THE LINKAGE BETWEEN CLIMATE CHANGE AND APPLE (*MALUS SPP.*) FRUIT PHENOPHASES IN THE CONTINENTAL UNITED STATES

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ABSTRACT: Apples constitute a large portion of the United States' horticulture industry, even more so in the Pacific Northwest and Atlantic Northeast regions. The fruiting phenophase of the apple (Malus spp.) can be affected by many temperature-dependent variables, including sun and heat exposure, pollinator emergence, and fungal severity and presence. However, while there is plenty of research on how the apple fruiting season can be affected, there is very little stated about the trend in the fruiting phenophase length over the previous decades. Therefore, we used data from the National Phenology Network to answer if and how the apple fruit phenophase length has been affected by increasing seasonal spring maximum temperatures over the last 15 years in the U.S.

Keywords: phenology, climate change, apples, Malus spp., fruit phenophase, temperature-dependent influences, Spring seasonal maximum temperatures, Pacific Northwest, Southwestern U.S., Central U.S., Southeastern U.S., Northeastern U.S.

Introduction

Phenology is the study of the seasonal changes and life-cycles of living things. In the case of plant phenology, the study of seasonal changes and phenophase start and end dates is important for many industries, up to and including agriculture and environmental preservation (Piao et al., 2019). Climate change can directly and indirectly affect plant phenology in numerous ways. Climatic factors are important for determining phenological stages of several fruit tree species, including apples (*Malus spp.*), during pre- and post-blooming periods. A fruit tree's environment can modify the fruit quality and productivity (Adnane et al., 2019). In the case of fruit crop production, the fruiting season phenophase may be shortened, lengthened, delayed, or advanced by one or multiple factors. Such factors include water availability, dry season length, seasonal temperatures (minimums and maximums), daily sun exposure, and the presence of fungal diseases and crop pests (Houston et al., 2018). However, while there is plenty of research on how the apple fruiting season can be affected, there is very little stated about the trend in the fruiting phenophase length over the previous decades. The purpose of this study is to measure the effect of seasonal temperature maximums on apple fruiting in the United States from the year 2009 onward.

Predicting when the dormancy period ends is important for growers; global warming could affect the suitability for some cultivars to survive or reproduce in any given location (Funes et al., 2015). Moreover, because profitable apple tree growth is dependent on the surrounding environment, more frequent extreme weather conditions in regions like Appalachian orchards are raising concerns amongst the agricultural and scientific communities (Veteto and Carlson, 2014). In addition to this, areas like the Himalayan regions of India believe that rising temperatures as a result of climate change are

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responsible for the decline in fruit size and overall quality (Basannagari et al., 2013). During the growing season, intense solar radiation and high temperatures produce problems with growth and fruit quality, reducing sustainability and profitability (Morales-Quintana et al., 2020).

In recent decades, apple (Malus spp.) fruit production has gone under threat from insufficient winter chill hours, sunburn, and low-quality yield in many regions around the world, including the Pacific Northwest (Houston et al., 2018). For a plant that is mainly suited to a cool climate within the late spring to early fall months, an increase in temperature could cause damage to the fruit and interrupt important phenophases (Lee et al., 2023). For example, sunburn symptoms in apples are directly caused by any increases in temperature and the amount of sunlight exposure during the growth season. There are three different types of sunburn associated with apple fruit, including sunburn necrosis, sunburn browning, and photooxidative sunburn. Orchards with severe cases of this visible browning on the skin can be forced to discard every fruit with major imperfections (Racsko et al., 2012). There is also an increasing risk of apple tree frost damage that is likely caused by climate change; this risk affects crop production due to the climatic sensitivity of apple trees and fruits. Apple trees are especially vulnerable to sudden frost days during their blossom period, which can lead to crop yield reduction (Pfleiderer et al., 2019).

