period started and ended. Linear regression was performed to estimate long-term (1973-2017) trends in the start and end dates of the vulnerable period, along with the length of the period.

Table 3.2. Vulnerable growth stages and associated GDUs for apple scab and cherry leaf spot.

Crop	**Disease**	**Vulnerable Growth Stage (start)**	**GDU - Growth Stage (start)**	**Vulnerable Growth Stage (end)**	**GDU - Growth Stage (end)**	**GDU - Base**
Apple	Apple Scab - Primary Infection	Green Tip	20 (C)	Petal Fall	165 (C)	5°C
Apple	Apple Scab	Green Tip	20 (C)	Harvest	Julian 258	5°C
Cherry	Cherry Leaf Spot	Petal Fall	181 (C)	2 Weeks After Harvest	Julian 220	4°C

Frequency of favorable temperature and moisture conditions

Hourly relative humidity time series for the long-term stations were used to find 5-hour or longer spells of uninterrupted relative humidity greater than 85%, since the minimum number of hours of leaf wetness required for the infection by either apple scab or cherry leaf spot was 5 (Wilcox 1993). These spells were interpreted as leaf wetness duration. The start time (year, Julian date, hour) and length (hours) were recorded for each spell. Next, the start time of a spell was compared to the beginning and ending dates of the potential infection periods for the specific year in which the spell occurred, and only spells that fell within these periods were considered further.

Favorable environmental conditions for infection are a function of temperature in addition to the length of the period of leaf wetness. For apple scab, approximate temperature and wetting period thresholds required for infection were earlier estimated by Mills through an experiment with high levels of inoculum in an orchard setting (1944) and later modified by Jones et al. who created an instrument to record temperature, leaf wetness, and relative humidity, then programmed the instrument to detect potential infection periods (Jones et al. 1980). In general, the wetting period required for infection decreases with increasing temperature until approximately 16°C, after which the required wetting period length increases as temperature increases. The next step was to determine whether the spell met the combined temperature and wetting period thresholds for infection. This was done sequentially, using the thresholds for light infection obtained from the adapted Mills table to linearly interpolate to 1 hour increments for the wetting period (Figure 3.4) (Michigan State Extension, n.d.).

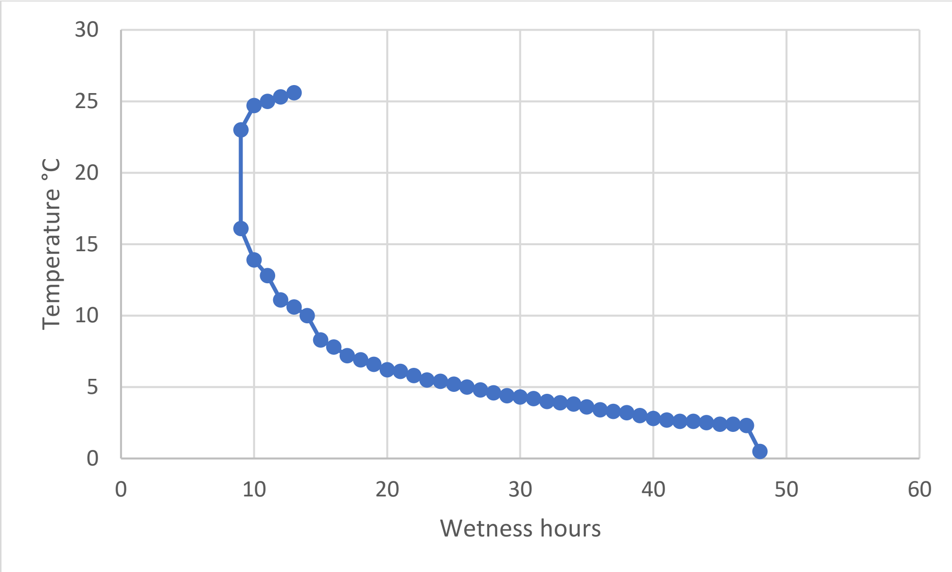

Figure 3.4. Wetness hours and temperature requirements for apple scab infection based on the adapted Mills table (Jones et al. 1980).

For apple scab, each spell was initially searched for 13 or more hours of temperatures ≥ 25.6°C, the warmest temperature included in the table. If this joint temperature/wetting period criterion was not met, the spell was searched for 12 or more hours of temperatures ≥ 25.3°C, and so on, initially decreasing the required wetting period by 1 hour until a minimum of 9 hours at 16.1°C, and then increasing the wetting period by 1 hour to a maximum of 48 hours at temperatures ≥0.5°C. Each temperature/wetting period criterion was referred to as a "type" of favorable environmental conditions. A spell that met 1 or more of the temperature/wetting period criteria was assigned the type with the highest temperature, and multiple potential infection periods within a spell were not permitted. For example, if 2 9-hour periods of temperatures ≥ 16.1°C occurred within a 24-hour spell, the spell was considered a single 9-hour leaf wetness period with temperatures ≥ 16.1°C of favorable environmental conditions for apple scab infection and was labeled "9h16.1C".

The same process was used for cherry leaf spot with temperature and wetting period thresholds appropriate for the pathogen (Figure 3.5) (Eisensmith and Jones 1981). These values originate from Keitt et al., who inoculated cherry with leaf spot in moist, temperature-controlled chambers to estimate the relationship between infection and temperature and moisture (Keitt et al. 1937; Eisensmith and Jones 1981). Eisensmith and Jones then used a regression model with these data to estimate the temperature necessary for cherry to become infected with leaf spot for various hours of wetness duration (1981). The results show that the range for this disease begins with a minimum of 5 hours of wetness when temperatures fall between 16.75°C and 17.25°C, while the maximum is 28 hours at temperatures less than 27.2°C and greater than 7.8°C (Wilcox 1993). Using these conditions, the number of periods of favorable environmental conditions for cherry leaf spot infection were found. The flow chart in Figure 3.6 summarizes the steps in identifying favorable environmental conditions for disease infection.

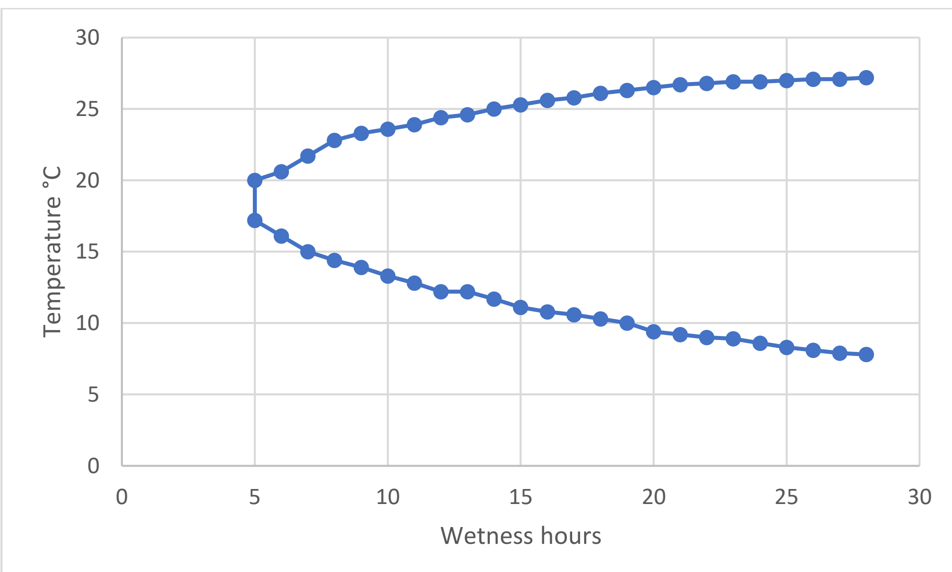

Figure 3.5. Hour and temperature requirements for cherry leaf spot infection (Wilcox 1993).

