APPLICATION OF A HIGH-RESOLUTION CLIMATE MODEL DATASET TO ASSESS HABITAT SUITABILITY FOR SPOTTED WING DROSOPHILA IN SOUTHWEST IDAHO

by

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The following individuals read and discussed the thesis submitted by student Elizabeth Padian, and they evaluated her presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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DEDICATION

This work is dedicated to my late father whose enthusiasm for the outdoors inspired my love of the earth sciences.

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Thank you to my committee members and members of the LEAF team who helped me through this entire process.

ABSTRACT

As global climate change continues to produce large deviations from the normals of the 19th and 20th centuries, the agricultural sector will need to adapt to these changes in order to maintain yields and feed the global population. Crop selections, yield amounts, and pest management techniques may need to be adjusted to adapt. The Spotted Wing Drosophila (SWD) is a small fruit fly-like bug that can infest berries and stone fruit crops by burrowing into the fruit (at most points in the fruit's lifecycle) and laying its eggs. These eggs will hatch and the larvae will burrow back out of the fruit. The fruit is then rendered unsellable through USDA markets. The duration of time for a generation of SWD to go from hatching to egg-laying is usually around two weeks, so several generations are likely in a growing season with suitable weather and climate conditions. SWD were first found in traps in west-central Idaho in 2012, after its range had been spreading through the broader Pacific Northwest for several years. Since then, it has been found in insect traps across the agricultural region in Southwest Idaho. If climate change patterns continue with higher temperatures for longer periods of the growing season, and an increase in the growing season length in general, this will provide more time and opportunity for SWD reproduction. This may manifest as the SWD having more suitable places to live and reproduce, and/or the SWD reproducing more generations per growing season in places that it has already been found. If there is an increase in acreage that is growing berries and stone fruits, this may also increase the presence of the SWD. Climate data, particularly the daily high and low temperatures can be used to assess the suitability of locations that the SWD has access to. Growing Degree Day values that are derived from daily high and low temperatures provide a proxy for suitable temperature ranges in which the SWD would be active and breeding. This study uses data from a high spatio-temporal resolution long term simulation with the Weather Research and Forecasting (WRF) model together with Oregon State University's Integrated Pest Management's (OPM) model for the SWD behavior expectations to estimate the SWD behavior within the local climate of Southwest Idaho. This study looks at changes in the cumulative growing degree day over the years 1987-2016, and how these changes could impact the expected breeding patterns of the SWD. With the growing season length increasing, the potential for a 6th generation now exists in the latter half of the 30 year span. Additionally, the amount of locations that reach degree day thresholds to support five full generations of SWD has nearly doubled in 30 years. This suggests that the SWD can become a much more of a problem for the agricultural sector in Southwest Idaho in the future.

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LIST OF ABBREVIATIONS

IPCC	International Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
USDA	United States Department of Agriculture
ISDA	Idaho State Department of Agriculture
NASS	National Agricultural Statistics Service
GDD	Growing Degree Day
EPA	Environmental Protection Agency
SWD	Spotted Wing Drosophila
SRV	Snake River Valley
WRF	Weather Research and Forecasting
OIPMC	Oregon Integrated Pest Management Center
DOY	Day-Of-Year

CHAPTER ONE: INTRODUCTION

Climate change is a broad term that is used to describe long term changes in weather patterns and temperatures, which in the last century has been largely attributed to human activity (United Nations, n.d). Humans must study, understand, and adapt to climate change in order to survive and thrive. This requires investments, but the cost of inaction is far greater (United Nations, n.d). Agriculture and the science of growing food for human consumption are intimately intertwined with weather and climate. Within agriculture science exists an overlap of entomology when looking at pest insects and their impact to crops. The following discussion will seek to quantify why agriculture science is important, how climate change will impact it at a global and regional scale, and dive deeper into a particular pest that is hypothesized to become more prolific in southwest Idaho.

In November of 2022, the world's population surpassed 8 billion people (United Nations, n.d). It is estimated that by the middle of the 21st century, the world's population will top out at around 9 billion people (Godfray et al., 2010). In order to feed this population, global agricultural production will need to double to meet the demand (Tilman et al., 2011). Increasing yield, rather than clearing more land for production, is the best way to meet this demand (Godfray et el., 2010). More attention needs to be paid not only to the way climate change will impact how we grow food, but also the ways in which pest behavior will change and potentially threaten yields.

While global food supply has become a large industry and has improved in efficiency and technology over the centuries, it still remains vulnerable to changes in temperature, precipitation and anomalous events. An increase in global temperatures of 1.5C, compared to the pre-industrial revolution, is expected to occur by 2040 (IPCC, 2022). The impacts of this threshold being surpassed will negatively impact human health and morbidity, all ecosystems, and global economies. North America is expected to experience "risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access." (IPCC, 2022). While the IPCC monitors broad patterns and impacts at a global scale, the measurable effect in specific regions in specific climate regimes can also be explored.

Similarly to global scale expected changes, Idaho is expected to experience an increase in temperatures, more variable precipitation, and a decreasing snowpack in the future (Abatzoglou et al., 2021). These changes will affect the types of crops that will be best suited for Idaho, and the yields of those crops (Abatzoglou et al., 2021). Stressed plants can attract pests and diseases, so a shift to more tolerant crops or species may be necessary to ward off drought stress, as water availability changes.

Climate Change's Influence on Agricultural Pests

Insects are considered to be poikilotherms, which mean that the temperature of their body is dependent on the environmental temperature, rather than the insect maintaining a consistent body temperature, like mammals. Changes in temperature have the largest impact in changing the way insect pests reproduce, survive, and spread (Kocmánková et al., 2010). For example, the warming climate of Europe has led to the northward migration of the oak processionary moth mainly because of the decrease in late frost events in the spring. (FAO). However, there is some mixed hypothesis of how a particular insect will respond to climate/temperature change. While most insects will increase their impact severity on crops, some may have a reduced ability to exist and reproduce (like in warm climates that warm further) or a contraction of suitable habitat (Lehmann et al., 2020). Potentially, some species may go extinct altogether (Skendžić, n.d). The general theory, though, is that global warming will expand suitable habitat, increase the number of insects that survive overwinter, and increase the risk of new invasive species entering new locations (Skendžić, n.d).

Climate change is also expected to change precipitation patterns. In many places, this will look like a decrease in frequency but an increase in intensity. This leads to more instances of droughts and floods. In some cases, smaller insect pests and their larvae can simply be washed away in heavy rains, or be negatively impacted by stagnant water (Shrestha, 2019). When a drought is occurring, herbivorous insects may enjoy a more suitable environment for reproduction, and/or drought stressed plants may attract more insects (Skendžić, n.d). For example, the Bee Mite and Black Currant Gall Mite are both listed as invasive species in Idaho (Idaho State Department of Agriculture, n.d.). These would be more susceptible to being washed away in heavy rains because they are relatively small. On the other hand, the Brown Marmorated Stink Bug (another invasive species to Idaho) hibernates during the fall and winter (Idaho State Department of Agriculture, n.d.). A warmer winter would create a more favorable environment for more of these insects to survive.

Temperature and Precipitation in Idaho

Southwest Idaho has a semi-arid climate, with variations between valley floors and the mountainous areas (Kottek et al, 2006). The National Oceanic and Atmospheric Administration (NOAA) has the Boise, Idaho airport as the designated climate site in the area. The average May to September temperature at Boise has been increasing since 1900 (Figure 1). Table 1 shows the statistics for these data. Over the 1987 to 2017 time frame, the daily maximum temperature’s rate of increase is 29% larger than daily minimum temperatures in the southwestern Idaho agricultural region (Becker, 2020). There is evidence to suggest that the growing season is increasing, even when looking at slightly different definitions of a “growing season”. One study looked at the growing season as “the number of days between the last day in spring with overnight low temperatures below 0°C and the first autumn day with low temperatures below 0°C" (Klos et al., 2015). It was shown that the growing season length has increased by 3.9 days per decade during 1975-2010, which is an increase of about 12 days total (Klos et al., 2015). In another study, the growing season was defined as the span between last frost in the spring and first frost in the fall, and it has increased by about 8 days from 1987-2016 (Becker, 2020).. Current climate modeling suggests that these trends of a longer growing season in higher latitudes in Idaho will continue (Abatzoglou et al., 2021).