Furthermore, the internal clock of apple trees that triggers blossom depends on various factors, such as the temperature history during winter and spring and the change in day length (Pfleiderer et al., 2019). Pollinator mismatch is one phenomenon that displays the indirect effects of climate change on fruit crop production. For instance, the spring emergence and flights of wild bees (*Bombus, Andrena, and Osmia spp.*) in England have been gradually shifting out-of-sync with peak apple (*Malus domestica)* flower bloom dates over the last few decades due to climate change (Wyver et al., 2023). The pollinator-plant mismatch phenomena has also been reported in the Pacific Northwest, as the end of bee hibernation and agricultural crop flowering dates are temperature dependent, but not quite as dependent on one another (Houston et al., 2018). Yet, in Norway and some other

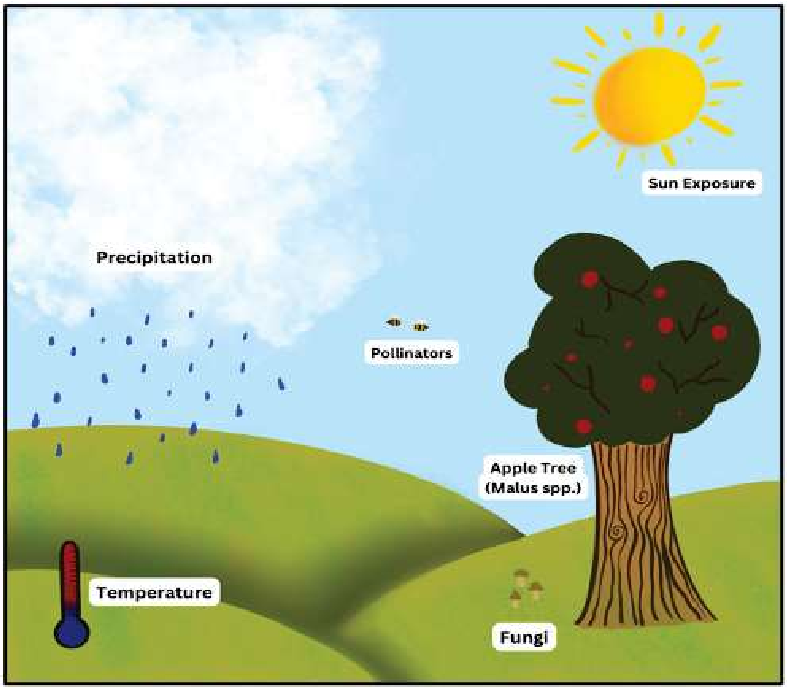

Figure 1: Environmental and climatic factors that affect apple fruit development and quality: sun exposure, precipitation, pollinators, fungi and pests, and temperature. Developed and created by F. Lambert and M. Juarez-Velazquez.

regions, climate change has had a positive effect by helping increase the amount of land that meets the heat requirement for apple growing by over 10% (Vuković et al., 2023).

The Literature Gap

Although apple fruit production plays a pivotal role in the agricultural industry around the world, there is very little scholarly literature on recent trends in the fruit phenophase length. Instead, most of the recent and current research focuses on the final product (the harvested apple) and how future cultivars may overcome the emerging growth and quality issues. As seen in a study conducted in Israel, the common "Golden Delicious" apple (*Malus domestica* Borkh.) responds to high environmental temperatures—also referred to as "heat stress"— by increasing the expression of expansin genes, which control the size (but not the number) of apple cells produced during early fruit development (Flaishman et al., 2015). Another factor caused by heat stress is a fungus called bitter rot; (Martin et al. 2021) identified the causal link between higher environmental temperatures and a larger presence of the fungus in apple fruit. Fungus monitoring can help with climate change in the growing process of apple trees, to be replaced for improvements and accessibility for agriculture (Čirjak et al., 2022).

To clarify, there is no doubt that this form of research is important for the future of the global apple industry. Such research includes investigations of the correlation between initiation and formation in *Malus spp*. and bloom time by identifying the floral development rates and stages before the life cycle of apple tree stops (Goeckeritz et al., 2023). However, studies like these fail to observe any meaningful trends in the *Malus* **fruiting** phenophase length and its relation to the changing climate and global warming. In order to resolve said gap in the literature, this report aims to shorten it by assessing the observational data and data visualizations provided by the United States of America National Phenology Network (USA-NPN) database. While the NPN data will inherently be limited by its source (citizen observers) and region (the United States), it will still provide useful information for analysis and conclusions of broader, global trends.