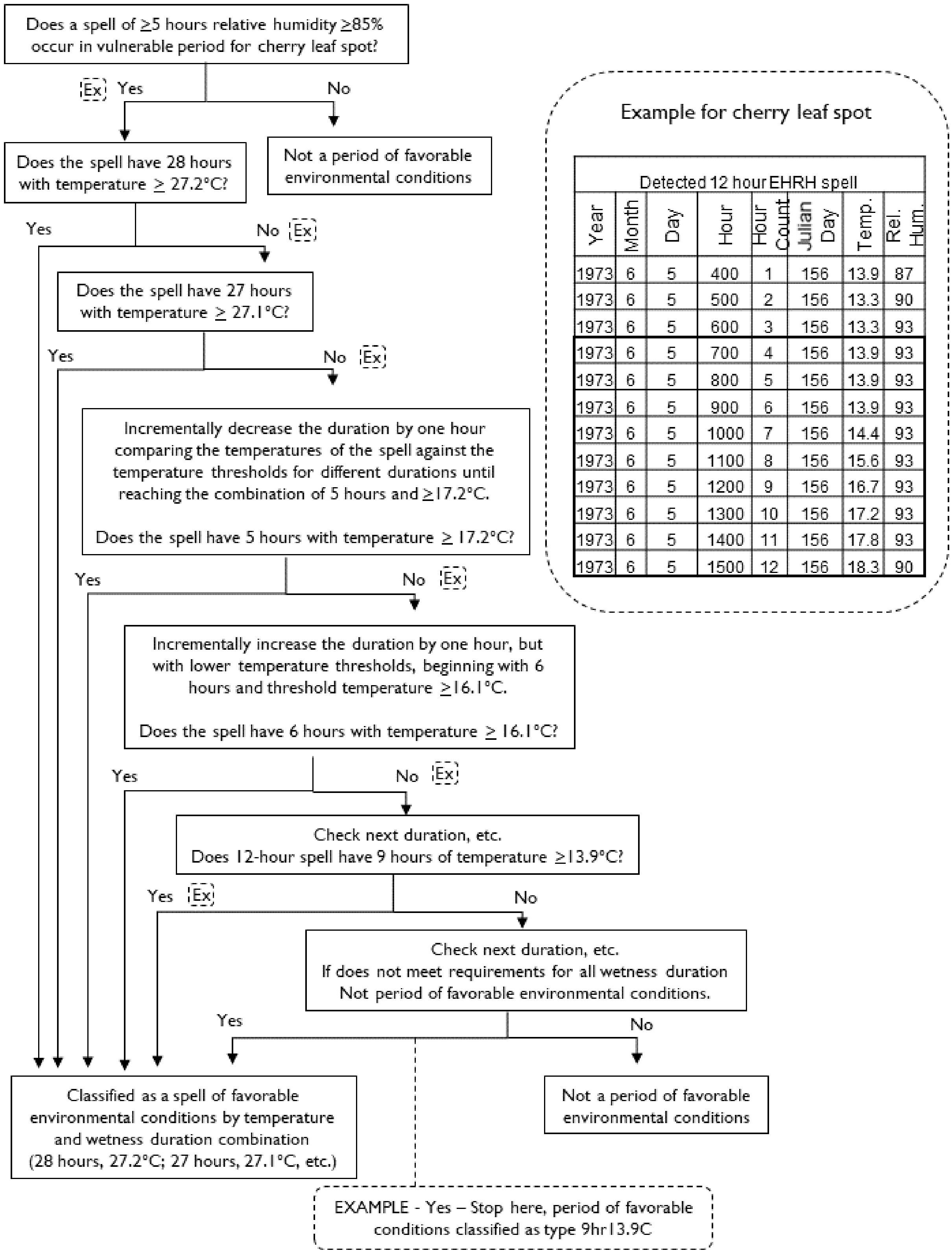

Figure 3.6. Flowchart for identifying periods of favorable environmental conditions for cherry leaf spot.

Once all the periods of favorable environmental conditions were identified for each crop, the data were used to calculate 1) the frequency of periods of favorable environmental conditions for disease infection, 2) the average number of periods of favorable environmental conditions per year, and 3) the frequency of the different types of favorable environmental conditions. Linear regression was employed to assess whether statistically significant trends in the frequency of favorable environmental conditions were evident. An alpha level of 0.05 was used to determine significance.

RESULTS

Length and timing of vulnerable periods for disease infection

The average length of apple's vulnerability to primary infection and to overall scab infection varies by station. As shown in Table 3.3, the shortest average length for vulnerable period is 39 days, observed for Alpena, Muskegon, and Traverse City. On average, Detroit has the longest vulnerable period of 47 days. The period during which apple trees are susceptible to any apple scab infection—both primary and secondary—is considerably longer with an average length ranging from 164 days at Alpena to 192 days at Detroit.

Table 3.3. Apple scab infection vulnerable period characteristics.

Apple - Primary scab infection vulnerable period						Apple - All scab infection vulnerable period	
Station	**Avg. St.**	**Avg. End**	**Avg. Length**	**Earliest St.**	**Latest End**	**Avg. Length**	**Latest End**
APN	94	133	39	67	151	164	258
DTW	66	113	47	7	131	192	258
FNT	74	116	42	29	134	184	258
GRR	75	116	41	29	132	183	258
LAN	73	116	43	30	133	185	258
MKG	82	121	39	52	138	176	258
TVC	88	127	39	53	142	170	258

Differences among stations in the average start date of the vulnerable period for apple scab are substantial, ranging from Julian day 66 (early March) at DTW to Julian day 94 (early April) at

APN. The differences among stations are somewhat smaller for the average date of the end of the primary infection period, with values from Julian day 113 (mid-April) at DTW to Julian day 127 (early May) at APN. During the 45-year study period, the earliest start of the primary vulnerable period occurred at Detroit on Julian day 7 (beginning of January) in 2008 whereas the latest end date of the vulnerable period occurred at Alpena on Julian day 151 (end of May) in 1997.

For apple, only 2 stations yield significant linear trends in the timing of the start date of the vulnerable period, both indicating an earlier start date. Detroit has a slope of -0.20, and Flint has a slope of -0.31 (Table 3.4). A trend could not be determined for the end of the overall scab infection period since it was constrained to the same day each year. 3 stations have statistically significant trends for the end date of the primary infection period. All indicate an earlier end to the primary infection for period, with a slope of -0.49 at Detroit, -0.46 at Flint, and -0.39 at Muskegon. None of the trends are significant for the length of the vulnerable period for primary apple scab, however for the combined primary and secondary apple scab vulnerable period both Detroit and Flint have statistically significant positive trends of 0.20 and 0.31 (Table 3.5), suggesting that the time during which apples are susceptible to this disease is increasing.

Table 3.4. Trends in the timing of the start of the vulnerable period for apple scab and the end of the vulnerable period for primary apple scab.

Apple - Trends in scab infection vulnerable period				
Station	**Start slope**	**Start p-value**	**End slope**	**End p-value**
APN	-0.21	0.19	-0.15	0.52
DTW	**-0.20**	**0.04**	**-0.49**	**0.02**
FNT	**-0.31**	**0.02**	**-0.46**	**0.03**
GRR	-0.18	0.20	-0.41	0.05
LAN	-0.19	0.18	-0.37	0.08
MKG	-0.27	0.11	**-0.39**	**0.05**
TVC	-0.23	0.11	-0.25	0.20

Table 3.5. Trends in the length of the vulnerable period for all apple scab and for cherry leaf spot.

