WINTER CLIMATE AND ITS EFFECTS ON TAYLOR'S CHECKERSPOT BUTTERFLIES (*EUPHYDRYAS EDITHA TAYLORI*) IN THE PUGET SOUND

by

Wendy Lagerquist

A Thesis Submitted
in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
June 2019

This Thesis for the Master of Environmental Studies Degree

By

Wendy Lagerquist

has been approved for

The Evergreen State College by

John C. Withey, Ph. D

Member of the Faculty

June 2019

ABSTRACT

Winter Climate and its Effects on Taylor's Checkerspot Butterflies (*Euphydryas editha taylori*) in the Puget Sound

The effects of three elements of winter climate on abundance of the Taylor's Checkerspot Butterfly in the Puget Sound were examined. Winter is the time the butterflies are hibernating in larval state diapause. The climatic variables examined were winter precipitation, humidity, and temperature. Butterflies on three sites of Joint Base Lewis McChord (JBLM) were examined. In one site (Range 76) there were no significant correlations of log-transformed estimates of peak abundance over time or with climate variables. In the other two sites, the variable with the most explanatory power on log-transformed estimates of peak abundance was not climate variables but the year. In one site (Scatter Creek South) abundance increased by 47%/year on average, while in the other (Range 50) abundance increased by 75%/year on average. There was some evidence of an association of climatic variables with estimates of peak abundance in these two sites, but those associations had much less evidence than the increase over time. These abundance increases could be an effect of the reintroduction of Taylor's Checkerspots to these sites, so the potential for climate to influence annual abundance should not be discounted.

TABLE OF CONTENTS

LIST OF FIGURES

RESULTS AND DISCUSSION

LIST OF TABLES

LIST OF APPENDICES

ACKNOWLEDGEMENTS

The butterfly field count data for this thesis was collected, compiled and analyzed by the biologists and data scientists at the Washington State Department of Wildlife (WDFW), notably Mary Linders, Gail Olsen, Ann Potter, Josh Cook, Emily Phillips, and Lisa Thompson-Randalf. Their work takes great skill from many years of practice. Mary Linders helped guide me on my research question and Lisa Thompson-Randalf kept me informed on the news of butterfly conservation. I also thank my co-students at The Evergreen State College (TESC). I will never forget Paris McClusky and his comradery as we suffered together in the CAL for hours and hours. Diane Nelson, Sarah Hieber, Tracy Scalici, and Keegan Curry gave excellent feedback on my work. I thank my kids, Sammy and Alex Tassoni for putting up with being without me and my husband Peter Tassoni for covering childcare duties and lending an ear when I needed empathy. He also aided me with formatting the thesis. I thank my coworkers, Dustin Wiersma, Brian Cosentino, Ian Trewella and John Talmadge, in the science division of the wildlife program at WDFW and Professor Mike Ruth for their expertise and feedback on some of the programming, data source and GIS-related questions. Dustin helped me a great deal with Python programming and GIS work needed for the presentation. I appreciate my supervisor, Shelly Snyder for her patience with my repeated requests for time off during the crunch times. The professors of TESC deserve mention because they taught me speaking, data analysis and writing skills, particularly Professors Kevin Francis, Erin Martin, Ted Whitesell, Michael Ruth, Kathleen Saul, Miranda Mellis and Shawn Hazbourn. Lastly, I owe a great debt of gratitude to my advisor and reader, Professor John Withey for his patience and excellent feedback on my dissertation. Dr. Withey’s expertise in ecological science and statistics was pivotal as he provided guidance on this project’s methods design and statistical analysis.

INTRODUCTION AND LITERATURE REVIEW

Introduction

For those who are paying attention, it is no surprise that there is a general trend toward a global loss of biodiversity and heavy ecological collapse everywhere due to anthropogenic climate change and habitat fragmentation (Burlew 2010; DeRosa n.d.; Ehrlich and Ehrlich 2009; Jarvis 2018; Sugarbaker 2017). We are embarking on an age of human-caused apocalypse—particularly among the insect populations of the world. This apocalypse is caused by human over population (Ehrlich and Ehrlich 2009).

In the last 20 years, the Monarch butterflies (*Danaus plexippus*) have had a 90 percent drop in population, a disappearance of 900 million individuals. The Rusty Patched Bumble Bee (*Bombus affinis*) had an 87 percent drop in the last 20 years (Jarvis 2018; "Rusty Patched Bumble Bee," n.d.; Szymanski et al. 2016).

In the Puget Sound region of the Pacific Northwest, there are many species of concern. The species that are getting the major attention these days is the Southern Resident Killer Whale (*Orcinas orca*) (DeRosa n.d.) and the Northern Spotted Owl (*Strix occidentalis caurina*), which has generated huge controversies with respect to conservation vs. the natural resource extraction interests (Glenn et al. 2011b).

The species of concern that will be the subject of this thesis gets less attention in the press. It too is being threatened by fragmentation of habitat and global climate change. It is the Taylor's Checkerspot Butterfly (*Euphydryas editha taylori*), a species of butterfly endemic to the Pacific Northwest. They are a listed species of concern by the US Fish and Wildlife Service (USFWS). There is a concerted effort by local and federal agencies as well as non-governmental organizations (NGO)s to save this species from extinction (Andrusyszyn 2013; Grosboll 2011; Linders, Lewis, and Curry 2016; Linders, Lewis, and Dorman 2016).