In summary, the literature explains how global warming directly and indirectly affects apple (*Malus spp.*) fruiting through the consequences of sunburn, heat stress, growing insufficient chill hours, promoting larger fungal and pest populations, introducing crop-pollinator mismatch, and changing the amount of arable land in regions around the world. Therefore, this article will add to the narrative, guided by the question: **"What – if any – is the relationship between maximum spring seasonal temperatures and the onset day of the fruiting phenophase of all apple varieties (*Malus spp.*) grown in the United States?"**

Methods and Materials

Data Summary

The data for this study were collected from the United States of America National Phenology Network (USA-NPN) via two subsequent sources: Nature's Notebook and the National Ecological Observatory Network (NEON). The data provided by the *Nature's Notebook* program are collected by citizen observers, who can range from university students to non-academics to legitimate phenology experts. Data collected from "certified observers" (participants who completed the *Nature's Notebook* orientation and training program) are deemed the most reliable. The data provided by the NEON are collected and shared by experts in the field(s) of phenology and/or ecology (USA-NPN, 2023).

In order to gather the required data for analysis, this study utilized the NPN Phenology Observation Portal. The data were downloaded after setting the following parameters: "status and intensity" data, 2009-2023, one of five

U.S. regions chosen (see: **Figure 2**), *Malus spp*. (apples), "fruits," no partner groups, *Nature's Notebook* and NEON 2013-Present. The "Output Fields" page was also utilized: "Species category," "Phenophase category," and "Phenophase name" were selected under the "Optional Fields" tab; "Tmax Spring" was selected under the "Climate Data Fields" tab. The latter was most important, as the climate data relates most to answering the proposed research question.

PNW (3): Washington, Oregon, Idaho

SW (6): California, Nevada, Utah, Arizona, New Mexico, Colorado

Central (13): Montana, Wyoming, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Minnesota, Iowa, Missouri, Arkansas, Louisiana

SE (10): Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, Tennessee, Kentucky, Virginia, and West Virginia.

NE (16): Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New Jersey, New York, Pennsylvania, Delaware, Maryland, Ohio, Indiana, Illinois, Michigan, Wisconsin

Figure 2: A political map of the U.S. detailing how the states (excluding Alaska and Hawaii) were divided into the five regions (Pacific Northwest (PNW), Southwest (SW), Central, Southeast (SE), and Northeast (NE)).

Because the NPN data were downloaded five times, each varying by region of focus, the data produced varying entry totals. The Pacific Northwest data contained 546 observations to download. The Southwest data contained approximately 2,500 observations to download. The Central U.S. data contained approximately 2,000 observations to download. The Southeast data contained 132 observations to download. The Northeast data contained approximately 10,700 observations to download. Added together, the NPN provided roughly 15,900 apple fruit phenophase observations over the last 15 years in the U.S. to download. However, the total number of data points used was considerably fewer than the amount downloaded, especially once unnecessary data points were filtered out (see: Analytical Approaches).

Analytical Approaches

For a detailed instruction of the data filtration and assortment, see the Appendix. A scatter plot and regression analysis were used in order to answer the proposed question, which asks about a hypothetical— and possibly causal— relationship between two variables: spring maximum temperatures and apple fruit onset days. A trendline, its equation, and related R-squared value were calculated via Microsoft Excel programming and included on each of the generated graphs. The slope of the line of best fit for each graph was used to evaluate how much the apple fruit onset day changes with rising spring maximum temperatures; i.e. a positive slope equates to later onset and a negative slope equates to earlier onset. The R-squared values

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were utilized to evaluate how much of the onset day variation is actually due to spring maximum temperatures. Most importantly, the R-squared values allowed for limitation claims during results interpretation.

Results

Pacific Northwest (PNW)

In the U.S. Pacific Northwest (PNW) over the last 15 years, for every 1° Celsius increase in maximum spring temperature, the apple fruit phenophase onset day happened approximately two days later (**Figure 3**). This claim is based on the slope of the linear trendline for the PNW data, which shows a small positive correlation between regional T` spring and fruit onset day of year. However, it is worth noting that the R-squared value for the line of best fit is .0007; this value means that the spring maximum temperatures explain 0.07% of the apple fruit onset day variation. Obviously, this R-squared value is extremely poor, suggesting that the relationship between the regional Tmax spring and apple fruit onset day is not linear (Figure 3). This non-linear relationship can also be easily observed by the three densely vertical groupings of data points at around temperatures 16.25, 16.75, and 17.5 degrees Celsius (**Figure 3**). These vertical groupings of the data also suggest that the relationship is not only non-linear, but may also not exist at all in the Pacific Northwest region. Alternatively, the vertical lines in the data could possibly be due to different varieties of apple fruit forming at the same temperature threshold but on different days, which are indistinguishable when all are recorded under "*Malus spp*." in the NPN.