Trends in infection vulnerable period length				
Station	**Apple - all infection**		**Cherry**	
	Slope	**P-value**	**Slope**	**P-value**
APN	0.21	0.19	0.17	0.50
DTW	**0.20**	**0.04**	**0.50**	**0.02**
FNT	**0.31**	**0.02**	**0.48**	**0.03**
GRR	0.18	0.20	0.38	0.08
LAN	0.19	0.18	0.40	0.06
MKG	0.27	0.11	**0.44**	**0.03**
TVC	0.23	0.11	0.25	0.20

The period during which cherry is susceptible to leaf spot begins at petal fall which occurs around 181 GDUs (Wilcox 1993). Since the disease can infect the plant even after harvest, the end of the vulnerable stage is set to Julian day 220 (early August), which occurs 2-3 weeks after harvest depending on location.

Table 3.6. Cherry leaf spot infection vulnerable period characteristics.

Cherry - leaf spot infection vulnerable period					
Station	**Avg. Start**	**Avg. End**	**Avg. Length**	**Earliest Start**	**Latest End**
APN	131	220	89	106	220
DTW	111	220	109	81	220
FNT	114	220	106	81	220
GRR	114	220	106	81	220
LAN	114	220	106	81	220
MKG	118	220	102	82	220
TVC	125	220	95	84	220

Table 3.6 shows that the earliest average start date of the cherry vulnerable period occurs at Detroit on Julian day 111 (mid-April), while, on average, the latest start occurs at Alpena on Julian day 131 (mid-May). The earliest start of the vulnerable period during the 45-year record occurs on Julian day 81 (late March) in 2012 at Detroit, Flint, Grand Rapids, and Lansing. The shortest average lengths of the vulnerable period occur at stations within or near the fruit belt

with 89 days at Alpena, 95 days at Traverse City, and 102 days at Muskegon. The station with the longest average length of the vulnerable period is Detroit with 109 days.

As for apple, linear regression was used to estimate the temporal trend in the start date of the vulnerable period at each station. 3 stations have statistically significant negative (i.e., earlier start dates) trends, including Detroit which has a slope of -0.50, Flint which has a slope of -0.48, and Muskegon which has a slope of -0.44 (Table 3.7). Trends in the length of the vulnerable period resulted in the same 3 stations demonstrating a statistically significant positive trend, Detroit, Flint, and Muskegon. Detroit has a slope of 0.50, Flint has a slope of 0.48, and Muskegon has a slope of 0.44 (Table 3.5). This suggests lengthening periods during which cherry is vulnerable to leaf spot, including at Muskegon, a station in the fruit belt.

Table 3.7. Trends in the start of vulnerable period for cherry leaf spot.

Cherry - Trends in leaf spot infection vulnerable period		
Station	**Start slope**	**Start p-value**
APN	-0.17	0.50
DTW	**-0.50**	**0.02**
FNT	**-0.48**	**0.03**
GRR	-0.38	0.08
LAN	-0.40	0.06
MKG	**-0.44**	**0.03**
TVC	-0.25	0.20

Frequency of favorable environmental conditions for disease infection

Figure 3.7 shows the percent of years in the 45-year record that had at least 1, 2, 3, 4, or 5 periods of favorable environmental conditions for primary apple scab infection. For convenience, periods of favorable environmental conditions for crop disease will be referred to below simply as “favorable environmental conditions,” recognizing that other meteorological conditions besides temperature and relative humidity, along with the state of the host and the presence of the pathogen, are not considered. Based on the historical record, the probability of having at least 1 spell in a given year of favorable environmental conditions for apple scab primary infection is high, ranging from 70% at Traverse City to 87% at Alpena. Having at least 2 spells in a year of favorable environmental conditions for primary scab infection is much lower, since most stations' percentages are around 40-53%, except Traverse City which only has 22% of years that contained at least 2 periods. Detroit has the highest percentages for greater than 3 and 4 periods, and the rest of the stations have values that remain below 25% for these categories. Experiencing 5 or more periods of favorable environmental conditions per year is rare with the largest probability (7%) at Lansing.

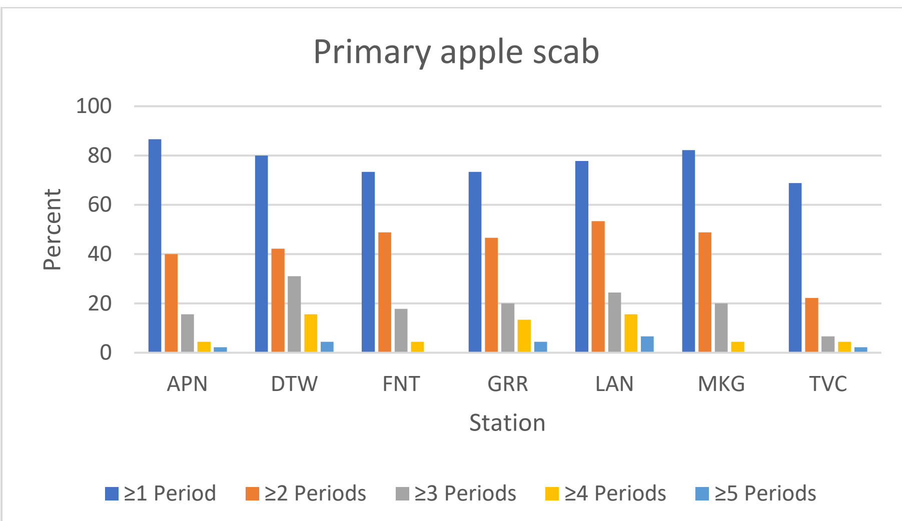

Figure 3.7. Percent of years from 1973-2017 with ≥1, ≥2, ≥3, ≥4, and ≥ 5 periods (spells) of favorable environmental conditions for primary apple scab infection.

The average number of favorable environmental conditions per year for primary apple scab infection was calculated by station (Table 3.8). Lansing and Detroit tie for the largest average value of 1.8 periods per year. Traverse City has the smallest average, 1.1 favorable periods per year, while Grand Rapids and Muskegon both have an average of 1.6 periods of favorable environmental conditions annually. The linear trend analysis produced a significant negative trend at the Flint and Lansing stations (Table 3.9), or, in other words, a decrease in the number of spells of favorable environmental conditions per year. However, neither of these stations are located near the major apple-growing regions of the state.

Table 3.8. Average number of periods of favorable environmental conditions for infection.

Station	Apple scab - primary infection	Apple scab - all infection	Cherry leaf spot
APN	1.5	33.4	24.0
DTW	1.8	26.9	26.6
FNT	1.4	29.9	26.2
GRR	1.6	34.0	30.1
LAN	1.8	36.6	30.1
MKG	1.6	33.8	28.7
TVC	1.1	25.3	21.3

Table 3.9. Trends in frequency of favorable environmental conditions for primary apple scab.

Apple scab - primary		
Station	**Slope**	**P-value**
APN	-1.48	0.43
DTW	0.94	0.48
FNT	**-3.52**	**0.04**
GRR	-1.53	0.28
LAN	**-3.08**	**0.02**
MKG	-0.96	0.60
TVC	-2.26	0.19

If primary infection occurs, the crop is then at risk for secondary scab infection when spores grow from the lesions created by the primary infection. This can occur through harvest, greatly increasing the length of the period during which apple is vulnerable, and consequently the exposure to spells of favorable environmental conditions for apple scab. Figure 3.8 displays the percent of years that experienced ≥ 10, ≥ 25, ≥ 40, and ≥ 55 periods of favorable environmental conditions for the combined primary and secondary infection periods. These intervals were chosen based on natural breaks in the data to highlight the unusual values, rather than using equal intervals, which would group potentially dissimilar values together. More than 90% of the years at the long-term stations have at least 10 periods of favorable environmental conditions for apple scab. Probabilities are still high for ≥25 favorable periods per year, with the probabilities for stations within the fruit belt ranging from < 60% at Traverse City to close to 80% at Muskegon. The smallest probability of at least 40 instances of favorable environmental conditions occurs at Traverse City (4%). Years with ≥ 55 periods of favorable environmental conditions are rare.