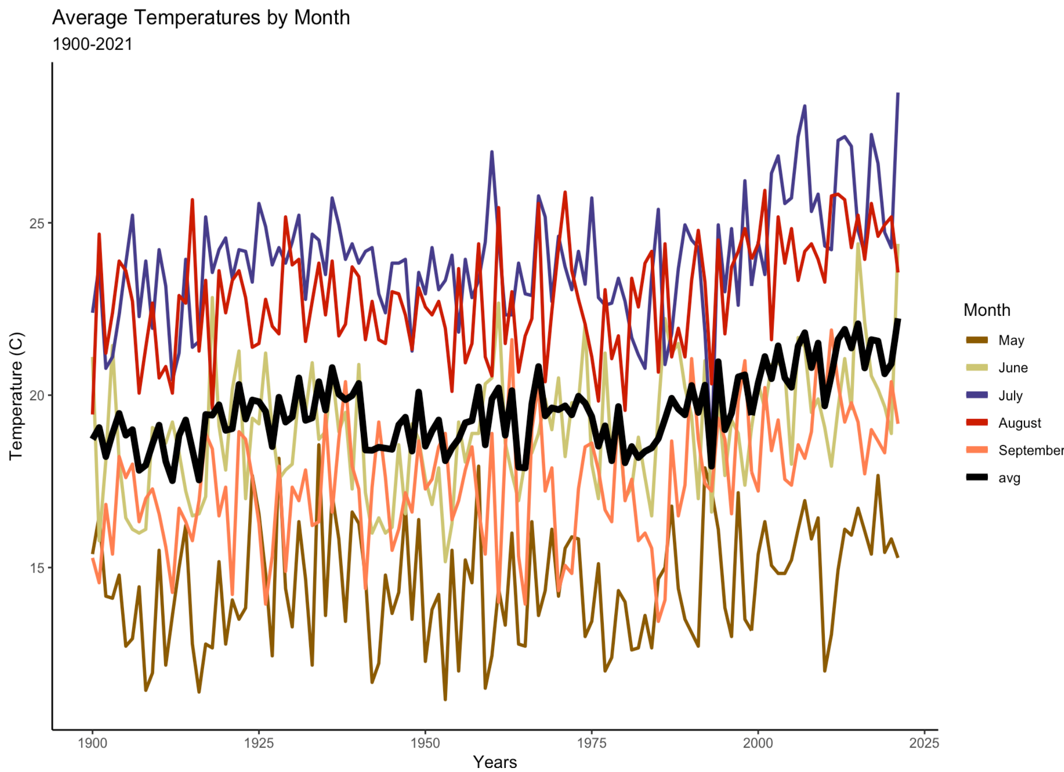

Figure 1 Average Temperatures by Month for Boise, ID

Boise, Idaho average temperature for each month May-September and an average from 1900 to 2021 in black. (Data Source: NOAA-NWS)

Table 1 Statistics for the Average Temperatures at Boise, ID 1900-2021

	Min Value C	Max Value C	1900-2021 Slope	p-value	1980-2021 Slope	p-value	Standard Deviation
May	11	19	0.01	<0.001	0.053	<0.001	1.7
June	15	24	0.018	<0.001	0.066	<0.001	1.8
July	18	29	0.018	<0.001	0.122	<0.001	1.7
August	19	26	0.018	<0.001	0.074	<0.001	1.6
September	13	22	0.021	<0.001	0.085	<0.001	1.8
Average	18	22	0.017	<0.001	0.08	<0.001	1.1

Trends for maximum and minimum temperatures during May through September exist as well. Figures 2 and 3 show the average maximum and minimum temperatures (respectively) for each month and averaged across those months. While some trend lines have a lower slope value than others, each of the months, and the period averages all show an increasing trend across both the maximum and minimum temperatures.

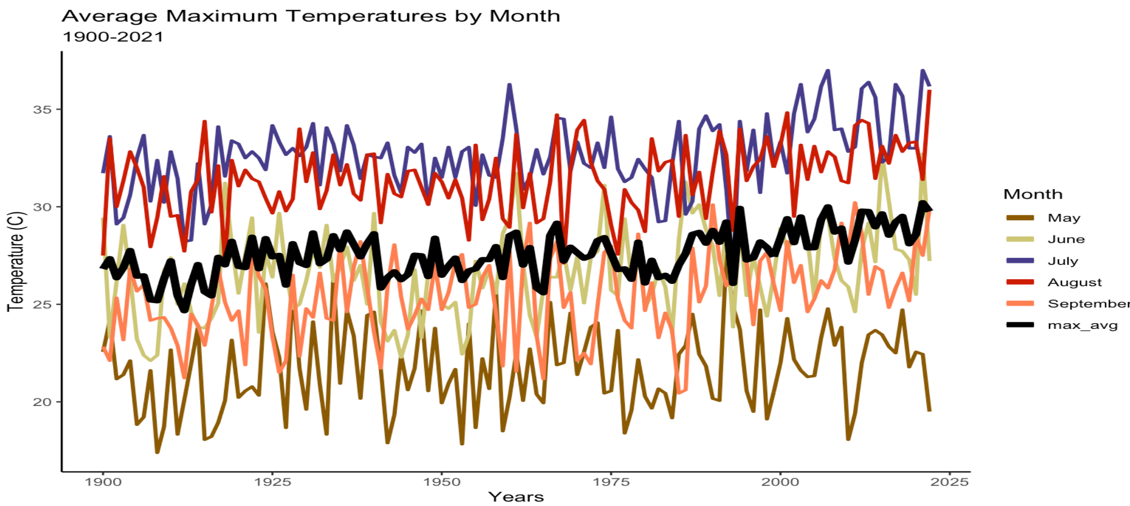

Figure 2 Average Maximum Temperatures by Month for Boise, ID

Average maximum temperature for each month May-September and an average from 1900 to 2021 in black. (Data Source: NOAA-NWS)

Table 2 Statistics for the Average Max Temperatures at Boise, ID 1900-2021

	Min Value C	Max Value C	1900-2021 Slope	p-value	1980-2021 Slope	p-value	Standard Deviation
May	17	28	0.012	<0.001	0.036	<0.001	2.2
June	22	33	0.022	<0.001	0.045	<0.001	2.3
July	26	37	0.021	<0.001	0.103	<0.001	1.9
August	27	35	0.017	<0.001	0.041	<0.001	1.8
September	20	30	0.022	<0.001	0.065	<0.001	2.1
Average	25	30	0.019	<0.001	0.058	<0.001	1.2