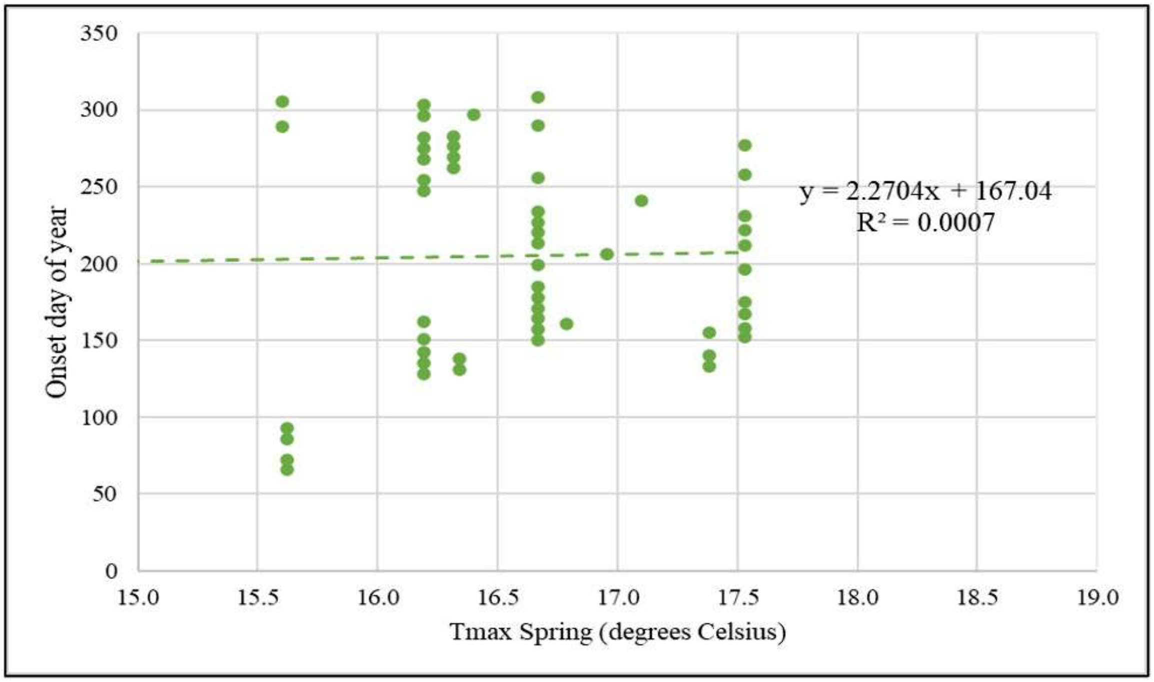

Figure 3: A scatter plot with regression analysis for spring temperature effects on Malus spp. fruit onset in the Pacific Northwest over the last 15 years. The scatter plot trendline is linearly positive, with a very gradual slope.

Southwestern U.S.

Figure 4 shows the correlation between the maximum spring temperatures and the onset day of the year in the Southwest region of the United States over the last 15 years. The trendline formed represents a negative slope of around 10, meaning that for every one-degree Celsius increase in maximum spring temperature, the apple fruit phenophase onset day occurred approximately 10 days earlier. It's worth noting that while there is a negative correlation between regional Tmax spring and fruit onset day of the year, the R2 value of the trendline is only 0.0888. This indicates that just 8.88% of the variation in the apple fruit onset day can be explained by spring maximum temperatures. Additionally, there are clusters of vertical groupings between temperatures of 22 to 23 degrees Celsius, indicating a lack of correlation. The vertical lines in the data could also highlight different varieties of apple fruit forming at the same temperature threshold at different times in the year. Because this NPN limitation makes the individual varieties of apple fruit indistinguishable, the correlation between fruit onset and spring temperatures remains unclear.