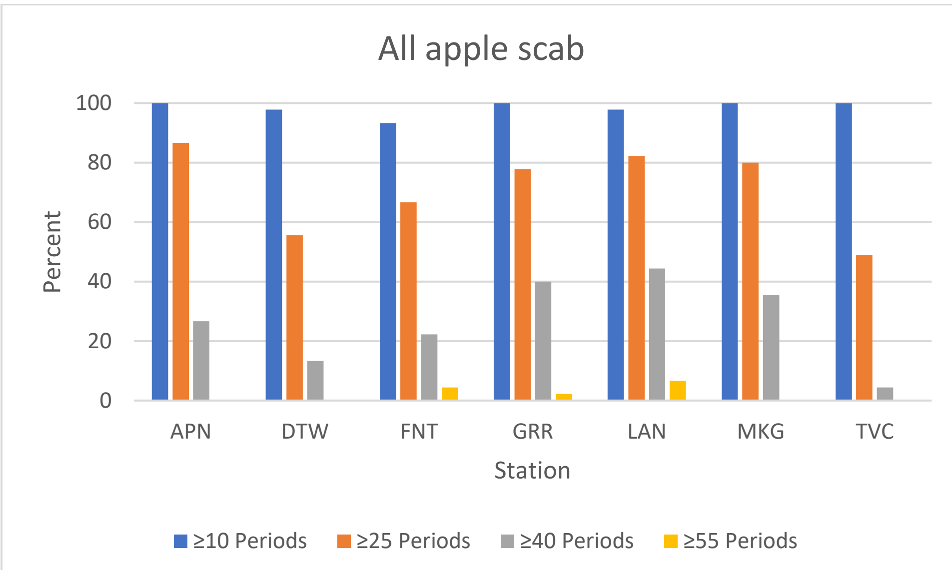

Figure 3.8. Percent of years from 1973-2017 with ≥10, ≥25, ≥40, and ≥55 periods of favorable conditions for apple scab infection.

Spatial variation in the average number of periods of favorable environmental conditions per year is small, with the average values ranging from 25 to 32 periods per year at most stations (Table 3.8). The smallest average (25.3 periods per year) is observed at Traverse City and the largest (36.6 periods per year) at Lansing. Both Grand Rapids and Muskegon have approximately 34 instances of favorable environmental conditions per year. Significant linear trends in the frequency of favorable environmental conditions per year for apple scab are found only at Lansing (slope of -0.55) and Muskegon (slope of -0.43) (Table 3.10). The negative slopes represent a decrease in the number of periods of favorable environmental conditions per year at these locations.

Table 3.10. Trends in frequency of favorable environmental conditions for apple scab.

Apple scab - all		
Station	**Slope**	**P-value**
APN	0.12	0.61
DTW	-0.16	0.39
FNT	-0.24	0.13
GRR	-0.34	0.05
LAN	-0.55	0.0002
MKG	**-0.43**	**0.02**
TVC	-0.36	0.11

The percent of years exceeding 10, 25, 40, and 55 instances of favorable environmental conditions for cherry leaf spot are shown in Figure 3.9 for each long-term station. All stations have a greater than 90% chance of experiencing 10 or more occurrences favorable for infection in a given year. The largest drop in probability for ≥ 25 spells of favorable environmental conditions is observed at Traverse City, where the probability falls to less than 30%. However, the probability remains high (> 60%) at most of the other locations. The probability of ≥ 40 periods of favorable environmental conditions per year drops to less than 15% at all locations.

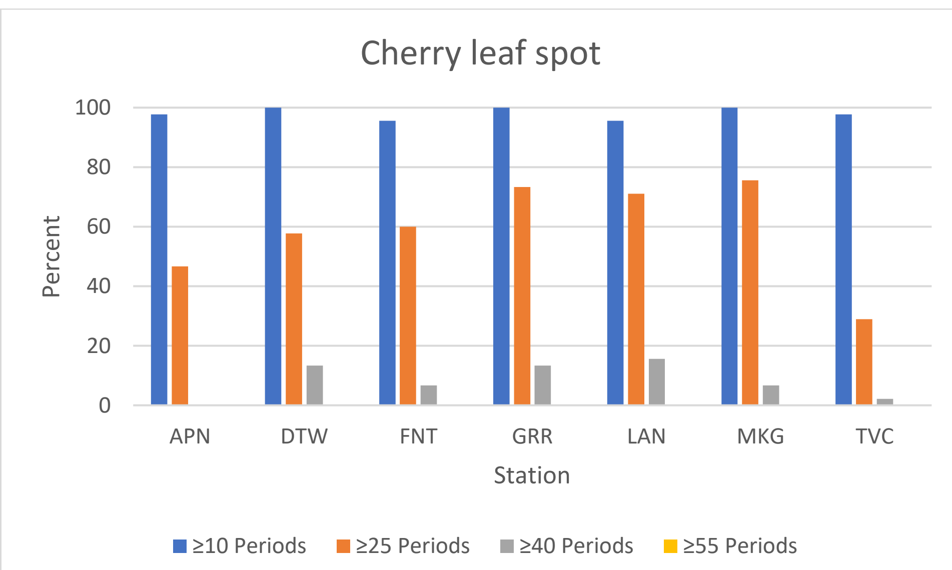

Figure 3.9. Percent of years from 1973-2017 with ≥10, ≥25, ≥40, and ≥55 periods of favorable environmental conditions for cherry leaf spot

Annual averages support less frequent favorable environmental conditions for cherry leaf spot at Traverse City (Table 3.8). The average value at this location (21.3 periods of favorable environmental conditions per year) is considerably lower than at other stations. The highest average value of 30.1 periods of favorable environmental conditions per year is found at both Grand Rapids and Lansing. Only Lansing has a significant linear trend in the frequency per year of favorable environmental conditions for cherry leaf spot with a slope of -0.46 (Table 3.11).

Table 3.11 Trends in frequency of favorable environmental conditions for cherry leaf spot.

Cherry leaf spot		
Station	**Slope**	**P-value**
APN	0.56	0.06
DTW	-0.13	0.53
FNT	-0.22	0.24
GRR	-0.34	0.14
LAN	**-0.46**	**0.02**
MKG	-0.29	0.28
TVC	-0.13	0.67

Characteristics of periods of favorable environmental conditions for disease infection

The next step of the analysis was to assess in greater detail the temperature and humidity characteristics of the opportunities for disease infection that were defined above based on favorable environmental conditions for apple scab primary infection, apple scab primary and secondary infection, and cherry leaf spot infection. As mentioned earlier, each period of favorable environmental conditions (i.e., opportunity for infection) was assigned a “type” based on wetness duration (as estimated from relative humidity) and the temperature threshold that was met for that period. The distribution of the types of favorable environmental conditions provides information on the typical temperatures and humidity durations associated with infection opportunities.

Beginning with apple scab primary infection, Figure 3.10 suggests that infection opportunities due to long (20 or more hours) wetness durations and cool temperatures are rare. Rather, regardless of station, the conditions for potential infection fall primarily between wetness durations of 9 hours and temperatures ≥16.1°C and wetness durations of 17 hours and temperatures ≥17.2 °C, although within this block of infection opportunities temperatures tend to be somewhat cooler and durations longer for the more northern or coastal locations compared to more southern or interior stations. For example, the frequency of infection opportunities with a 10-hour wetness duration and temperatures ≥ 13.9°C is largest at Flint and Lansing, whereas infection opportunities of 16-hour duration and temperatures ≥7.8 °C occur more frequently at Grand Rapids and Traverse City.