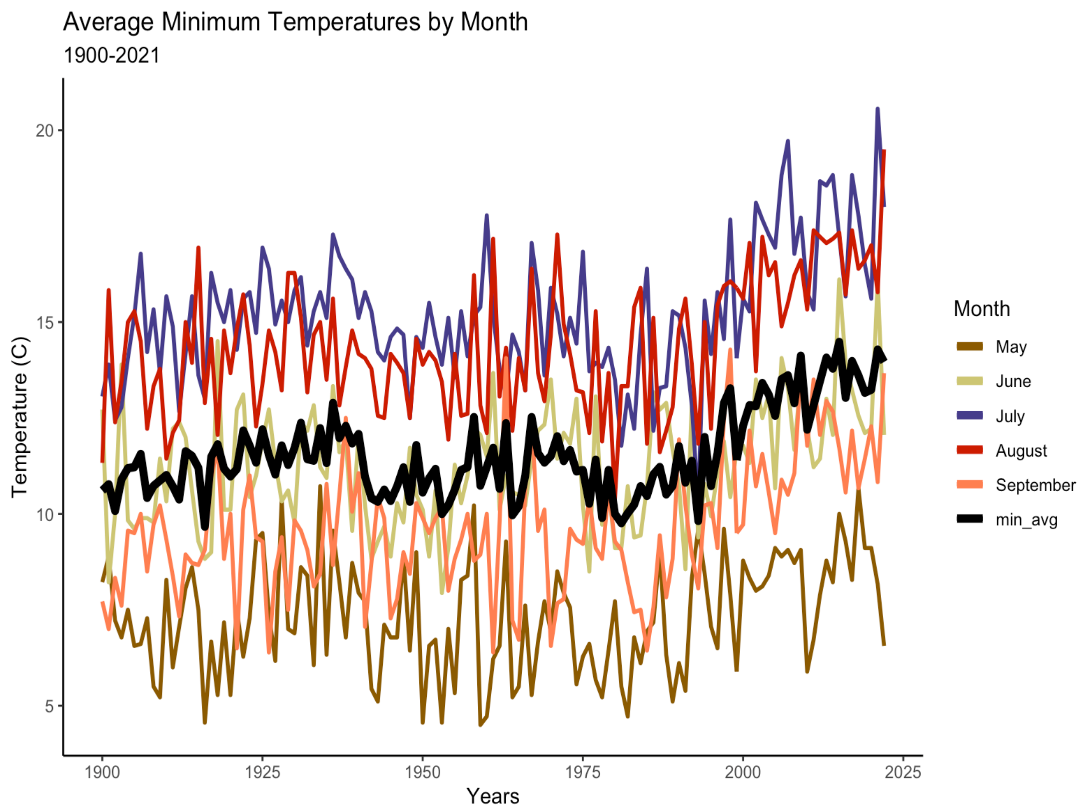

Figure 3 **Average Minimum Temperatures by Month for Boise, ID**

Average minimum temperature for each month May-September and an average from 1900 to 2021 in black. (Data Source: NOAA-NWS)

Table 3 **Statistics for the Average Min Temperatures at Boise, ID 1900-2021**

	Min Value C	Max Value C	1900-2021 Slope	p-value	1980-2021 Slope	p-value	Standard Deviation
May	4.5	11	0.0088	<0.001	0.07	<0.001	1.5
June	7.9	16	0.0146	<0.001	0.088	<0.001	1.6
July	10.2	21	0.0164	<0.001	0.141	<0.001	1.7
August	10.4	17	0.0191	<0.001	0.108	<0.001	1.7
September	6.4	14	0.0203	<0.001	0.105	<0.001	1.7
Average	9.7	14	0.0158	<0.001	0.102	<0.001	1.1

Individual precipitation observation trends in Idaho are less obvious than temperature trends and contain more interannual and decadal variations (Abatzoglou et al., 2021). One potential reason for this is that observation stations in the mountainous areas are more sparse than in the more populous valley, thus, it is difficult to compare ground truth to modeled output. More broadly though, precipitation intensity is increasing in Idaho. Across 1975 to 2010, the largest single-day in spring precipitation amount increased by 5.1% per decade. Over that same period the largest single-day annual precipitation amounts increased 2.9% per decade (Klos et al., 2015). This suggests that while the overall precipitation amounts on a yearly or decadal scale show no major trends, the times when there is a larger precipitation event, more water is falling than before. The risk of flooding increases with the increase in precipitation intensity and frequency of these events, which in turn can impact pests as mentioned above.

Agricultural Value of Idaho

Idaho contains over 11 million acres of farmed land operated by over 24,000 entities/farmers/growers (USDA, 2021). 17% of Idaho's economic output and 12.5% of Idaho's GDP is from agriculture (Wilder et al., 2022). While Idaho is most known for its potato production, its other lucrative revenues are cattle and calves, milk, hay, and wheat (Wilder et al., 2022).

Forecasted and preliminary numbers for 2022 show Idaho farmers' collective gross income (sometimes referred to as "cash receipts") was around $11 billion, a 29% increase from 2021 (Wilder et al., 2022). Net farm income was estimated at $3 billion, which is 56% higher than 2021 (Wilder et al., 2022). These numbers include livestock and crops. Finalized numbers from 2020 show the total gross and net farm income numbers are $8 billion and $2.5 billion respectively (Wilder et al., 2022). Across 2013-2022, crops make up around half or slightly under half of the total yearly gross incomes (Wilder et al., 2022).

Fruit trees and berries are lumped under "other crops" in some reports and the last time any fruits were included as their own category in the USDA's non-organic census was 2017. In that year, apples' and peaches' production was valued at $8.1 million, and $6.6 million respectively (USDA, 2017). Values were acquired for years prior to 2017 and are shown in figure 4. The value of apples varies more than peaches and cherries, but these values were large enough to be included in the annual surveys. Benjamin Johnson at the USDA National Agricultural Statistics Service in Idaho said in an email that statistics for these fruit crops after 2017 are not available because Idaho wasn't producing enough of them to be included in the annual surveys. Additionally some data on fruits is "withheld to avoid disclosing data for individual farms" (USDA).

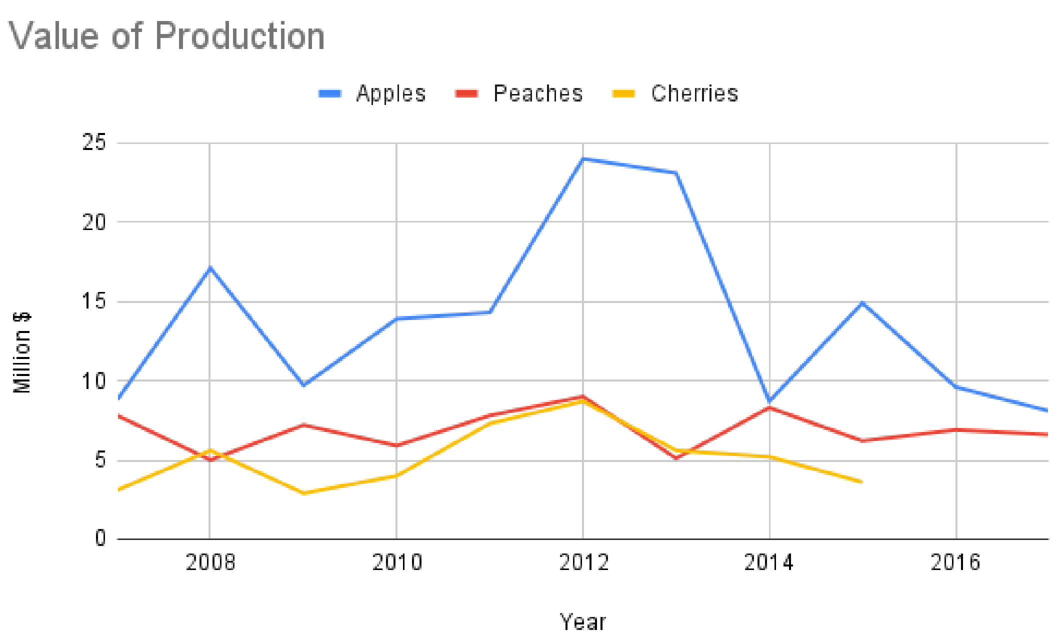

Figure 4 **The Value of Fruit Production**

The value of fruit production of apples, peaches, and cherries for Idaho 2007-2017. Data from USDA NASS annual surveys.

The University of Idaho's Pomology and Viticulture Program hosts the Parma Research and Extension Center, in Parma Idaho, which is a 200 acre research facility founded in 1925 focusing on research needs to improve the productivity of crops grown in southwest Idaho (About Parma Research and Extension Center, n.d.). Among its many projects, the pomology program has introduced the Fuji apple to the area and has found it to have superior quality to other states. They are also working on projects to improve the efficiency of thinning apple, plum, and peach blossoms. Research into better rootstocks and new chemicals for treating plants have also been ongoing at this research center. While there is no formal data to show the growth of fruit production in Idaho since 2017, there is investments in its future and research being done for its viability moving forward. Idaho, with its warm and long spring and summer days with cool nights, currently has very suitable climate conditions for apples, cherries, grapes, plums, apricots, and peaches (About Parma Research and Extension Center, n.d.).