Conservation organizations are becoming over-stretched by the need to actively manage populations and the only way to fix this problem is to bridge fragmented habitats and repair the damage to renew vigor to the ecosystems that support life (Parmesan et al. 2015). This sentiment was echoed by the keynote speaker for The State of Washington's GIS Day 2017. Larry Sugarbaker, the keynote speaker discussed the shifting of attitudes that have happened during his career in public lands that had started in 1979 when the prevailing attitude about disturbances to the earth at the time in public lands management as, "The earth will heal by itself and it is OK to do damage" to one of "conservation of the environment" during his tenure at the Department of Natural Resources. Larry Sugarbaker spoke of his own evolution in thinking as an individual, as well as the DNR's natural resource professionals toward "conservation" and away from "The earth will heal itself" sentiment. His main point was that working to save individual species from extinction is the same as working to prevent whole ecological systems from collapse.

This literature review will cover the past research on the effects of climate on the *E. editha* and its subspecies and the differences in climate tolerance between the Bay Checkerspots of California and Taylor's Checkerspot Butterflies of the Pacific Northwest. It will touch on phenological asynchrony in general and the scholarship in such phenomena. It will discuss the statistical modeling of California's Bay Checkerspot populations, as well as similar research on other organisms such as the local populations of the Northern Spotted Owl and how the climate and its various components affect that listed species. It will touch on the lack of knowledge there is of climate elements and how they affect *E. editha* in the Pacific Northwest and the importance of research in this area, finalizing on the ecological imperatives for conservation in general, tying the efforts to save one species with the overall goal of preventing whole-scale ecological collapse.

Phenological Asynchrony

The relationship between many species of butterflies and their hosts had evolved to be a precisely timed event, where the host plant and butterfly match their development to the timing of each other's' life stages (Abarca and Lill 2015; M. C. Singer and Parmesan 2010).

Unfortunately, global climate change has lengthened the "green" season, prolonging summer and shortening winter. Spring in the temperate zones arrives earlier and major weather events such as sudden cold snaps and late storms are more frequent (Miller-Rushing and Primack 2008; Abarca and Lill 2015).

Change in the climate may have caused *E. editha* to be one of the many species to fall subject to phenological asynchrony (the animal needing plant food when it is not available). Most of the stress is nutritional and hydrological-the plant will age before the caterpillars are ready from hydrological conditions and degradation of their food source, thereby starving the larvae. (Michael C. Singer and Parmesan 2010; Weiss and Weiss 1998; McInnis 1997; Raloff 1996; Cohen 1996; "Edith's Checkerspot" 2007; Parmesan et al. 2015; Parsons 1995; Bonebrake et al. 2010; Liu et al. 2012; Olson 2017).

Synchrony between the host plant timing and many species of a moth or butterfly is a honed, precise evolutionary trick programed in the genetics of these creatures (Raloff 1996; Ehrlich and Hanski 2004a; Hanski et al. 2004). For example, in the case of Eastern Tent Caterpillars (*Malacosoma americanum*)it has been shown that asynchrony has been triggered by warmer temperatures early in the season (Abarca and Lill 2015). Global climate change has brought about the prevalence of a longer green season, particularly earlier springs and later winters (Miller-Rushing and Primack 2008). The reason *E. editha* is so susceptible to global climate change is that many species have been forced to migrate north and to higher elevations to survive. *E. editha* have a complex relationship with their host plants and are also known to be stationary in their habitat (non-migratory) due to this complexity. Several studies done on the Bay Checkerspot butterfly (*E. editha bayensis*) state that the stress posed by climate change is forcing Bay Checkerspots of California to move north and to higher elevations where the climate is damper and cooler. (Cohen 1996; "Edith's Checkerspot" 2007; Parmesan et al. 2015; Lacy et al. 2017; Parsons 1995; McInnis 1997; Michael C. Singer and Parmesan 2010).

Habitat work with the Puget Sound Taylor's Checkerspots

Here in the Pacific Northwest, it has been suggested that microclimates need to be studied to be able to assess the habitat needs of the Taylor's Checkerspot Butterfly (Olsen 2017). Due to urban interference and climate change, plans may be made to move the species to new locations based on predicted weather-pattern changes, depending on findings with respect to the climatic requirements of the local *E. editha* populations. Habitat degradation generally causes increases in migration rates (Raloff 1996; Linders, Lewis, and Dorman 2016). Up to this point, the choice of habitat locations have been selected using a rapid habitat assessment using the multitude of variables that affect the *E editha* populations (Linders, Lewis, and Dorman 2016). Microclimate research with respect to populations of *E. editha* will help in future habitat assessments.

Biology of Checkerspot Butterflies and Components of their Survival

Taylor's Checkerspot Butterfly populations are affected by a variety of factors including genetics, pollution, pesticides, behavior, predation dynamics, habitat location, reproduction and site management. *E. editha* have predators and parasitoids that prey upon it. Their natural predators include ants, birds, wasps, and a few other members of the Hemiptera order (true bugs) such as assassin bugs (Ehrlich and Hanski 2004b). Humans have used a parasitoid wasp known as *Cotesia* to control Cabbage Butterflies, and *E editha* have been collateral damage. *E. editha* lose about 67% of their larvae to 1-3 parasitoid species (James, Nunnallee, and Pyle 2011). *E. editha* caterpillars are brightly colored, warning birds that they are unpalatable due to their iridoid glycosides they get from their host plants. *E. editha* larvae eat when they sense host plants that provide them with a defensive chemical called, iridoid glycosides that help them to defend against predation by birds. Such plants include *Castilleja* (Indian Paintbrush), *Plantago* (Plantain), and *Collinsia* (Blue-Eyed Mary) plants. *Castilleja* plants are used by the very young caterpillars in the summer, and the *Plantagos* and *Collinsias* are used later by older, half-grown caterpillars in the spring after they have passed through the winter months (James, Nunnallee, and Pyle 2011).

An understanding of Checkerspot reproductive biology will be critical to their conservation. Reproductive biology of Checkerspot butterflies is a model system that has numerous directions. Though the attempt to understand the decay of *E. editha's* genetic variability by quantitative genetics analysis has not been successful, there are technological advances allowing researchers to work out the small evolutionary forces that affect their phylogeny with their problems of small populations (Ehrlich and Hanski 2004a).