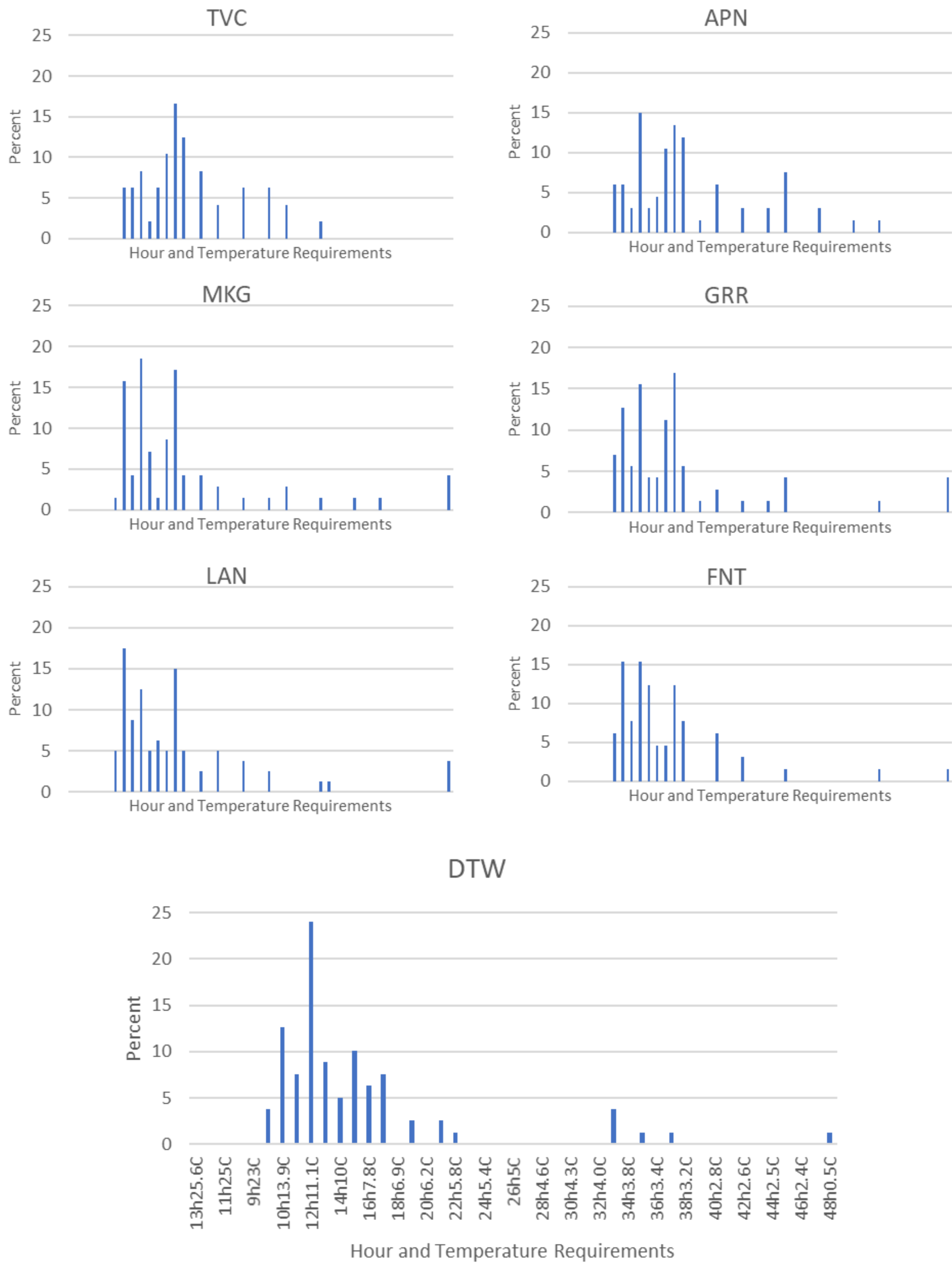

Figure 3.10. Frequency (in percent) of each type of temperature and relative humidity duration combination for periods of favorable environmental conditions for primary apple scab infection.

When secondary infection is considered in addition to primary infection, the type of infection opportunity shifts to shorter durations at higher temperatures (Figure 3.11). This is not unexpected, as the secondary infection period occurs during summer compared to the springtime primary infection period. The findings emphasize, however, that infection opportunities can be associated with relatively short wetness durations with higher temperatures. For all locations, the most commonly recorded type of favorable environmental conditions for primary and secondary infection combined is 9 hours wetness duration and temperatures ≥16.1°C, with frequencies varying from a minimum of 45% at Alpena and a maximum of 70% at Detroit.

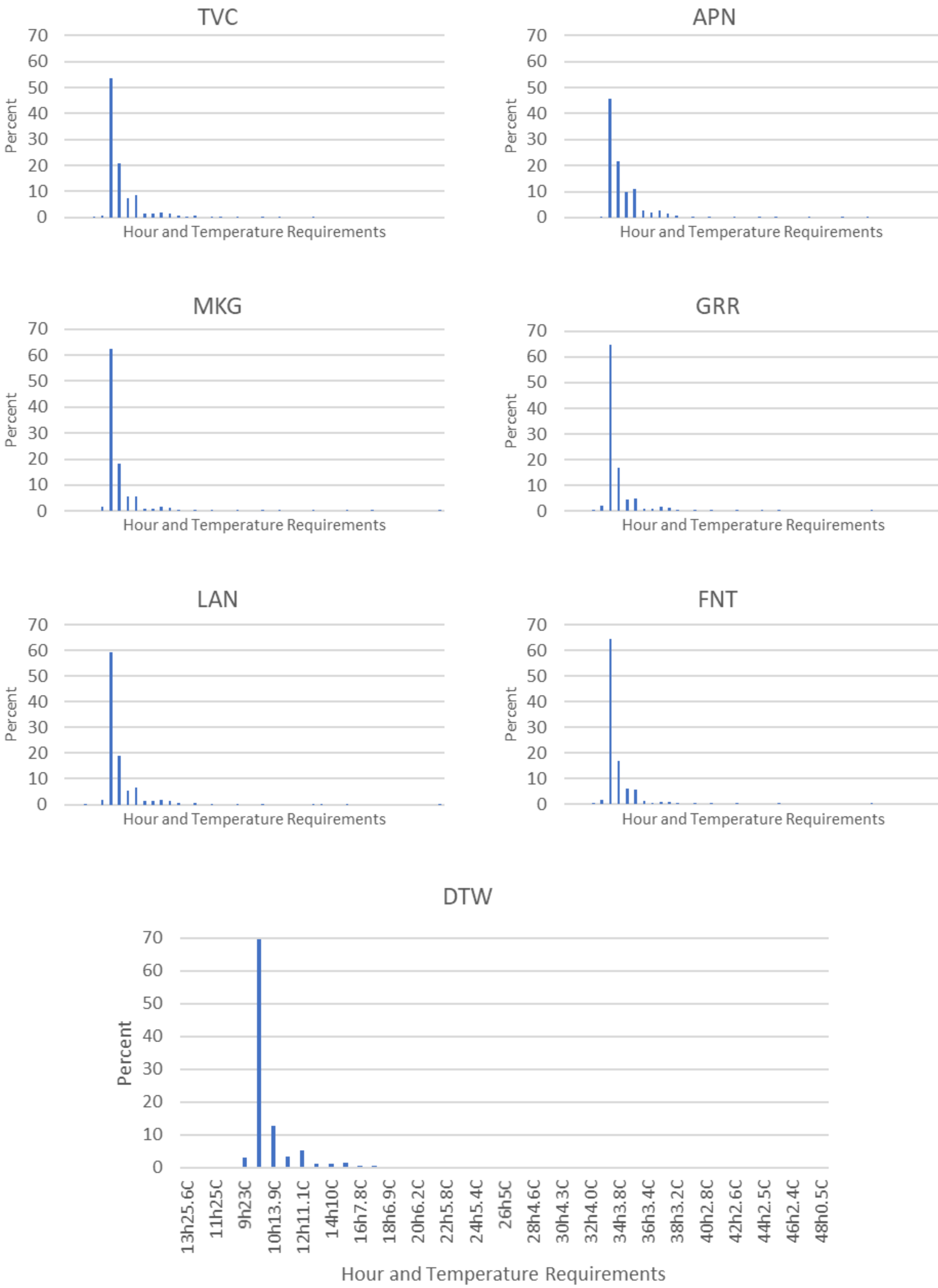

Figure 3.11. Frequency (in percent) of each type of temperature and relative humidity duration combination for periods of favorable environmental conditions for primary and secondary apple scab infection.