Changes in Growing Degree Day Values

One common measure of the activities of plants, pests, molds and mildew based on weather is the growing degree day (GDD) unit. GDD is a more appropriate way of measuring the activity of pests because it takes into account the current conditions. Basing pest activity solely on calendar dates is less advantageous because it is based only on past observations, and doesn't account for anomalous changes in temperatures and patterns that could be occurring in real time. In this context, it is a unit metric to explain the relationship between weather and pest behavior. Over long periods of time, it can show patterns in climate and pest behavior.

There are many ways to measure GDD which are often specific to a given plant or animal. Generally, GDD is calculated for a calendar day, and the warmer the day is, the higher the GDD value will be. The EPA tracks GDD to help a variety of people and industries respond to plants and insects changing behavior. The EPA has noted that between 1948 and 2020, GDD values have increased at 75% of the long term reporting stations in the United States (US EPA, 2021). These stations are experiencing an increase in average temperatures over time which increases the acceleration and peak of GDD cumulative values. Most of the stations where GDD values are increasing are located in the western contiguous United States. GDD changes in a particular region can facilitate understanding of changes in behavior of molds, pests, water availability, and crop yields.

Spotted Wing Drosophila

The Spotted Wing Drosophila (SWD) is relatively new to the Pacific Northwest region (Washington, Oregon, and Idaho) of the United States. It was first discovered on the western US coast in 2008 in California. In less than 2 years it spread to Oregon and Washington (*Tiny Fly Poses Huge Threat*, n.d.). It was first identified in insect traps in Moscow, Idaho in the summer of 2012 in relatively small numbers (Quinn, 2016), but has been found across the agricultural region of Southwest Idaho in the past several years.

The SWD is an insect similar in size and shape to a common fruit fly, but is considered a pest because of the female's serrated ovipositor that allows them to cut into host fruits to lay eggs (Lee et al., 2011). This pest impacts stone fruits (apricots, peaches, etc), berries (raspberries and strawberries), and sometimes grapes, by using these fruits to lay its eggs. (Baker et al., 2010). The adult female SWD will burrow into a suitable fruit, often without humans being able to visually identify that it's happened. Once the egg hatches, the larvae will feed inside one the inside of the fruit for about a week. Then, more of the larvae will pupate, burrow back out of the fruit and fall to the ground. The pupa then turns into an adult and begins to mate immediately, as adults live for about 3 to 4 weeks (Spotted-wing Drosophila: An Emerging Berry and Stone Fruit Pest, 2022). Once the egg laying occurs, the inside flesh of the fruit is compromised and the crop is ruined.

For farmers and growers, a widespread infestation of this insect can cause massive damage and thus, produce catastrophic financial losses. In 2009, some peach growers in Willamette Valley, Oregon experienced up to 80% loss of their crops from the SWD (Dreves, 2009). Likewise, in that same year, California lost around ⅓ of its cherry crop in the area from Davis to Modesto (Dreves, 2009). Understanding this insect and how it will evolve and survive in this region under a changing climate is important for farmers so they can create or adjust mitigation strategies.

CHAPTER TWO: SUITABILITY

Given that the climate is changing in southwest Idaho, it is important to explore how these changes will manifest in the agricultural sector and more specifically, for pests. The Spotted Wing Drosophila is already surviving in the area. The two ways to assess the potential of the SWD becoming more of a problem to growers and farmers are the availability of suitable habitat to lay eggs and survive over winter, and the impact of having more suitable temperatures for longer periods of time during a calendar year. If these conditions are becoming more favorable, and there is an increase in stone fruit and berry production, the SWD could become a pest worthy of more monitoring and mitigation.

Site Description

The study area is located in the Snake River Valley (SRV) in southwestern Idaho (Figure 4). The elevation peaks around 3700 ft. MSL and slopes downward from east to west to around 2100 ft. MSL near the Idaho-Oregon border. The valley itself is referred to as the Snake River Valley Viticultural Area. Hop vines are also a prominent specialty crop in the region, though the main crop export remains potatoes and onions.

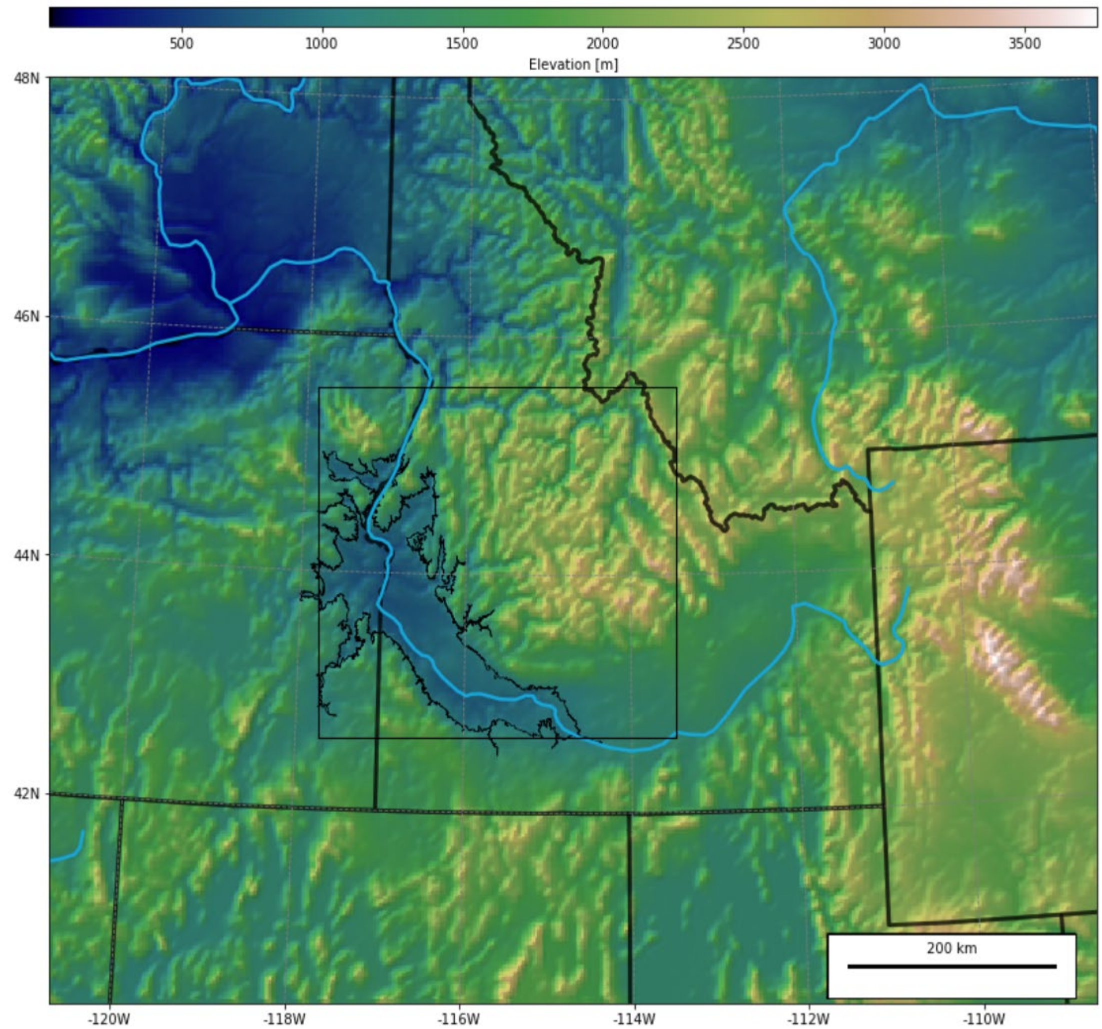

Figure 5 WRF Domain

The outer 3 km. WRF domain with the 1 km nested domain. The mapped outline is the Snake River Valley referenced in this study. (Image courtesy of Becker, 2020)

he SRV has a cold, semi-arid climate (Kottek et al., 2006). This climate is broadly described as having low precipitation (the Boise, ID average is 294 mm/year) and has high interannual variability (Arnfield, 2022). This area also exhibits low relative humidity values and high evaporation rates which leads some to describe this area as a high desert (Arnfield, 2022). The Boise, Idaho airport is the region's climate site for the National Weather Service. The airport's records (1940-2020) indicate that the lowest amount of precipitation in a calendar year was 6.64 inches (168.7 mm) in 1966, and the highest was in 1983 with 18.77 inches (476.8 mm) (National Weather Service. (n.d.)). Given the latest 1991-2020 climate normals, the average calendar yearly precipitation for the Boise Airport is 11.48 inches (291.6 mm). The mountainous areas immediately adjacent to the study area receive more and highly variable precipitation. The Boise Airport, though, is a good proxy for the climate and weather observations for the entire study area in the valley.