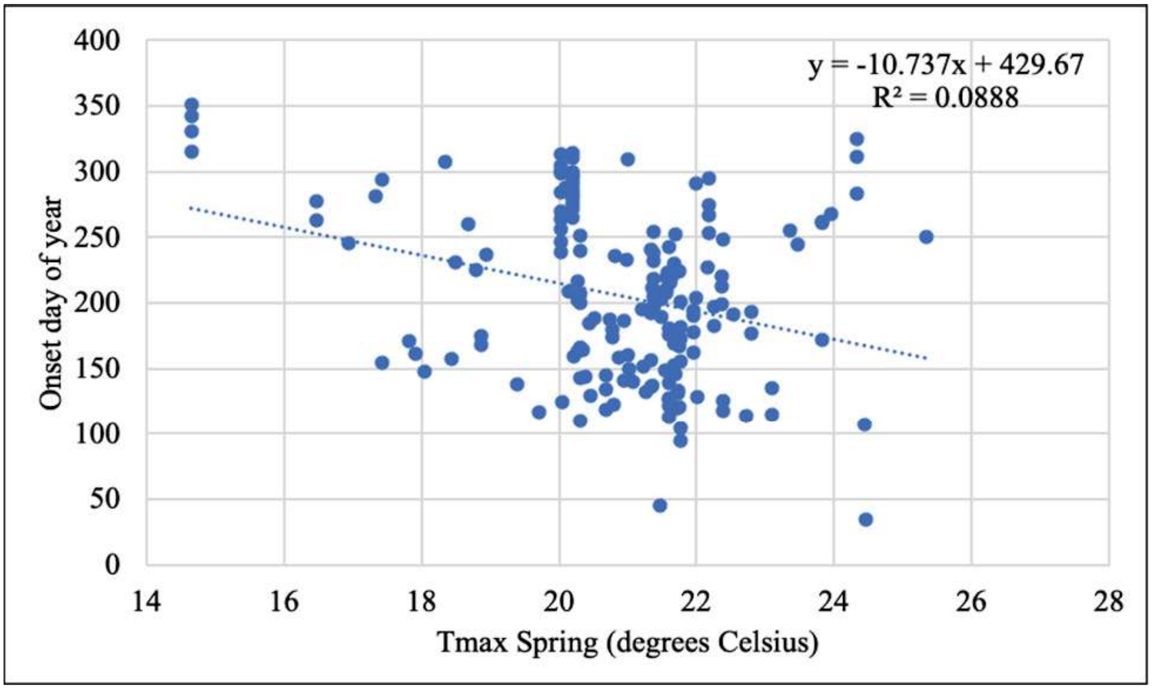

Figure 4: A scatter plot with regression analysis for spring temperature effects on Malus spp. fruit onset in the Southwestern U.S. over the last 15 years. The scatter plot trendline is linearly negative, with a relatively steep slope.

Central U.S.

Figure 5 depicts the correlation between the maximum Spring temperatures and the onset day of the year over the last 15 years in the central region of the United States. The trendline formed has a positive slope of about 17 (Figure 5). This means that for every 1° Celsius increase in maximum spring temperature, the apple fruit phenophase onset day happened approximately 17 days later. While there is a positive correlation between regional Tmax