Infection opportunities for cherry leaf spot are infrequently associated with extended periods of cool temperatures and never associated with extended periods of very high temperatures, both of which require long wetness durations for infection (Figure 3.12). The most common type of infection opportunity at all stations is a wetness duration of 5 hours accompanied by temperatures ≥ 17.2 °C. In general, the infection opportunities for cherry leaf spot occur at higher temperatures and shorter wetness durations compared to apple scab combined primary and secondary infections, reflecting differences in the heat and wetness requirements for the fungi responsible for these diseases and the timing of the respective vulnerable periods.

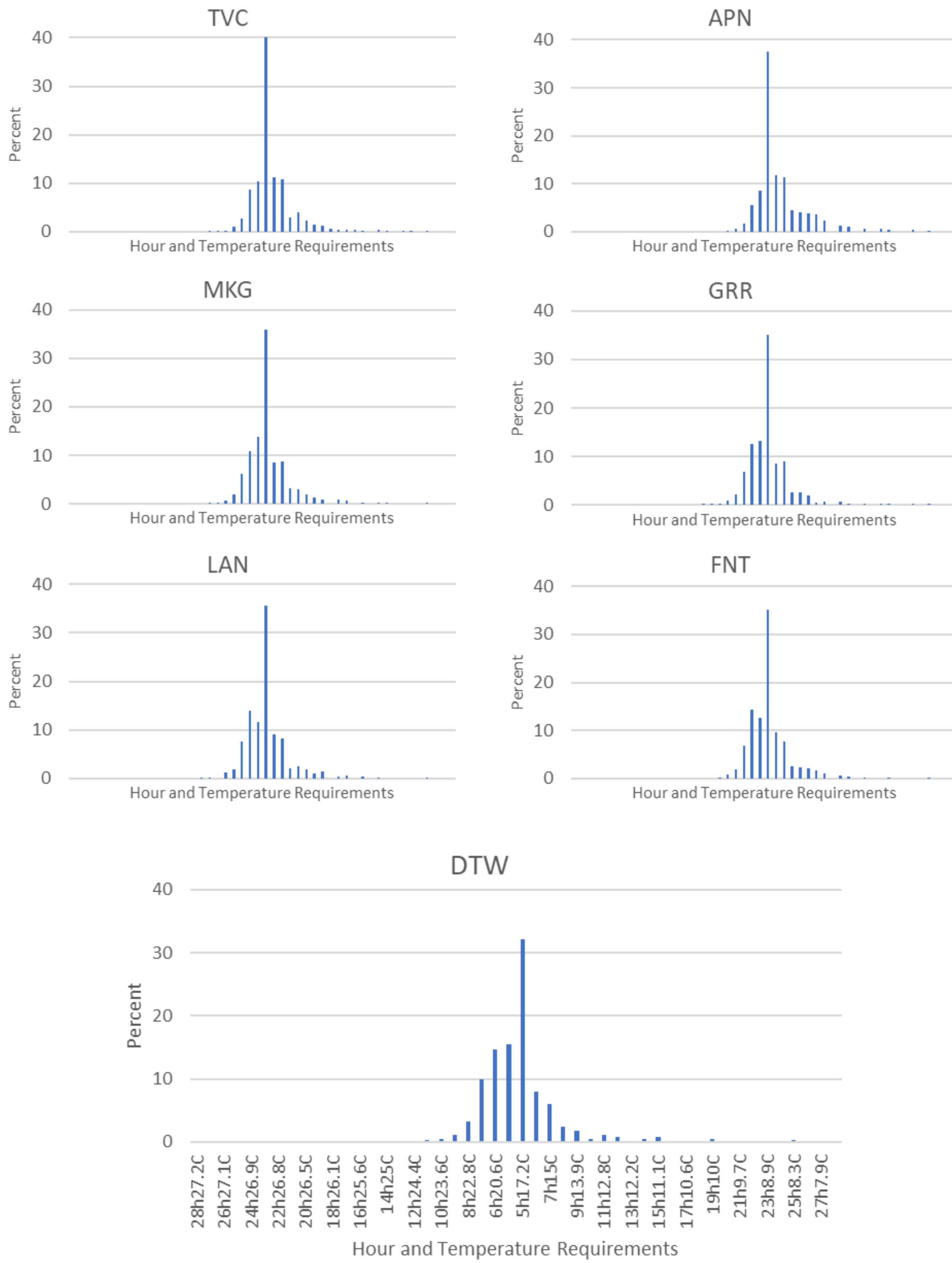

Figure 3.12 Frequency (in percent) of each type of temperature and relative humidity duration combination for periods of favorable environmental conditions for cherry leaf spot infection.

DISCUSSION

The study findings provide novel information about the spatial and temporal variations in the frequency of environmental conditions favorable for apple scab and cherry leaf spot infection in the Lower Peninsula of Michigan. The results also provide a baseline for evaluating future changes such as might be expected with climate change. Below the key findings of the analysis are integrated and suggestions are provided for disease monitoring and management. In addition, the limitations of the study are discussed, and avenues of future research are identified.

Implications for disease risk

The study highlights that frequent favorable environmental conditions contribute to the risk of apple scab in the Lower Peninsula of Michigan. The probability of experiencing at least 1 incidence of a favorable wetness duration/temperature combination in a given year is greater than 70% during the springtime vulnerable period for primary apple scab infection, including at locations within Michigan's main apple production regions. The frequency of favorable environmental conditions increases dramatically for the summertime secondary infection period with multiple (10 or more) spells of favorable environmental conditions expected each year. These findings highlight the need for careful monitoring for apple scab infection and control of an initial infection, as the frequent favorable environmental conditions for a secondary infection will make control more difficult later in the season. Monitoring is complicated by the large variability in the start of the vulnerable period for primary infection. Based on the earliest date during the 45-year (1973-2017) record that the GDU requirements were met for green tip (i.e., the start of the vulnerable period for primary scab infection), monitoring for favorable environmental conditions for apple scab infection within Michigan's fruit belt may need to begin as early as Julian day 29 at Grand Rapids, Julian day 52 at Muskegon, and Julian 53 at Traverse

City. Furthermore, producers need to carefully monitor temporal trends in the timing of the start of the primary vulnerable period. Although linear trends were insignificant for the stations located within the fruit belt, significant trends towards an earlier occurrence of the beginning of the vulnerable period for primary apple scab infection were found for several of the other stations included in the analysis (e.g., Detroit, Flint). The analysis also suggests that the length of the vulnerable period is increasing at these stations, while the linear trends for apple scab period length were insignificant for the fruit belt stations. For management, producers need to consider the characteristics of the favorable environmental conditions for apple scab, noting that most infection opportunities are of short wetness duration accompanied by moderate temperatures. Opportunities for infection typically have shorter wetness durations and higher temperatures during the secondary infection period compared to the primary infection period.