Methods

For this study, growing degree day values will be calculated and evaluated as it relates to studied SWD behaviors. WRF modeled data are used as a proxy for actual weather observations. Both of these come with limitations and assumptions.

SWD activity and associated behaviors has been extensively studied in Asia and only in the last decade or so has been studied in the Western United States. The active temperatures of the SWD and the behaviors associated with that were done using trap sampling with different baits in Asia (Kanzawa, 1939). However, as the SWD is adapting to different areas in the US, these thresholds are likely to vary and are being updated in the Pacific Northwest (Douglas et al., 2011). No formal trapping regime exists in Southwest Idaho for the SWD, but they are being found in general traps used for other insects. Additionally, some of the trapping being done is on private land using private contractors so the data is sparse and incomplete. For these reasons, modeling the behavior in anticipation of further study and trapping studies specific to this area is the direction chosen.

The network of observations across the US is relatively sparse especially in the western US. The WRF data (described more below) allows for a more seamless picture of the degree day values and thresholds across the area than a single point observation station would allow. Boise Idaho is the climate site for the area, but more nuanced differences exist in temperature across the AVA.

The Weather Research and Forecasting (WRF) model is a numerical weather prediction model that was used to create climate data for this study (Skamarock et al., 2008). The WRF was designed for use in operational forecasting and atmospheric research, so it has the ability to be initialized for actual observations or idealized conditions (Skamarock et al., 2008). This study spans the water years 1988 - 2017 and has a 3 km outer domain with a 1 km nested inner domain (Figure 4, Becker, 2020). Each simulation was one water year (October 1 through September 31) and had a two week model spin up (Becker, 2020).

Calculation of Growing Degree Days

A degree day is a proxy of physiological time for a plant or animal organism to move from one part of their life cycle to the next. Often, there are temperature thresholds in the calculation that correspond to the observed maximum and minimum temperatures in a 24-hour period. These values dictate a quasi-potential energy calculation of how much of that day is available for that organism to be developing. When the accumulation of degree days meets a given threshold, that insect or plant is expected to change or exhibit a certain behavior or life cycle event (*Degree-Days: About Degree-Days--UC IPM*, n.d.). There are several different methods to calculate a degree day unit for a given day, but most of them are described as an accumulation or a cumulative summation from the beginning of the calendar or water year. Degree day calculations are sometimes tailored to a specific plant, or a group of insects or plants.

The Oregon Integrated Pest Management Center (OIPMC) created a model for the SWD based on three main datasets. The first two include trapping data in the wild or agricultural fields and observations of lab insects' behaviors. The third is the weather (or simulated weather) observations that correspond to the SWD's trapping patterns or behavioral observations. These data established the temperature range of SWD activity to be between 50°F and 88°F. It also is the basis for the degree day thresholds that correspond with expected SWD behavior (table 4).

Table 4 Thresholds and Expected/Modeled Behavior (Data adapted from http://uspest.org/wea/swdmodel2.pdf)

Degree Day Threshold	Expected/Modeled Behavior
261	1st egg laying by overwinter females
510	Peak egg laying by overwinter females, and 1st adults emerge of 1st generation
565	1st egg laying by 1st generation females
755	Peak adult emergence of the 1st generation
995	Peak egg laying by 1st generation females
1249	Peak adult emergence of 2nd generation
1489	Peak egg laying by 2nd generation females
1743	Peak adult emergence of the 3rd generation
1983	Peak egg laying by 3rd generation females
2237	Peak adult emergence of 4th generation
2477	Peak egg laying by the 4th generation females
2731	Peak adult emergence of 5th generation
2971	Peak egg laying by 5th generation females

The SWD-specific GDD was calculated for the domain in R using the single sine method developed by the OIPMC. The calculations for the single sine method uses the high and low temperature for each day as input, and the degree day value is given as output. The output is based on where the high and low fall in relation to the high and low thresholds established for the SWD (50 and 88 degrees F). The diurnal temperature curve of a day is a way to show or visualize the temperature variations throughout a calendar day. Typically they have time on the x-axis (midnight to 23:59), and temperature on the y-axis. The temperature can be plotted hourly or sub hourly and the curve of that line usually looks like a sin or cosine wave. The single sine method assumes that the diurnal temperature curve is symmetrical around the daily maximum temperature (*Degree-Days: About Degree-Days--UC IPM*, n.d.). The degree days are calculated graphically by the area under the sine curve that represents the diurnal temperature curve for a given 24 hour period and between the established temperature thresholds (*Degree-Days: About Degree-Days--UC IPM*, n.d.).

Mathematically, the growing degree day value for a given location on a given day is represented by equations based on different scenarios. Each of the scenarios is described with their corresponding equations below. (Equations 1-4 and tables 5 and 6).

Table 5 Variables and Descriptions.

Variable name	Description
a	2 * Lower threshold = 100
b	2 * upper threshold = 176
min	Minimum temperature for the day
max	Maximum temperature for the day
s	Sum of min and max
d	Difference of max and min
GDD	Growing Degree Day Value

Table 6 GDD Calculations and Scenarios

IF	Equations
Min > 88	GDD = 38
Max <= 50	GDD = 0
Min >= 50	$GDD = \frac{s-100}{2}$

If the maximum temperature for the day is greater than 88 degrees, equations 1-4 are used to calculate 2 different theta values (based variables s or d) and heat temp, where "heat temp" is a growing degree value using the variable "d" that is used in subsequent scenarios.

Equation 1:

$$\theta_d = arctan[(100 - s)/\sqrt{d^2 - (100 - s)^2}\,]$$

If θ > 0 and (100-s) < 0,

Then, $\theta = \theta - \pi$

Equation 2:

$$heat\ temp = \frac{(d * \cos(\theta)) - [(100 - s) * (\frac{\pi}{2} - \theta)]}{2\pi}$$

Equation 3:

$$\theta_s = arctan[(176 - s)/\sqrt{d^2 - (176 - s)^2}]$$

If $\theta > 0$ and (176-s) < 0,

Then, $\theta = \theta - \pi$

Equation 4:

$$GDD = (heat\ temp) - \frac{(d * cos(\theta)) - [(176 - s) * (\frac{\pi}{2} - \theta)]}{2\pi}$$

If none of the previous conditions are met, then equation 5 applies

Equation 5:

$$GDD = heat\ temp$$

Sources of Error

At this point, the way to view modeled behavior of a SWD as it relates to temperature has been established. However, there are sources of error associated with each step. While the literature doesn't support a direct margin of error for the single sine method, this is an opportunity to discuss potential sources of error and variation. Initial trapping research by Kanzawa in 1939 shows that the egg stage can last from two to seventy-two hours. Adults can live 21-66 days (Kanzawa, 1939). Some studies that use trapping data have traps checked on a daily or weekly basis which can introduce some error in when exactly those insects are entering the trap. Another source of error can be the distance between weather stations and the location of traps and/or fruit crops.

In 2014, Harris wrote about a two year monitoring project on a 212,000 m2 plot of land with a variety of fruits where the traps were interspersed on the plot. The trapping data was compared to temperature and precipitation data from a weather station that was nearby but not on site (Harris et al., 2014). Micro climates on the plot of land could produce errors in the patterns observed with the weather data provided by the nearby station. Additionally, different kinds of weather monitoring equipment have their own inherent margins of error based on the quality of the sensors.