Behaviors of *E. editha* are important to consider because of their consequences for population change. They include feeding behaviors such as what larval host plants are used, adult nectar feeding, how the animal responds to environmental disturbances, and how they interact with their natural predators (Ehrlich and Hanski 2004a; Grosboll 2011; Husby 2012; Michael C. Singer and Parmesan 2010; Aubrey 2013; James, Nunnallee, and Pyle 2011; Weiss and Weiss 1998).

Available Data and Statistical Models from Similar Research

Available and needed data

Long-term population monitoring with respect to microclimate studies are imperative because *E. editha* are so weather dependent. Understanding of weather patterns and meteorology with respect to global climate change and the different climatic factors such as rainfall, temperature, and sunlight will be vital to *E editha* behaviors such as feeding, migration, mating, the structure and dynamics of *E editha* population models and different stages of development of *E editha* (Parmesan et al. 2015).

Since rainfall is known to delay eclosion (emergence from pupae) of adults, amount and timing of precipitation should be considered. Minimum and maximum temperature, as well as the amount of insolation (sunlight) should be measured with respect to geographic location. The local re-introductory effort needs brood data to its link to bad years versus good years.

At this point, there is an abundance of data available about climate and adult butterfly counts. We have field butterfly counts dating back to 2007. WDFW has collected larval and adult distributions through distance sampling by sub-dividing study area samples into grids and counting the numbers in quadrats (one-square-meter squares) every 9-25 meters (Murphy and Weiss 1988; Linders, Lewis, and Dorman 2016; Grosboll 2011). Furthermore, WDFW has data on temperatures dating back to 2006. Mary Linders, a WDFW biologist working with the Taylor's Checkerspots noted the 2006 July temperature fluctuations were large, varying from around 20-40 degrees Celsius in areas she put out the heat sensor data collectors. She stated the cases were plastic and should not be getting hotter than the surroundings. This is significant because the Bay Checkerspots are losing the night time cooling effects during the summer, which could have implications for *E. editha* (Arndt 2015). Given the large amount of data WDFW has with day and night time fluctuations, we may be able to answer the question about night-time warming as mentioned by Arndt. This could be the focus of future research.

Digital Elevation Data

Due to the fact that the climate data is dependent on elevation in that the greater the elevation, the higher the precipitation and the lower the temperature, it was important to look at the elevation data for our Joint Base Lewis-McCord sites available on the University of Washington's School of Oceanography website (Finlayson et al., n.d.) with respect to the butterfly count locations and the weather station locations. Elevation data has been considered with the climate data used in the analysis. The data used for the final analysis incorporated elevation and other factors such as slope and aspect (Daly et al. 2008).

Climate Data

Ideally, climate data used for research similar to this thesis should be accurate to the distance sampling plots, and precise to the count data. Due to the fact these counts are daily numbers, the weather data needs to be daily too. A good source of weather data is Wunderground, the website that contains the daily weather values in the Joint Base Lewis McChord area and is based off the closest weather station (Gray Army Airfield). The primary source of data this thesis will use is from a model used for a project at Oregon State University that has assembled spatial climate datasets for short- and long-term climate patterns known as Parameter-elevation Relationships on Independent Slopes Model (PRISM). PRISM uses a linear regression model to estimate temperature and precipitation as a function of elevation (Daly et al. 2008). A review of the weather stations used by PRISM revealed that the Gray Army Airfield is included in the PRISM model, thereby making this model a more reliable data source for the data analysis.

Statistical Model Ideas based on Past Research

Variance components analysis is what is currently being considered by the Puget Sound wildlife professionals in the same way they have analyzed the local effect of climate on the Northern Spotted Owls. Variance components analysis is a way to compare populations of *E.editha* to these different co-variates. The use of variance components analysis elucidates if climate is a significant influence on the local *E. editha* populations (Olsen 2017). Hypotheses for this thesis will be chosen based on the components of climate and the choice of statistical models will be formulated to the hypotheses. The process of comparing populations to the different co-variates of climate to other co-variates, such as habitat and site management gives wildlife managers an idea if climate is a significant influence on the local *E. editha* populations (Olsen 2017).

There is also another approach to climate modeling on the Taylor's Checkerspots in the Pacific Northwest. Climate patterns have been evaluated through the use of species distribution models with respect to location to determine range shifts depicted on geographic maps (Parmesan et al. 2015). There are linear regression models outlined in the publication where Parmesan et al. (2015) and Weiss and Weiss (1998) calculated range-shifts of Checkerspots through meta-analysis of different datasets to identify patterns evident in climate data and current Puget Sound population models for the Taylor's Checkerspot Butterflies (Parmesan et al. 2015; Weiss and Weiss 1998).

Past Research on how climate affects populations in general and how it relates to this project

Statistical models that have been used to analyze the variance of climate components on the Northern Spotted Owl reproduction and populations are being considered by the Puget Sound wildlife professionals involved with the management of the Taylor's Checkerspot Butterfly Glenn et al. (2011a, 2011b). Researchers have examined the relationship of survival rates of populations of Northern Spotted Owl to local weather and regional climate variables. Perhaps these studies could be a direction for the efforts to understand the local effects of weather on the Taylor's Checkerspots of the Puget Sound region (Glenn et al. 2011a).

Since rainfall is known to delay eclosion of adults, precipitation should be considered. Minimum and maximum temperature, as well as the amount of insolation (sunlight) should be measured with respect to geographic location. Weiss and Weiss (1998) measured these weather variables as a function of location, taking data points every seven days (Weiss and Weiss 1998).