The findings for cherry leaf spot need to be interpreted more cautiously, as insufficient literature existed to confidently identify the plant growth stages associated with primary and secondary infection. Hence, a single infection period was used in the analysis, which likely overestimates the risk of infection based on favorable environmental conditions given that a primary infection is needed for secondary infection to occur. Nonetheless, the analysis provides useful information for disease management. Similar to apple scab infection, the intra-annual variability in the start of the vulnerable period is considerable. For the 3 stations closest to the cherry production region, the earliest start of the vulnerable period occurred on Julian day 81 (Grand Rapids), 82 (Muskegon), and 84 (Traverse City). Growers should consider monitoring for favorable environmental conditions as early as mid-March. Trends in the timing of the vulnerable period also need to be considered for cherry leaf spot as significant trends to an earlier start were found at Muskegon, located within Michigan's fruit belt but outside the major cherry production region, and at 2 stations outside of the fruit belt (Detroit and Flint). These 3 stations also had significant positive trends in the length of the vulnerable period, increasing the amount of time during which cherry is susceptible to leaf spot infection. Environmental conditions favorable for cherry leaf spot infection occur frequently during the vulnerable period, with 10 or more infection opportunities occurring every year at Grand Rapids and Muskegon and in 98% of all years at Traverse City. However, the probability of 25 or more instances of favorable environmental conditions in a given year was only 29% at Traverse City, which is located in the county where tart cherry production is highest, compared to over 70% for most of the other stations, including Muskegon and Grand Rapids. Even so, Traverse City has on average 21.3 spells of favorable environmental conditions for cherry leaf spot, highlighting the risk of this disease on production and the importance of monitoring the weather for favorable environmental conditions for infection. Like apple scab, the most common type of favorable environmental conditions are short wetness durations accompanied by moderate to high temperatures. For example, at Traverse City most infection opportunities fell between 6 hours of wetness duration and temperatures ≥20.6°C and 7 hours of wetness duration and temperatures ≥ 15°C types.

Contribution to apple scab and cherry leaf spot research

Beginning in the early 1920s, Mills (1944) began experiments to determine the relationship between leaf wetness duration, temperature, and apple scab infection since the disease was problematic for apple producers (MacHardy and Gadoury 1989). The study produced the well-known Mills criteria for predicting infection severity based on apple tree exposure to various durations of leaf wetness and temperatures (MacHardy and Gadoury 1989; Mills 1944). Many studies followed this one, which aimed to improve and expand prediction to a greater number of factors along with more detailed information about infection severity and effects based on phenology (MacHardy and Gadoury 1989; Jones et al. 1980; Hartman, Parisi, and Bautrais 1999; Schwabe, Jones, and Jonker 1984). While all these studies advanced knowledge and improved short-term prediction of infection periods, none of them addressed the climatological frequency of favorable conditions. Characterizing periods meeting the necessary conditions for apple scab infection in the Lower Peninsula of Michigan is crucial for industry members to understand the variability in apple scab risk and for long-term planning of preventive strategies against this disease.

Cherry leaf spot has long been a problem in Michigan, which is the top producer of Montmorency tart cherries, a variety that does not possess high resistance to cherry leaf spot (Iezzoni and Karle 1998). Although attempts were made in the early 1980s to develop cultivars that produced high quality fruit but with greater resistance to cherry leaf spot (Agriculture 2016; Iezzoni and Karle 1998), alternative varieties have not displaced Montmorency cherries as the most popular variety. Consequently, different strategies for decreasing leaf spot's influence have been employed including integrated pest management, frequent scouting, and weather monitoring (Edson et al. 1998). Growers frequently reference the model produced by Eisensmith and Jones (1981) that focuses on temperature requirements during particular wetness duration lengths (Edson et al. 1998; Eisensmith, S P; Jones 1981). The climatological analyses presented in this study provide a context for real-time monitoring, especially as pointed out by Edson et al. (1998) information about the long-term frequency of periods with favorable environmental conditions for infection in the Lower Peninsula of Michigan is scarce (Edson et al. 1998). Thus, the findings of this study fill a gap in integrated pest management for cherry leaf spot.

Limitations of the analysis

The analysis identifies periods of favorable environmental conditions for apple scab and cherry leaf spot infection based solely on relative humidity and temperature for 7 long-term stations in the Lower Peninsula of Michigan. This leads to some limitations in the application of the results. First, since leaf wetness is rarely measured, relative humidity greater than or equal to 85% was used as a surrogate for leaf wetness based on Sentelhas et al. (2008). Although the threshold of 85% was found to be appropriate for Elora, Ontario, which is nearby, leaf wetness information was not available for Michigan to evaluate the adequacy of this threshold for the Michigan stations. Additionally, weather stations tend to be located in urban or low-lying areas, compared to hilltops and slopes where fruit is commonly grown. Consequently, the relative humidity measurements and leaf wetness estimates from the weather stations may differ from the conditions in fruit orchards. Another restriction is the limited coverage of weather stations throughout the state. There were few stations with long-term records, decreasing spatial coverage, especially within the fruit belt, which is the focus of this study. In particular, a large data void exists in the southwestern Lower Peninsula, a major fruit-growing region.

For apple scab infection, the wetness and temperature thresholds used were those determined for light infection rather than moderate or heavy infection. If requirements for moderate or heavy infection had been used, fewer periods of favorable infection may have been found since these infection severity levels require less common, longer spells of wetness duration. Furthermore, the duration of wetness required for primary scab infection by ascospores is approximately 2.5 hours shorter than the duration for secondary scab infection by conidia, which was not accounted for in this analysis (MacHardy and Gadoury 1989).

For cherry leaf spot there was an absence of criteria for infection severity, so the temperature and wetness duration thresholds are not associated with light, moderate, or heavy infection, decreasing information about the level of expected risk. Additionally, data on growth stages and primary and secondary infection was not available, so the vulnerable period was not divided into primary and overall infection vulnerable periods. This may result in overestimation of frequency of periods of favorable environmental conditions since primary infection must occur for secondary infection to be possible.

Finally, the defined periods of favorable environmental conditions only include information about wetness duration and temperature. Other important environmental conditions that contribute to disease infection include wind and rain, which were not considered in this analysis. Additionally, the environment is only 1 vertex of the fundamental disease triangle. Whether infection will occur also depends on many other factors, such as the health and susceptibility of the host and the abundance and dispersal ability of the agent.

Future work

To address sparse spatial coverage in crucial fruit-growing areas, a long-term station in nearby northeast Indiana should be used to better estimate conditions in the southwest region of the Lower Peninsula. To assess the reliability of the model, the frequency of periods of favorable environmental conditions for infection should be compared to observed disease occurrence for both apple scab and cherry leaf spot at horticulture stations in the study area. This will help verify that times when disease occurred were flagged as periods of favorable environmental conditions for infection. A final improvement to the study would involve expanding the analysis to other perennial crops important in Michigan like grape or blueberry.