Data Analysis

The data was subset to the lowland agricultural areas below 1000m and divided into four equal bands created between the lowest elevation (498 m) and the highest. The first band (498 m - 623.5) represented such a small area it was removed to examine the other 3 bands more closely (623.6 m -749 m, 749.1-874.5, 874.6-1000). Time series blocks were created for three decades (1987-1996, 1997-2006, 2007-2016), and 15 year blocks (1987-2000, 2001-2016).

Averages for each of the thresholds over time and space were calculated to look for patterns in the SWD behavior as it relates to changing climate patterns. Each year and at each location has a set of days of years calculated for when each of the thirteen thresholds are met. One way to visualize changes in these data over time is to look one when a particular threshold is met each year at each location, and then average that value at each location. This will provide a plan view map of an average DOY that a threshold is met with an average value existing at each point. Another way to visualize these averages is to look at locations below 1000 m (or any subset of the data) and use a line plot to map the DOY that a GDD threshold is met. The x-axis would be time (each year of the domain) and the y axis would be the averaged DOY across all of the chosen locations. Both of these methods detailed above can be calculated for any of the 13 thresholds described in Table 1.

The average DOY that a threshold is met across a decade at each location was created for the oldest decade (1987-1996) and the most recent decade (2007-2016). The 1987-1996 decade average is subtracted from the 2007-2016 decade and calculated at 1km by 1km grid, and is shown by equation 6.

Equation 6:

For each 1km by 1 km grid cell,

D = day of year at which a given threshold is met,

$$\left[\sum_{2007}^{2016} D\right]/15 - \left[\sum_{1987}^{1996} D\right]/15$$

For example, if the average day of year that a 261 GDD threshold is met across 2007-2016 at a particular grid point is the 100th day of the year, and is the 105th day of the year in 1987-1996, then the result of the equation would be negative, indicating that that threshold is being met sooner in the year. The inverse is true where a positive number in equation 6 means that the threshold is occurring earlier in the year. While the earlier thresholds for egg laying occuring by the overwintering females (261 DD) is occurring, on average, later in the year (figure 7), the average thresholds for peak emergence for the 3th and 5th generations (1743 DD and 2731 DD respectively) is occurring earlier in the year (figure 8). This pattern would suggest that the onset of these thresholds may be occurring later in the year (possibly due to late spring cold snaps), but the later thresholds are occurring earlier because the rate of DD accumulation is increasing over the decades.

Results

One goal of this study was to see if there is an increase in suitable areas where the SWD can breed, and if that area was increasing over time. While the day of the year was around the same time, the spatial area that reached the threshold of "Peak egg laying by the 5th generation" (2971 GDD) has increased by 92%, from 5278 km2 to 10135 km2 during the first decade to the last decade. This equates to about 1.2 million additional acres of suitable SWD habitat. The expanded area is shown in figure 6. These figures suggest that the available and suitable area for the 5th generation females is increasing and could allow a next generation and/or more individuals in each and the last generation in a growing season.

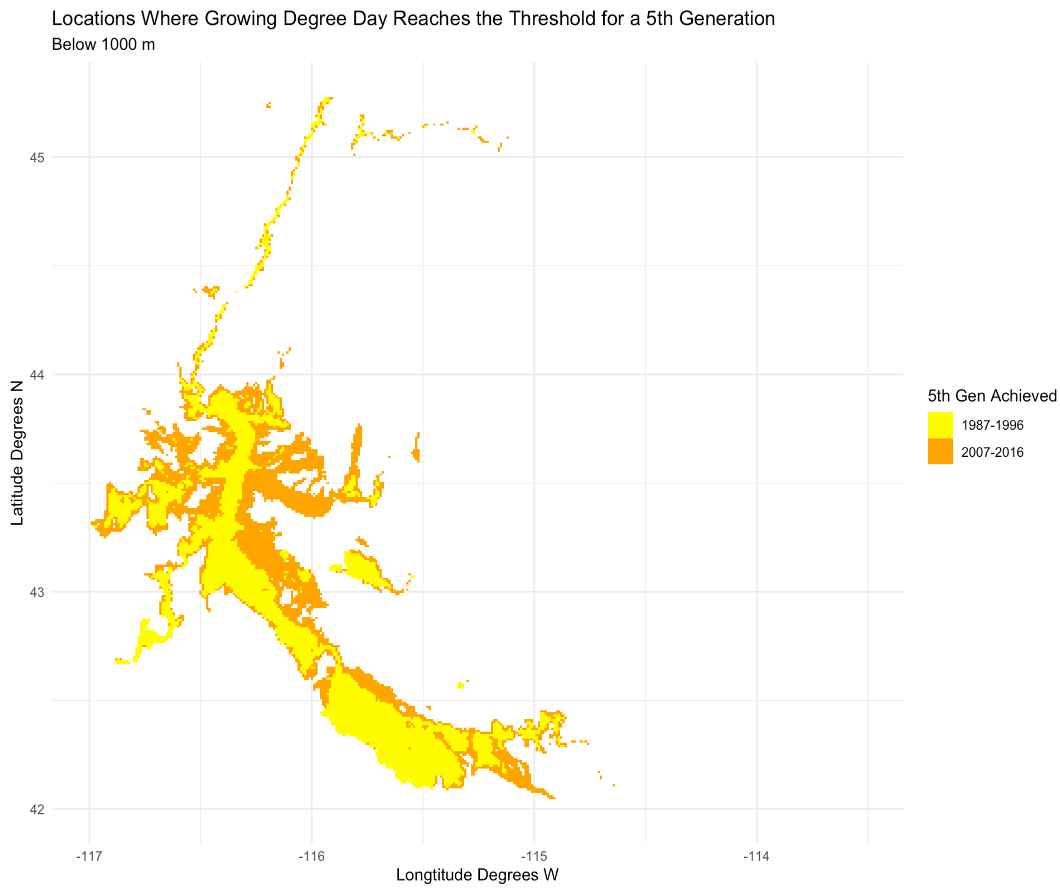

Figure 6 Locations for a 5th Generation

The calendar day that the 5th generation is reached is averaged in the decade and then if the threshold is met during the respective decade, it is colored in. All values are below 1000 m. The orange areas show the increase in available area for SWD to reproduce in the latter 15 year span.

Shifts in Timing

Another way to look at changes is to assess the shift in timing of thresholds being met over time. In this case, the day of the year that the 261 degree day threshold (overwintering females laying eggs) occurs, is averaged across all locations and in two 15-year spans (1987-1996 and 2007-2016). The difference between the averages shows a shift in the timing of this threshold being met. When subtracting the older 15-year span from the more recent span, positive numbers mean the event is occurring later into the calendar year (figure 7). Conversely, negative numbers mean that the threshold is occurring sooner in the calendar year, as shown in figure 8 with the same method being applied to the degree day threshold that matches with the 5th generation emerging.