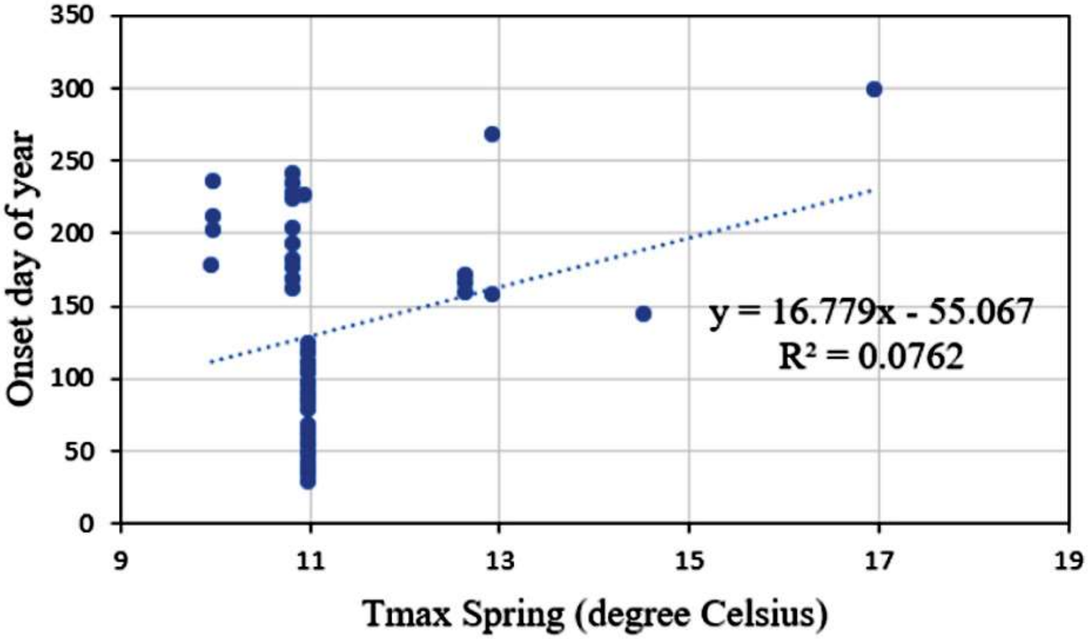

Figure 5: A scatter plot with regression analysis for spring temperature effects on Malus spp. fruit onset in the Central U.S. over the last 15 years. The scatter plot trendline is linearly positive, with a steep slope.

spring and fruit onset day of year, it is important to acknowledge that the R² value of the trendline is 0.0762 (**Figure 5**). This means that the spring maximum temperatures explain only 7.62% of the apple fruit onset day variation. Furthermore, much of the data is clustered in vertical groupings between temperatures 9 and 11 degrees Celsius, which indicates a lack of correlation (Figure 5). Alternatively, the vertical lines in the data could represent different varieties of apple fruit forming on different days at the same temperature threshold, which are indistinguishable in the NPN.

Southeastern U.S.

In the Southeast over the last 15 years, for every one degree Celsius increase in Spring temperature, apple phenophase happened 9 days earlier (**Figure 6**). The trendline above represents a negative slope nine between the regional Tmax Spring and fruit onset day of the year. The R2 value for this trendline is 0.1195, which means the correlation between apple fruiting and spring maximum temperature translates to 11.95%. The relationship between temperature and fruit onset day is barely linear; observations can be made by the two groups between 20 and 21 Celsius and 23 and 24 Celsius, indicating the lack of correlation (**Figure 6**).