In addition to the work done by Glenn et al. (2011a, 2011b), climate and weather work done by Parmesan et al. (2015) and Weiss and Weiss (1998) provide viable templates for calculating the range-shifts of Checkerspots through meta-analysis of different datasets to identify patterns evident in climate data and current Puget Sound population models for the Taylor's Checkerspot Butterflies. Climate patterns will need to be evaluated through the use of species distribution models with respect to location to determine range shifts depicted on geographic map. There are linear regression models outlined in the Parmesan et al. (2015) publication.

What we already know about the climate and how it affects *E. editha* from past research

There has been comprehensive research on future habitat models with regard to the Bay Checkerspot Butterflies, a different sub-species of Checkerspot butterfly in Southern California (Parmesan et al. 2015). Climate change brings different climate situations to different places. California's funding situation has allowed for studies to be done on the *E. editha* in that area, namely the Bay's Checkerspot, *E. editha bayensis*. Research has shown that in California, drought has played a major role in climate perturbations to the species who are struggling in this bug apocalypse. For the Bay Checkerspots in California, drought has nasty implications such as lack of time for the larvae to develop before their host plants senesce. This phenomena has caused the natural resource managers of this area responsible for the California Bay Checkerspots to actively relocate this non-migratory species to higher elevations and northward (Raloff 1996; McInnis 1997)

The Need for Climate Modeling for the Puget Sound Re-Introductory Effort

Much like California Bay Checkerspots, one of the major problems facing *E. editha taylori* has been global climate change. The local weather patterns and regional climate oscillations affect *E. editha* and the food plants on which they depend. Understanding of weather patterns and meteorology with respect to global climate change and the different weather factors such as rainfall, temperature, and sunlight will be vital to understanding *E editha* behaviors such as feeding, migration, and mating. It will also be important for the understanding of the structure and dynamics of *E editha* population models and different stages of development of *E editha* (Parmesan et al. 2015).

Due to the differences between the heavily studied Bay Checkerspots in California and the Taylor's Checkerspots here in the Northwest, wildlife planners in the Puget Sound need to have *local* information on how our regional climate patterns affect this endangered species. The dynamics and differences of the phylogenic asynchrony may be different for Taylor's Checkerspot as opposed to the Bay Checkerspot of California.

Here in the Pacific Northwest, the effects of global climate change may be much different. The Northwest is a cool, wet place with variable climate such as droughts and wet years. *E. editha* requires basking in the sun to survive. Climate change here in the Pacific Northwest will bring hotter, dryer summers and warmer, wetter winters (Glenn et al. 2011a; Parsons 1995). Voltinism (number of broods this insect has in a year) is indicative of climate, as well as the number of instars it has (larval growth stages). Here in the Puget Sound, *E. editha* vary in both. This genus uses diapause (dormancy such as hibernation) to overcome stresses related to weather (James, Nunnallee, and Pyle 2011).

Eclosion (emergence) depends on rainfall and the first flight season of butterflies determines the oviposition preferences (distribution of eggs).

Excessive rainfall will retard post-diapause (hibernation) larval development, delaying the time the butterflies can have a chance to fly before their plants die, leaving their larvae to starve (Parsons 1995). Mary Linders, the biologist in charge of the Washington State Department of Fish and Wildlife's *E. editha* conservation work stated that there is a concern here in the Pacific Northwest that the excessive moisture may be causing the pupae to rot in their cocoons before they have a chance to eclose. This is a theory that needs to be researched, because it is a completely different effect that global climate change has brought to the local *E. editha* here in the Pacific Northwest than what has been in California. Adding to the problems facing these creatures, *E. editha's* reproductive behaviors are being impacted by climate change causing a "lag effect", where the butterflies are effected by the previous year's climate (Parmesan et al. 2015; Weiss and Weiss 1998). Herein lies the challenge of reintroduction and habitat planning for the biologists and conservationists involved in the Pacific Northwest.

The 2017 final annual report to the US Fish and Wildlife Service, Joint Lewis-McChord, and the ACUB Technical Review Committee compiled by the Washington State Department of Fish and Wildlife (WDFW), the Oregon Zoo, and The Evergreen State College (TESC) dedicated much of its discussion at the end of the report calling for research on climate-related effects on Taylor's checkerspot populations in the Puget Sound to help answer questions they have about habitat quality such as patch size and connectivity. (Linders, Lewis, and Curry 2016).

The methodology for climate research outlined by biologists are as follows (M. J. Linders, 2013):

- Combine the climate components data
- Find gaps in the data (in number of days)
- Compile start and end flight season dates per year per site
- Look for patterns of checkerspot abundance with respect to climate elements.
- Look for anomalies in the climate data: find average range of temperature and precipitation on a monthly basis.
- Generate a summary of butterfly abundance and phenology with respect to the climate elements.

The data sets come from a variety of different sources, most notably, Wunderground, PRISM, and NOAA.

Study of the local populations with respect to the local weather patterns should assist the wildlife managers in finding suitability in habitat assessments. Because of the lack of knowledge of the local Puget Sound Taylor's Checkerspots (*Euphydryas editha taylori*) with respect to the provincial weather patterns and regional climate oscillations due to the lack of available funding to conduct such studies. Long-term population monitoring with respect to microclimate studies are imperative because *E. editha* are so weather dependent. WDFW biologists have stressed that adult eclosion (emergence) depends on rainfall and the first flight season of butterflies determines the oviposition preferences (distribution of eggs).