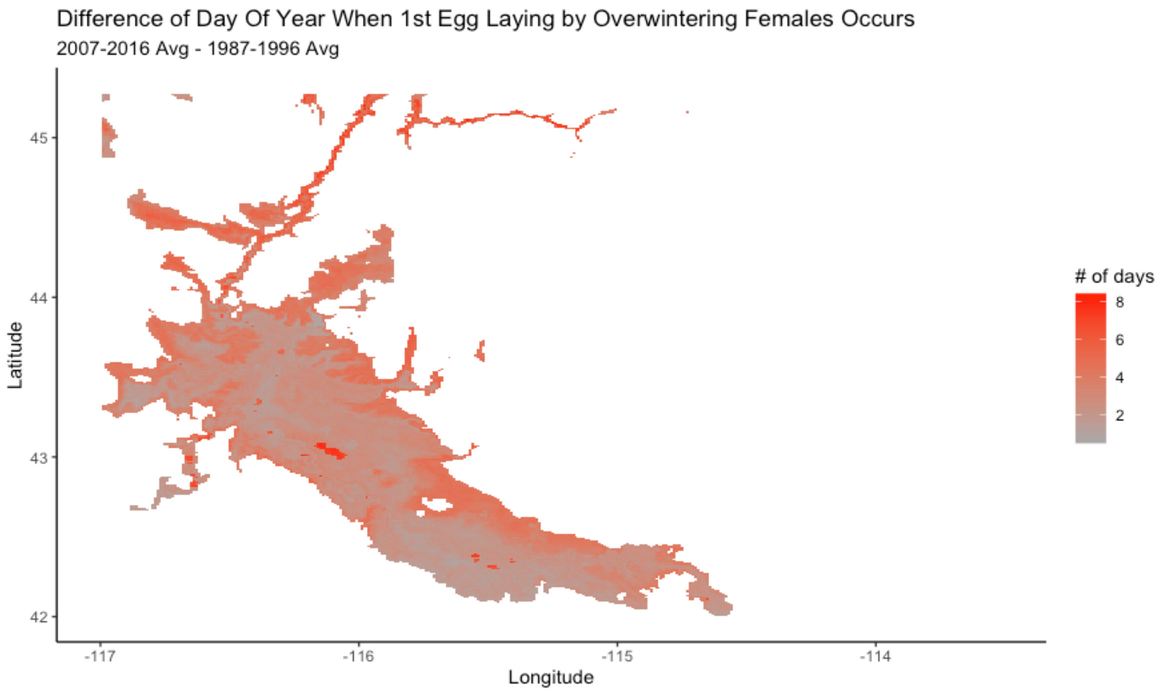

Figure 7 Differences in DOY for 1st Egg Laying

The average DOY across 2007-2016 that the 261 threshold (1st egg laying by overwintering females occurs) is met at each location minus the average DOY across 1987-1996 that the 261 threshold is met at each location.

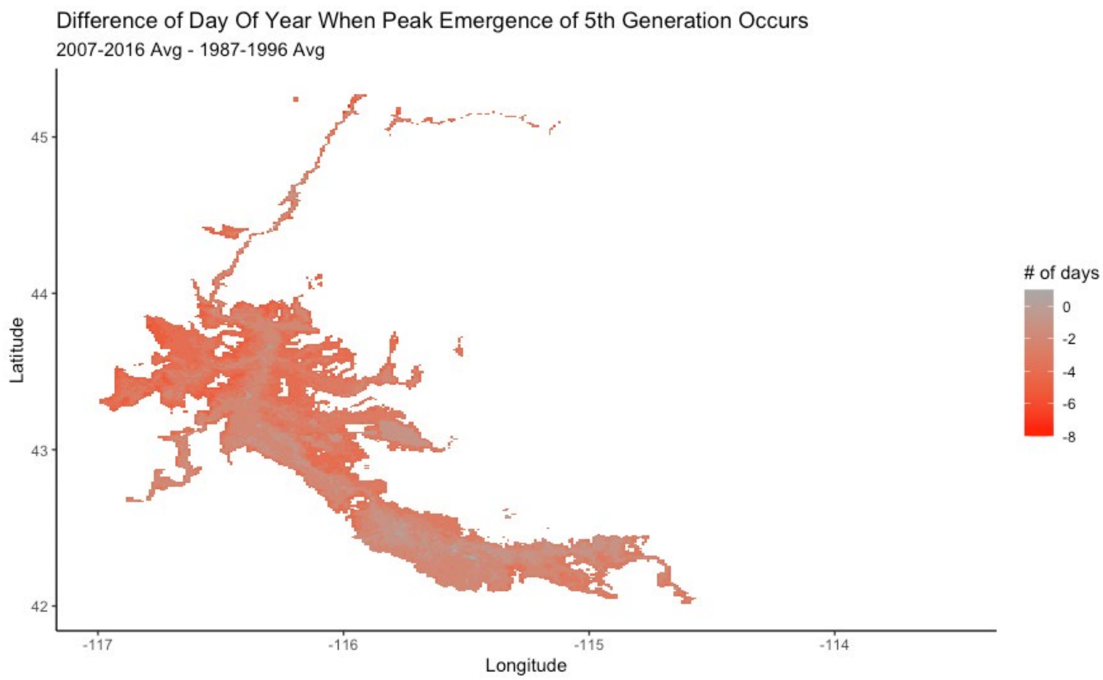

Figure 8 Differences in DOY for Emergence of 5th Generation

The average DOY across 2007-2016 that the 2731 threshold is met at each location minus the average DOY across 1987-1996 that the 2731 threshold is met at each location.

Extrapolating Out to a 6th Generation:

After the peak emergence of the 2nd generation, the pattern of degree day thresholds becomes alternating +240 GDD then +254 GDD. With this extrapolation, a potential sixth generation would be emerging at 3225 degree days and peak egg laying would occur at 3465 degree days. Histograms of the maximum degree day achieved across the entire temporal domain (1987-2016) were analyzed to see if a 6th generation of activity was even possible within the confines of the SWD thresholds. Figure 9 shows the shift of distribution of the maximum degree day in comparison with the 3225 and 3465 thresholds. The black histogram is 1987-2002, and the red histogram is 2003-2016. The shift in the latter 15 year span is to the right, meaning locations are meeting or exceeding the 6th generation thresholds more often than the former 15 year span.

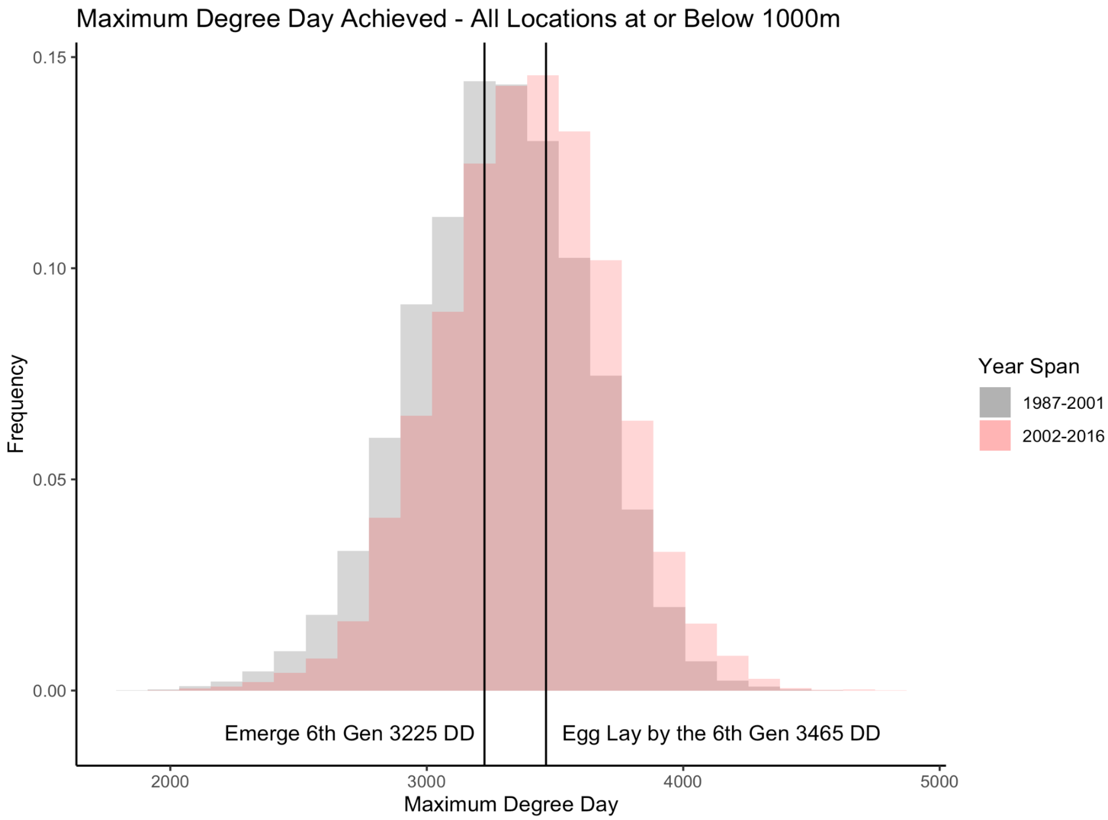

Figure 9 Maximum Degree Day Achieved

The histograms of each 15 year span's respective maximum degree day achieved overlaid with the x-intercepts of the 6th generation's DD thresholds (3225 and 3465).