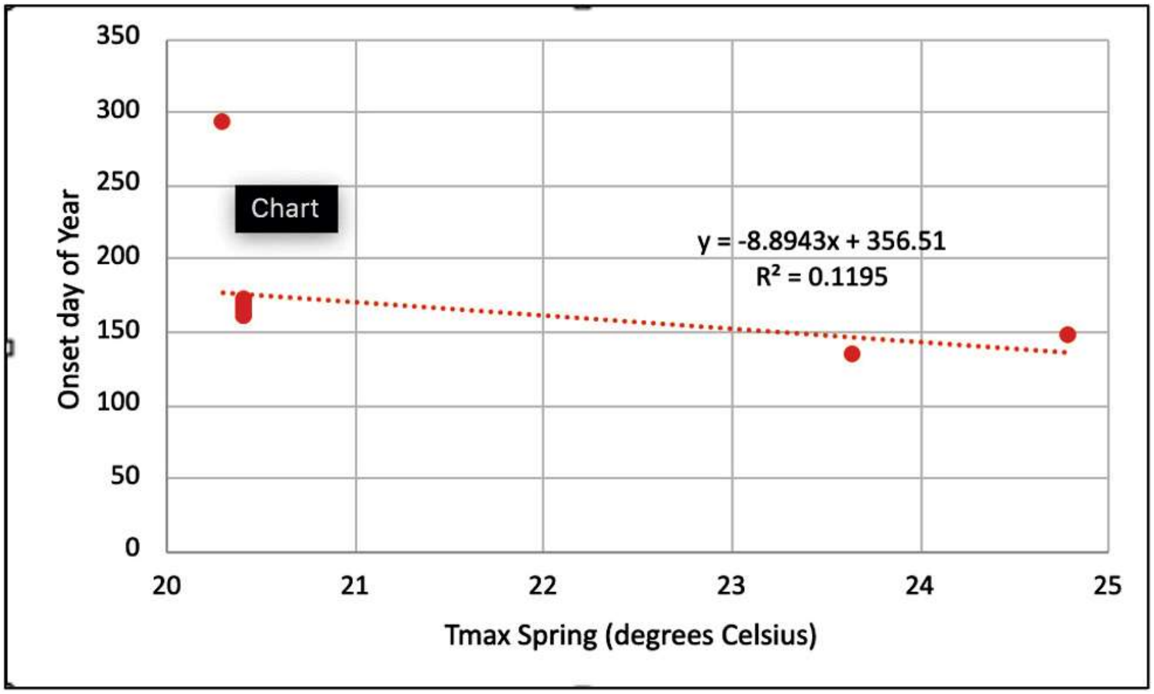

Figure 6: A scatter plot with regression analysis for spring temperature effects on Malus spp. fruit onset in the Southeastern U.S. over the last 15 years. The scatter plot trendline is linearly negative, with a somewhat steep slope.

Northeastern U.S.

Over the last 15 years in the Northeast there has been a correlation between the fruiting onset day of year and Tmax spring temperature (degrees celsius). The negative trendline implies that the apple tree phenophase onset day had occurred approximately 16 days earlier in the Northeast. The R2 value is 0.0409, which translates to 4.09% of the apple onset data being explained by temperature. This also means that the variation is caused by other factors than temperature. Non-linear data can be seen between 12-16 □, showing the lack of correlation between the onset day of year and spring maximum temperatures (**Figure** 7). Alternatively, the clustering in the data could be due to different apple varieties requiring the same temperature threshold but emerging on different days, which is indistinguishable when all are recorded under "*Malus spp*." in the NPN.

Results Summary

Based on the lines of best fit for each region, changes in the apple fruit phenophase onset differ widely across the U.S. for the last 15 years. Although the lines of best fit are limited and cannot allow for broad or definitive claims, they still provide a somewhat helpful insight into which regions appear to have experienced the greatest changes (**Table 1**). Specifically, apples grown in the Central and Northeastern U.S. regions display the greatest sensitivity to temperature, with the former trending positively and the later trending negatively. Additionally, looking at the R-squared values, the Southeast appears to have the "best" trendline; that is, the trendline explains that 11.95% of the onset day variation is due to temperature. Contrastly, the PNW data has the "worst" trendline, with only 0.07% of the onset day variation due to temperature (**Table 1**).

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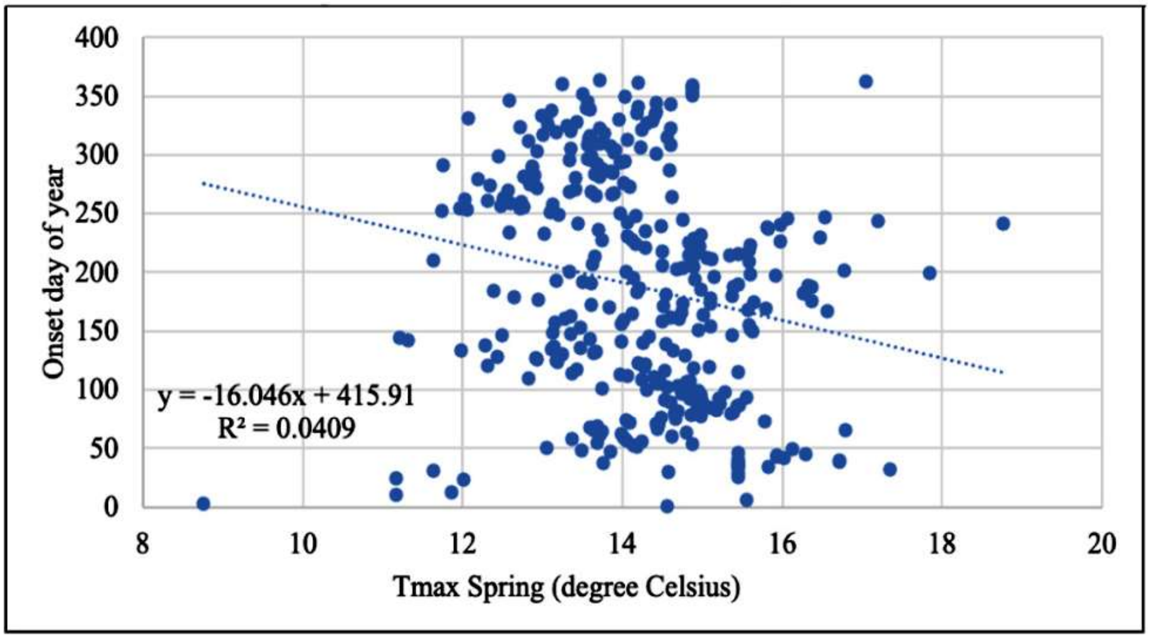