Conservation of Taylor's Checkerspot

E. editha are in danger of going extinct. They were listed in 2000 as endangered and there are only about 100 left in Canada ("Edith's Checkerspot" 2007). We need to look at how this species is being affected by global climate change locally and compare these effects to other taxonomic groups (Ehrlich and Hanski 2004a). Phenological asynchrony is not just hurting *E. editha*. It is a problem for the prairie plants who depend on the timing of their pollinators (Husby 2012). Ecological conservation is not just about one species, it is about systems and the collapse of entire web networks of organisms that depend on each-other. The plight of the local populations of *E. editha* is just a small component of a breath-taking problem of ecological collapse.

Research such as this brings to light the local problems caused by global climate change and highlights the importance of habitat conservation. It helps in shifting public attitudes on global climate change through demonstration of the local effects of weather and climate change through time and the effects of these changes on specific species. Studies such as these show that it is imperative habitats are not only repaired but expanded to prevent the biological apocalypse from happening. This study on climate and how it affects *E. editha* is necessary because conservation managers such as WDFW and the Oregon Zoo must make informed management decisions such as when and where to place captive bred Taylor's Checkerspot Butterflies for maximum probability of reintroduction success knowing that climate and weather will be a component of survival.

METHODOLOGY

Data Collection for population counts of *E. editha* adults

The Washington State Department of Fish and Wildlife (WDFW) biologists used distance sampling to obtain the population count data. The advantage of distance sampling is that it is a statistically based methodology that accounts for imperfect and variable detectability brought about by climate, vegetation, observer, time of day, or number of individuals. Detectability declines with distance (Olson, 2017), and this can be modeled to account for variability in data collection.

Distance sampling is a technique where observers walk along transect lines that are established with fixed coordinates and marked with colored flagging. The observer walks along the lines looking for the butterflies and records the perpendicular distance from the line to the butterfly. This is a difficult skill to learn and takes extensive training or sophisticated measurement equipment (Olson, 2011). They used a survey technique called "line transect sampling", which accounts for differences in detectability of the butterflies in some sites vs. others (Brown & Boyce, 1998). Transects are imaginary 700-meter lines drawn through a sampling area. The spacing between the lines are 100 meters with the segment length altered to be 25 meters (M. J. Linders & Olson, 2014a; M. Linders, Lewis, & Curry, 2016). The definition of a segment is a unit within the 700-meter transect where butterflies are counted. Essentially, each segment is the "container" containing each butterfly count. The counts were performed between 1000 and 1630 hours (M. J. Linders & Olson, 2014). The WDFW biologists have collected data in the Pacific Northwest on adult presence, distribution, and relative abundance. Surveys and transects were conducted only if the ambient temperature was ≥11.7° C, there was sufficient sunshine to cast a soft or distinct shadow, or if no shadow temperature was >15.5°C.

Project sites

There are six project sites in the Puget Sound chosen for the rehabilitation activities.

- The Scatter Creek Wildlife Area-South Unit (SCS)
- Range 50, Joint Base Lewis-McCord (JBLM)
- The Pacemaker Airstrip, JBLM
- The Glacial Heritage Preserve
- Training Area 7 South, JBLM
- Range 76, JBLM

Because of data availability, only three of the six sites will be used for this particular study: Range 76 (R76) and Range 50 (R50) at JBLM, and Scatter Creek Wildlife Area-South Unit (SCS).