Statistical Test of the 6th Generation Assessment

A Welch Two Sample t-test was performed on the two 15-year spans' distributions of the extrapolated 6th generation. The number of data points was 8,451,151 and the t-value was -462.68. Combined with a p value that is 2.2*10^-16, this test shows that there is high confidence that the mean of the 2 distributions is not the same number. The Two-Sample Kologorov-Smirnov Test also produced the same p value, which further solidifies that these are 2 distinct and statistically significant different distributions.

Linear Relationship

A simple linear regression was performed on each threshold versus the last modeled threshold of a cumulative growing degree day of 2971. As you compare each of the thresholds, the linear relationship becomes more apparent. This conceptually makes sense. The R^2 values increase from 0.51 when comparing 261 versus 2971, to 0.73 with threshold 510. The maximum R2 value is 0.98 when comparing 2731 to 2971. Also of note, in figure LR, showing 261 vs 2971, the data shows that the earliest that egg laying window occurs was DOY90, which corresponds to march 31, whereas the latest date was 134 corresponding to may 14. While this is a span of 44 days, once the 261 threshold has been met, it is likely on a trajectory of accumulation that has an analog. It is theorized that with climate change, this relationship would become less linearly correlated because of the potentially more chaotic freeze events.

Individual Locations

Patterns can emerge when looking at individual locations rather than an elevation band or decade. The threshold patterns look extremely similar across the years at each location, which is expected. However, the threshold graph for Boise shows the potential that all of the thresholds are starting to occur earlier in the year. This would allow for a 6th generation more easily and earlier in the year during or just before harvest when the fruit is ripe. A larger and/or more prolific outbreak right at harvest time could be financially devastating for growers.

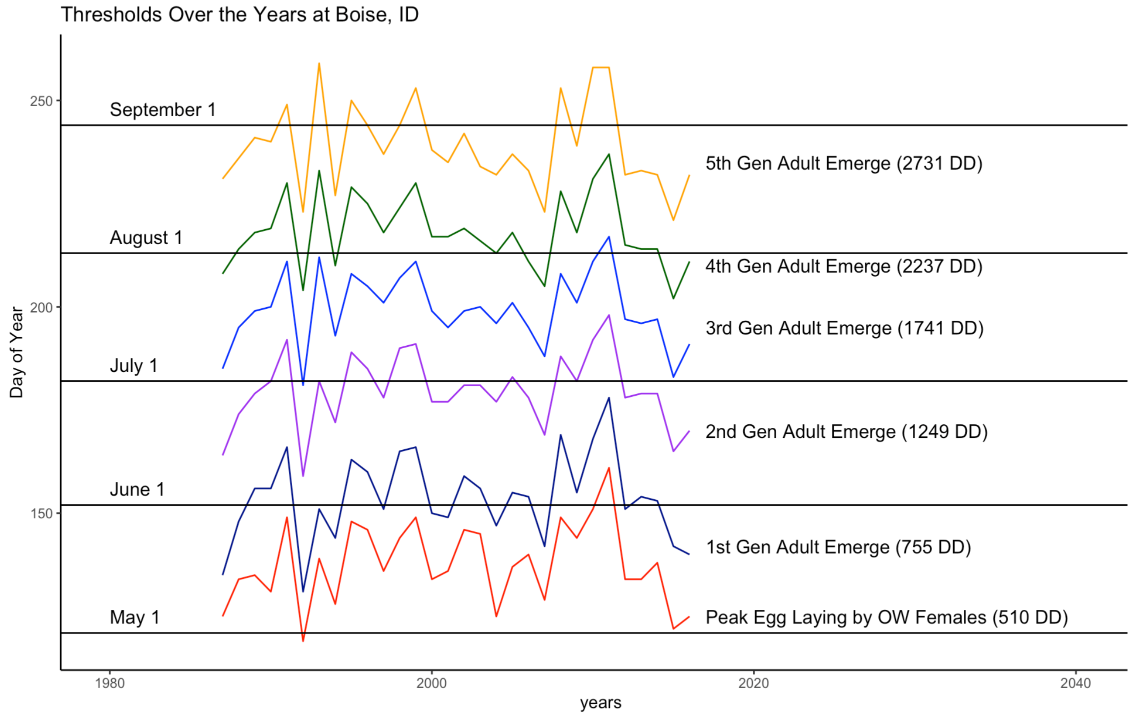

Figure 10 Threshold Time Series

Threshold time series 1987-2016 at Boise, Idaho. DOY is displayed on the y-axis with the corresponding calendar dates.

Discussion

The SWD is a known pest that has been able to adapt to a variety of climates across the northern hemisphere and southwest Idaho is no exception. Given the climate changes across 1987 to 2016 in Idaho, there is already a warming trend that would expand the growing season and allow another full generation of SWD to lay eggs and hatch (thus ruining potentially ripe and ready-to-harvest fruit). With current projections of global climate change, the local climate of southwest Idaho is expected to warm even further. This warming will create a longer and warmer growing season that would likely allow more suitable conditions for the SWD. Many other factors go into the overall survival of the SWD though, including mortality changes over winter, predators, plant stress' impact on egg-laying, and human management strategies.

One major factor that ties into climate change is the changing ability of the SWD to survive over the winter. The temperatures examined in this study focus on the growing season, but the overwintering females are the ones to begin the process of reproduction in the spring. A study done in 2016 showed that no SWD survived with prolonged temperatures below 1C (Ryan et al., 2006). The area covered in this study regularly dips below 1C in the winter. But, Renault et al. in 2004 suggests that insects that are exposed to fluctuating temperatures are more able to survive relatively shorter bouts of freezing temperatures. If the winters in the SRV are generally warming, that would be advantageous to the SWD, but evidence suggests that they would still be able to survive cold snaps that occur within the overall warming (Renault et al., 2004).

The weather and climatological factors that impact the SWD's ability to proliferate also impact known predators, like earwigs, spiders, and ants (Jana et al., 2019). In the case of earwigs, the balance between a scenario where there are more SWD and more predators and what that would do for overall SWD populations is something that would need to be explored further. In general, insects respond similarly to regional climate changes, but differences exist between native and invasive species.

Because there is no formal trapping regime that specifically looks for the SWD in southwest Idaho, the OIMPC's model says that it is partially validated for the weather stations it uses. Some trapping of the SWD has occurred indirectly from traps set out on private land that are used to monitor other insects. However, these data are informal, incomplete, and in some cases, not publicly available. Though, the SWD has long been a pest that needs regular intervention in other parts of North America. It is theorized that with an increase in the agricultural growing season, and the warming winters, the SWD will become more prolific and may need more or new monitoring and mitigation strategies within southwest Idaho.

Species Distribution Models (SDM) can provide a more holistic view of a species' proliferation in a given area. In one study, a SDM was utilized using occurrence records in native areas, invasive areas in Europe, and both combined (Ørsted and Ørsted, 2019). These results found that the models performed better when they were using records from the region that was being modeled, even if there were fewer records overall (Ørsted and Ørsted, 2019). This suggests that more trapping data in the southern Idaho area would provide entomologists a better understanding of how the SWD could proliferate using SDMs.

Moving forward, if stone fruits become more desirable in the region, and growers decide to convert more land over to stone fruit and berry production, then mitigation techniques may need to be modified. There are biological, physical, and chemical remedies for the SWD, but all should be done with monitoring practices as well (Kaur, 2023). Current natural predators are a good way to suppress the population and there are several in southern Idaho, but not all predators are commercially available (Lee, 2019). The chemical remedies are widely available but need to be strategically implemented (Kaur, 2023).

Overall, there is a need for more trapping data over space and time to better understand the SWD's impact to growers in the region. WRF tools, SDMs, and human decision-making all rely on ground truth data to test and refine monitoring and short-term predictions. Currently there are many resources for growers at the Pacific Northwest Handbook, and the Parma Research Center. There is also the climate viewer located at bwc.boisestate.edu/climate-viewer that can provide past climate data using the WRF data used in this research. This hope is that through additional work at Boise State through the Idaho Department of Agriculture, this can be another tool for growers and farmers to look at weather and climate at the field scale.

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