Figure 7: A scatter plot with regression analysis for spring temperature effects on Malus spp. fruit onset in the Northeastern U.S. over the last 15 years. The scatter plot trendline is linearly negative, with a steep *slope.*

Table 1: Summary of "Results" (trendline equations, slope analysis, and R-squared values).

U.S. Region	Linear trendline equation	Trendline slope meaning: for every 1°C increase in Tmax spring, the annual apple fruit onset happens…	R-squared (% data variation explained by trendline)
PNW	$y = 2.2704x + 167.04$	~2 days later	0.0007 (0.07%)
SW	$y = -10.737x + 429.67$	~11 days earlier	0.0888 (8.88%)
Central	$y = 16.779x - 55.067$	~17 days later	0.0762 (7.62%)
SE	$y = -8.8943x + 356.51$	~9 days earlier	0.1195 (11.95%)
NE	$y = -16.046x + 415.91$	~16 days earlier	0.0409 (4.09%)

Discussion

As stated previously, the research question we set out to answer was, "What– if any– is the relationship between maximum spring seasonal temperatures and the onset day of the fruiting phenophase of all apple varieties (*Malus spp.*) grown in the United States?" Based on the data we collected and analyzed from the NPN, our proposed answer is: there is no significant or causal relationship between apple (*Malus spp.*) fruit onset day and spring maximum

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temperatures over the last 15 years in any region of the continental United States. Although the data from some regions– like the Central and Northeastern U.S. – displayed a steep change in fruit onset day with increasing spring temperatures, the regression analyses of these datasets suggested that the spring temperatures were very unlikely to explain the onset day variation. Because these poor correlations were observed in all regions, we are inclined to state there is no relationship between apple fruit onset day and any trends in spring maximum temperatures over the last 15 years. More importantly, the phenological data we collected were for *Malus spp*., which encompasses all varieties of apple fruit. Alternatively, if we had chosen *Malus domestica* (common "Golden Delicious" apple) or some other variety, we may have observed clear trends in fruit onset day based on temperature. Because of this limitation in the NPN options, our data collection exhibits all trends in apple varieties, which amounts to no overall trends.

Now, with our own research conducted, the highlighted gap in the Malus spp. research literature is understandable but still unfortunate. Most of the *Malus spp*. fruit research we gathered reported temperature-adjacent factors that can affect apple fruit growth (i.e. sun exposure, pollinator emergence, pests, and/or fungi presence) (Čirjak et al., 2022; Houston et al., 2018; Martin et al., 2021; Morales-Quintana et al., 2020; Racsko et al., 2012; Wyver et al., 2023). There were very few results that found a direct relation between environmental temperature itself and the *Malus spp*. fruiting process. As climate change continues to affect global temperatures and the Earth's biosphere, it is important to consistently study *Malus spp*. fruit because, while there may be no causal relationship now, temperature could become a major factor in the fruiting phenophase. As we have learned from the NPN *Nature's Notebook* (2023), it is just as important to report a "no" as it is to report a "yes" to a phenophase because it can help narrow when that switch happened; the same is true for climate factors related to a plant's phenophase.

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We did not use AI for writing or image generation anywhere throughout this report.

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