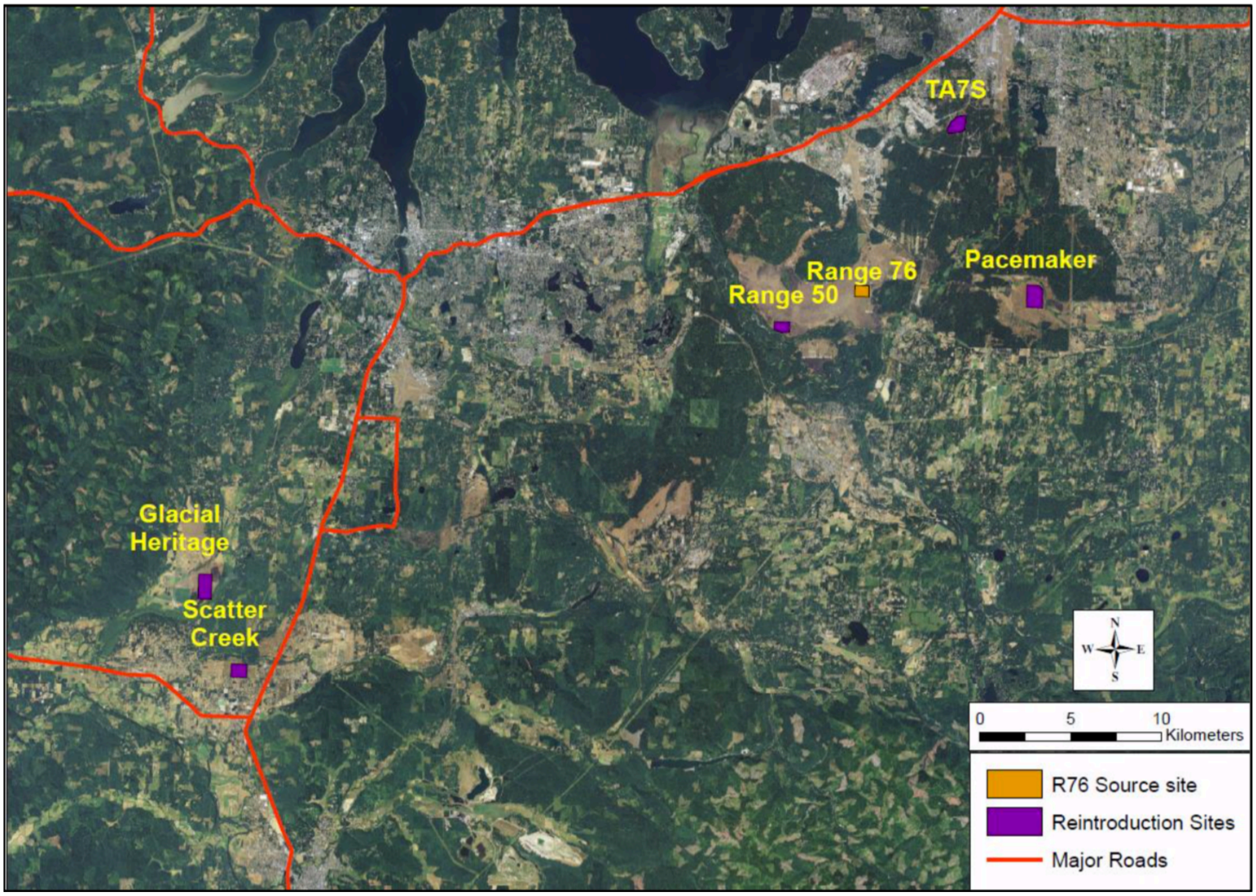


Figure 1 Taylor's checkerspot rehabilitation sites (Linders, Lewis, & Curry, 2016)

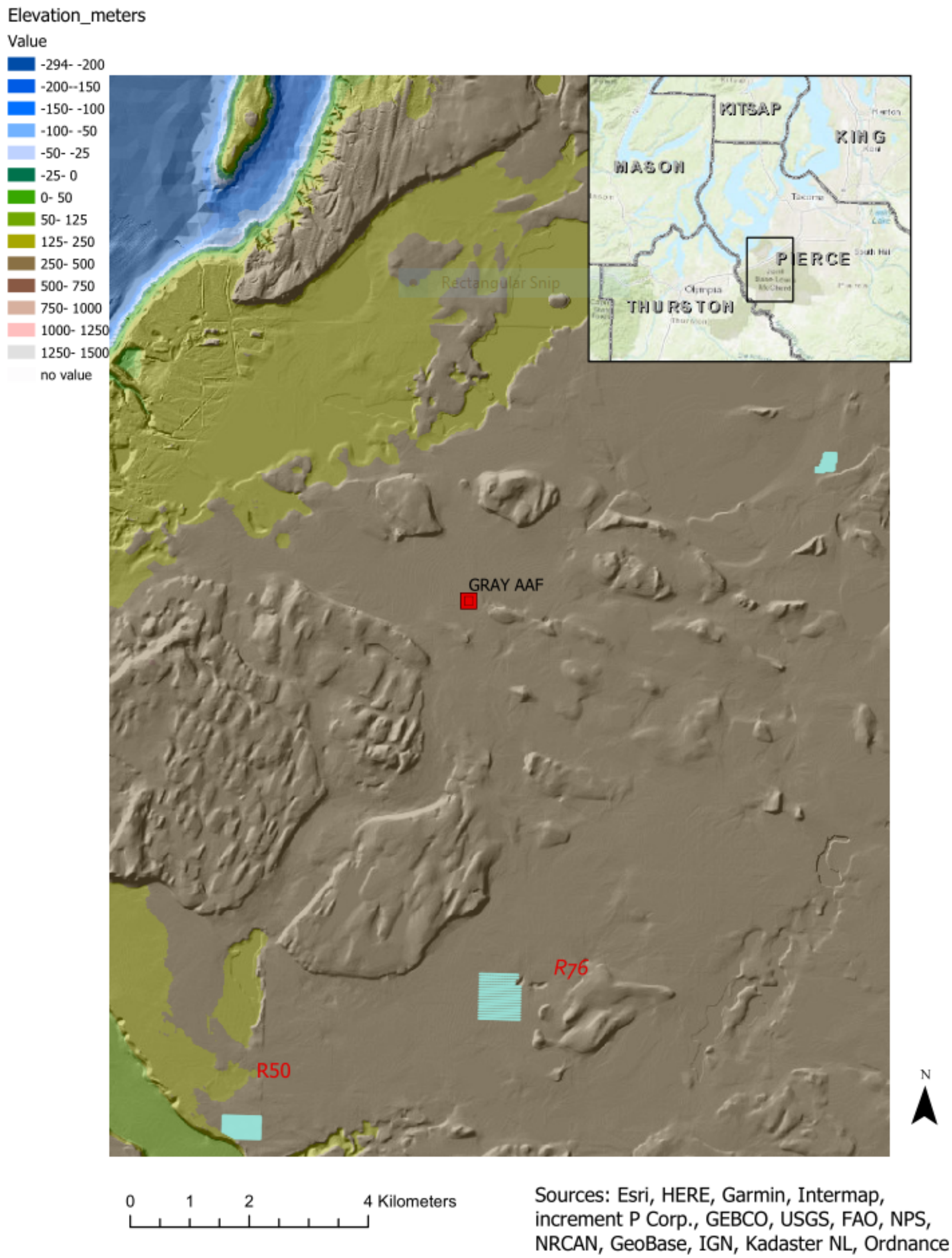
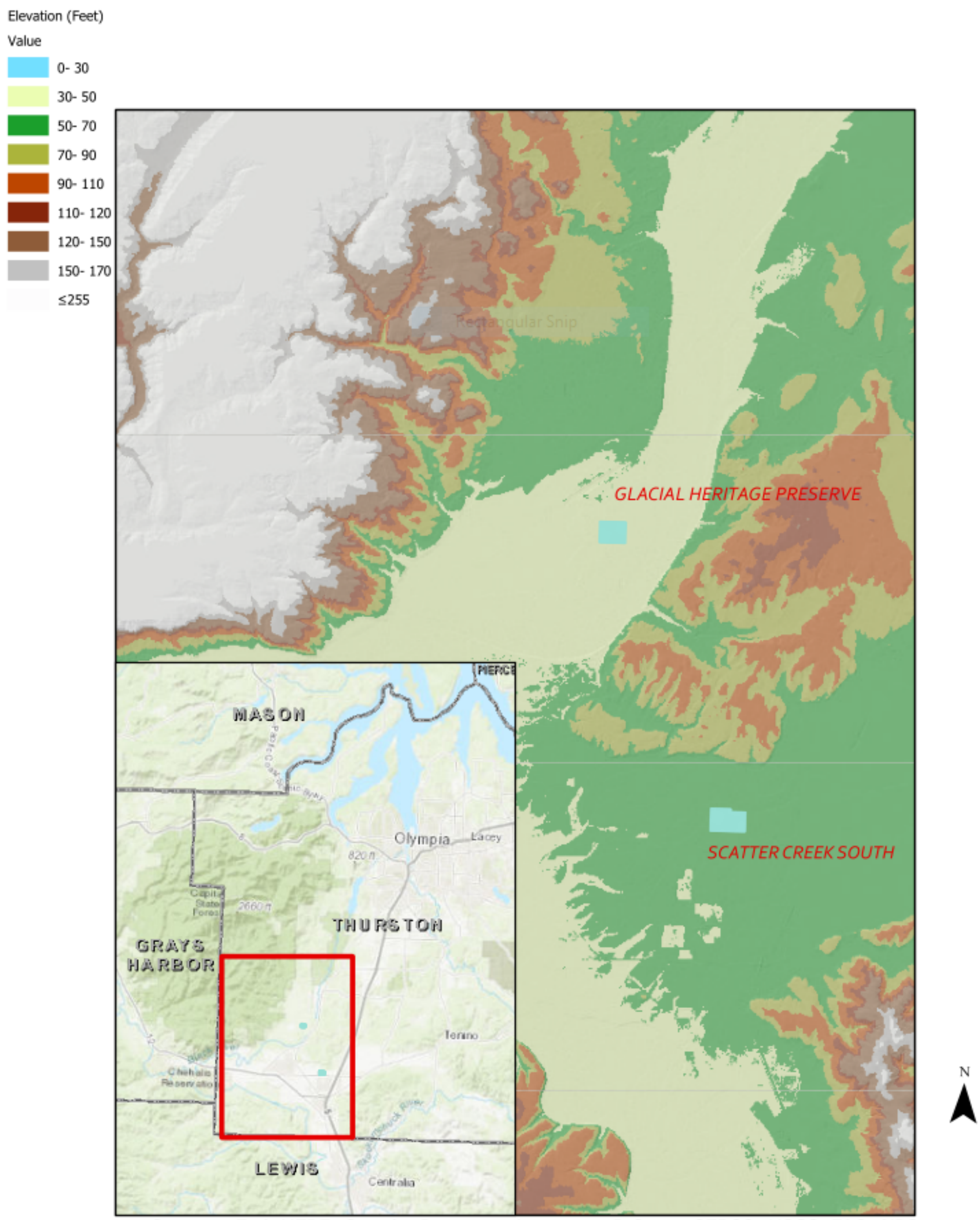