CONCLUSION

Previous research on the necessary conditions for apple scab and cherry leaf spot infection has focused on predictive disease models. While this information is helpful, it serves as a short-term warning system without providing a baseline for long-term planning, especially under a changing climate. This study is unique because it is one of the first to focus extensively on the environment vertex of the fundamental disease triangle, including providing a climatological analysis of the frequency of periods with favorable temperature and relative humidity conditions for these diseases. Knowing the historical relative humidity characteristics of areas near Michigan's major fruit production region is crucial to being prepared for infection prevention for the current and future climate. Focusing on the locations within or close to Michigan's fruit belt, some key climatological findings include:

- At Grand Rapids the vulnerable period for primary apple scab infection lasts on average 40 days from early March to late April. It is common (>70% probability) to experience at least 1 period of favorable environmental conditions for infection during the vulnerable period for primary infection. If primary infection occurs, an average of 34 separate periods of favorable environmental conditions can be expected during the secondary infection period. The average length of the vulnerable period at Grand Rapids for cherry leaf spot infection is 95 days, starting in late April and ending in early August. Around 70% of all years had at least 25 periods of favorable environmental conditions for infection, and the average number per year is 30.1.
- Apple growers near Muskegon should watch for primary scab from late March to early May. A high chance of at least 1 period of favorable environmental conditions enhances the risk of secondary infection. For the combined primary and secondary infection

vulnerable period, on average 33.8 separate infection opportunities can be expected. A statistically significant negative trend in the end date of the vulnerable period for primary apple scab infection suggests a shift in the timing of vulnerability to apple scab which needs to be carefully monitored. In addition, this location has experienced a shift to fewer periods with favorable environmental conditions, although the number of opportunities for infection remains large. Infection opportunities for cherry leaf spot are numerous at Muskegon with, on average, 29 separate opportunities per year. In addition, the length of the vulnerable period for cherry leaf spot has been increasing at this station.

- Although the probability at Traverse City of at least 1 occurrence of favorable environmental conditions for primary scab infection is like that of the other stations (i.e., 70%), the likelihood of 2 or more periods is much lower. Similarly, the average number of favorable periods for the combined primary and secondary periods is lower at Traverse City than elsewhere, although on average 21.3 separate periods can be expected.
- At all 3 stations favorable environmental conditions for disease infection are characterized by short wetness durations and moderate to high temperatures. Longer wetness durations with cooler temperatures are infrequent.

The next step to developing a more holistic estimation of periods of favorable infection is integrating the frequency of favorable temperature and relative humidity conditions with the many other factors that enable disease infection. This entails expanding the environmental conditions to include other weather variables that facilitate pathogen dispersal and affect leaf wetness duration. The spatial distribution of the host and the pathogen also must be considered to ensure that an interaction could occur between them, and, furthermore, the health and susceptibility of the host should be evaluated. Moreover, the amount of inoculum present and its ability to disperse and infect the host should be included to assess the likelihood of infection. With these additions, the 3 vertices of the disease triangle for apple scab and cherry leaf spot are addressed, improving our understanding of the risk for these diseases and providing more useful information for industry members.

CHAPTER 4: CONCLUSIONS

The purpose of this thesis is to understand how persistent high relative humidity events vary inter-annually, intra-annually, and spatially in the Lower Peninsula of Michigan, and the impacts of these events on various activities in the region. To achieve this, 2 steps were taken. First, using data from 1973-2017, a climatology of persistent relative humidity greater than or equal to 60% and relative humidity greater than or equal to 85% was created to serve as a reference for a range of industry members and as a baseline to compare to as climate changes. Secondly, this climatology was employed to assess potential impacts of persistent relative humidity spells greater than or equal to 85% on facilitating periods of favorable environmental conditions for the diseases apple scab and cherry leaf spot, both of which are major threats to fruit production in Michigan.

To complete analyses, hourly temperature and relative humidity data were obtained from ASOS and AWOS stations. 36 stations with at least 15 years of data and 7 long-term stations with at least 45 years of data, were included in the analysis. All 36 stations were used to find spatial variations in the probability of EHRH (≥85% relative humidity) and HRH (≥60% relative humidity) events, while the long-term stations were used to find maximum runs of EHRH and HRH spells and temporal trends in EHRH and HRH variation. The 45 long-term stations were also used for the apple scab and cherry leaf spot analysis. Crop disease analysis involved using relative humidity greater than or equal to 85% as a proxy for leaf wetness, and growing degree units to estimate crop phenology. The stages during which apple and cherry are susceptible to disease were associated with particular GDUs, which were accumulated for every year, noting the Julian days during which the crops were at a vulnerable stage. Once Julian day windows for vulnerable periods were obtained, the frequency of favorable temperature and moisture conditions was found. Analysis included finding averages of the start and end, along with the length of vulnerable periods, along with averages of the number of periods of favorable environmental conditions for the diseases. Linear regression was applied to the same data to determine whether significant trends exist in the start, end, and length of the vulnerable period or in the frequency of periods of favorable environmental conditions. Finally, the frequency of the different types of periods of favorable environmental conditions was found.

Main findings for the climatology of persistent EHRH and HRH events include:

- The low spatial variation in EHRH and HRH events shows that the probability of experiencing both types of spells is slightly higher in the central and north portions of the state.
- At least 1 short spell of EHRH (9 or 12 hours) and HRH (15 or 18 hours) occurred in 80% of the recorded years, while at least 1 long spell of EHRH (15 or 24 hours) and HRH (36 or 48 hours) occurred in a minimum of 30% of the years.
- Long-term trends in the frequency of EHRH and HRH events are variable, however for most stations and biweeks there appears to be a decreasing trend in the number of events.
- Runs of EHRH $\geq$ 33 hours and runs of HRH $\geq$ 114 hours have occurred at least once in all biweeks of the year during the 45-year record at all stations.

Main findings for implications of persistent relative humidity for apple scab and cherry leaf spot infection include:

- Trends in the vulnerable period for apple scab and cherry leaf spot show that the start and end dates are occurring earlier and the vulnerable period length is increasing, although significant trends were found at only a few stations.
- There is a high chance of experiencing periods of favorable environmental conditions for apple scab if a primary infection occurs. For example, at Grand Rapids and Muskegon on average 34 separate instances are expected each year.
- There is a lower chance of experiencing periods of favorable environmental conditions for cherry leaf spot than apple scab, but the frequency is still high (for example, annual averages of 30 and 29 occurrences at Grand Rapids and Muskegon, respectively).
- Traverse City has a substantially lower number of periods of favorable environmental conditions for both apple scab (average of 25 periods per year) and cherry leaf spot (average of 21 periods per year) compared to the other stations.
- The majority of favorable environmental conditions for either apple scab or cherry leaf spot infection are instances of short wetness duration with high temperatures.

Since persistent relative humidity affects both natural and anthropogenic processes, this climatology is important in demonstrating potential risk and provides a useful baseline of conditions against which to compare future changes. The crop disease analysis will be particularly beneficial to apple and cherry growers, who will gain information specific to crop and location about the inter-annual variability and long-term trends in favorable environmental conditions for disease infection.

This study is constrained by some limitations. For the climatology of high relative humidity, spatial coverage throughout the state is lacking, producing extensive areas of interpolated values for the probability of relative humidity events. There were few stations with at least 45 years of data, none of which were located in the northern central or southwest regions of the Lower Peninsula, leaving in a large gap. For the crop disease analysis, spatial coverage in the fruit belt was limited, resulting in absence of information for the major-fruit production region in southwest Michigan. Additionally, the data used for the analysis were from weather stations, which may not be representative of field conditions. In the same vein, the environmental analysis only includes temperature and moisture without considering other environmental factors. Focusing on the environmental vertex of the disease triangle misses important contributors to crop disease infection, in particular the susceptibility of the host and the abundance of the agent. Lastly, data about crop vulnerable stages, associated GDUs, and favorable environmental conditions for infection were difficult to find, restricting analysis to solely apple and cherry crops.

Many of the limitations are a consequence of data restrictions, however some improvements can be made to make this analysis more effective. This includes adding more relative humidity thresholds to the climatology, potentially considering low relative humidity events, as these also have impacts on human health. For assessing opportunities for crop disease, a long-term station outside of the state, but in close proximity (Indiana) should be added to cover the southwest portion of the Lower Peninsula. Another improvement involves including other weather variables like wind and rain to the environmental analysis, and integrating characteristics of the host and agent, which would make the evaluation of infection opportunity more complete. Implementing these changes and expanding the research to a greater number of crops would make the important findings of this thesis even more helpful to industry members in addition to providing information that would benefit the state's environment and its residents socially and economically.

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