Figure 2: Location of R50 and R76 shown with Gray Army Airfield weather station location (included in PRISM network)



Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community

Figure 3: Location of Scatter Creek South site

Adult butterfly counts

The biologists conducted surveys of adults up to three times during the flight season, which ranges from between early April and late May. They chose the locations of the survey sites to be the sites of reintroduction with a 200-foot buffer to include those butterflies that wandered off the reintroduction sites.

Analysis for butterfly count data

Observer differences, especially in 2016 where there were a few observers who were in training who broke the guidelines that had been set by Linders and Olson in 2014 (M. J. Linders & Olson, 2014) created confounding factors. Due to this problem, the biologists had to perform data manipulation to fit curves to the data and increase the 95 % confidence intervals.

WDFW biologists analyzed the data with the program called, "Distance, Version 6.2"(Thomas et al., 2010). They first generated summary statistics in SAS statistical software. Models of analysis were developed to account for the observer differences. Akaike's Information Criterion (AIC), goodness of fit tests, and additional criteria were used to detect the variability (error) in encounter rates at transect lines. Variance estimates of density were calculated using the method of Fewster et al. (2009). Otherwise a non-parametric bootstrap method was used (Marques, Thomas, Fancy, & Buckland, 2007). This method makes sense in that count numbers to the expert eye should be in higher numbers near the transect with a smooth drop off in sightings the farther the distance from the observer. The program, "Distance" takes these curves in the data and generates density estimates, which are calculated to account for total butterfly abundance for each study site. The abundance calculations were then used for the general additive models (GAM) that estimate the peak abundance values for each study year.

Data collection for climate elements

Overall, the climate elements biologists at WDFW find pertinent are:

- Insolation
- Degree days
- Rainfall (precipitation)
- Overwinter moisture, total and delivery in heavy flood-prone events
- Number of days below freezing.

This thesis used weather data available on the PRISM website maintained and managed by the University of Washington's School of Oceanography. PRISM offers a datasets from an interpolation of a network of weather stations that account for slope, distance from the coast, elevation, and aspect (Daly et al., 2008). The data from PRISM is available in the form of a geographic raster DEM format where the climate elements can be converted to Z-values or can be simply downloaded from a point source as a direct download in comma separated values into a spreadsheet. The most popular data from PRISM are the 30-year average datasets, can be used to discuss the findings for long term implications, or be used to examine climate anomalies (Figure 4).

This thesis used the point source data downloads option to obtain the climate measurements closest to the study sites. Before downloading the data, it was confirmed the weather stations included in the network are close to the study sites. The Gray Army Airfield is the weather station located closest to the sites in Joint Base Lewis-McCord.

Range 76 is 4.0 miles and Range 50 is 5.9 miles away. The Centralia weather station is the closest weather station to Scatter Creek at a distance of 6.5 miles.

Only precipitation, humidity, and temperature were used as the independent variables for this analysis and only the winter climate elements were examined. Winter values are for the months of December, January, and February preceding a given year's butterfly abundance estimates. Temperature (temp) was calculated as the average, in degrees Fahrenheit, for the winter months, humidity was the winter average max vapor pressure deficit (VPD, a measure of dryness), and precipitation was the total winter sum of precipitation in millimeters (mm). Humidity and temperature values were measured value readings, and precipitation was a measure summed value from PRISM.

The analysis included the average winter temperature (average of the mean values returned from PRISM). The overwinter precipitation values was the total sum of precipitation for the winter months (PRISM measure converted to millimeters and added over the entire winter), and the over winter humidity was an average of the *maximum* dryness for each winter month as opposed to the average of minimum dryness. Taking the maximum dryness values in vapor pressure deficit was a judgement call to measure how maximum dryness is affecting the butterfly populations.

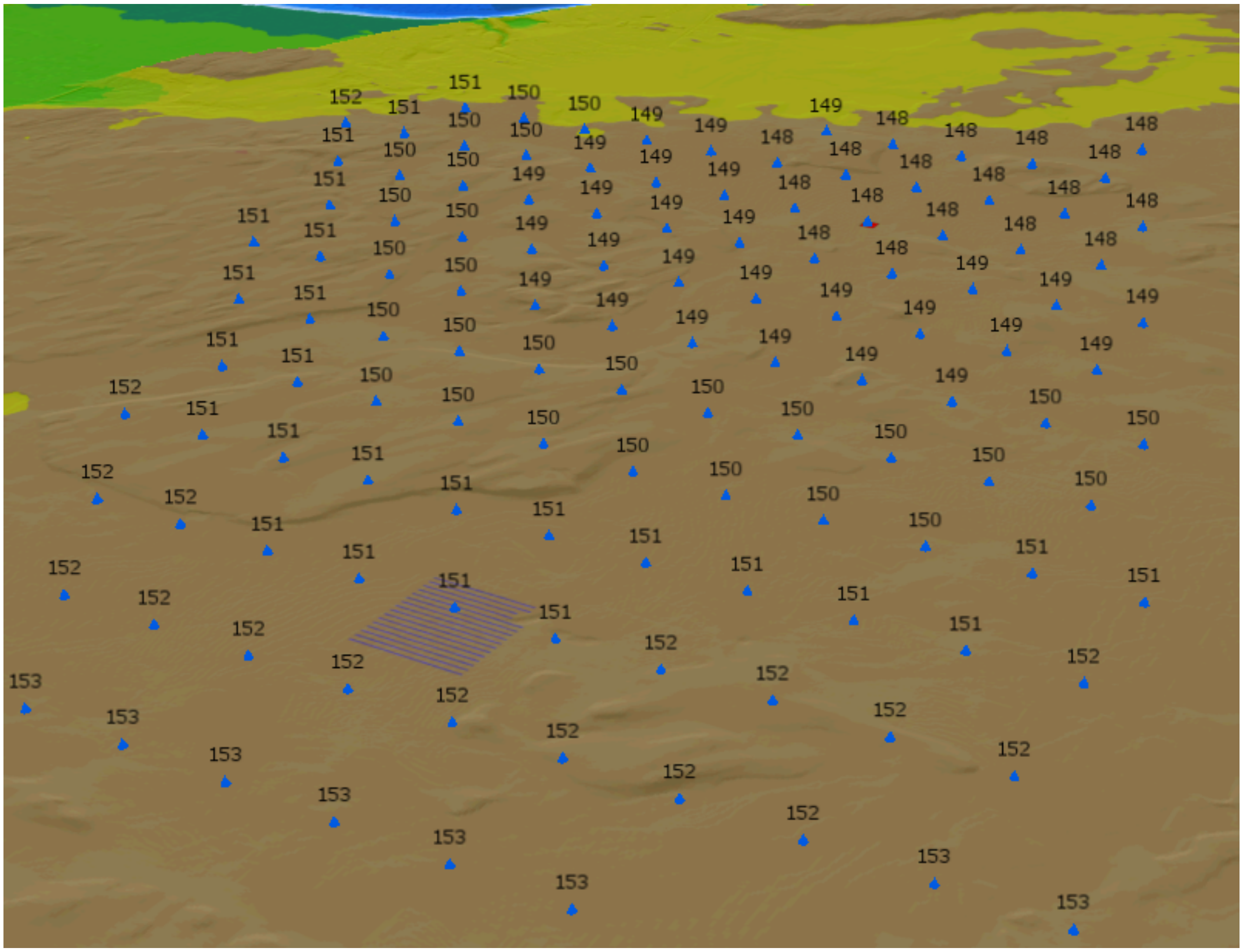


Figure 4: 30-year average from 1981-2010 of precipitation values in millimeters on and near site R76

Methodology for the statistical analysis

The purpose of this thesis is to assist land managers in the task of predicting the phenology of the Taylor's Checkerspot Butterfly in the areas of reintroduction. The question this thesis aims to answer is, "Do winter climate variables in the South Puget Sound predict the population counts of Taylor's Checkerspot Butterflies?" We already know that post-diapause larvae are dependent on insolation to develop at the correct physiological time (Weiss, Murphy, Ehrlich, & Metzler, 1993; Weiss & Weiss, 1998).

The statistical analysis

The statistical analysis chosen for this thesis included regression models performed in R: A Language and Environment for Statistical Computing (R Core Team 2019). Each climate element was inspected with respect to the peak general additive model (GAM) values for abundance. The choice to use a generalized linear model was affirmed by an examination of all the plots of the residuals, which indicated reasonable model fit.

For the three sites with enough data for analysis (R76, R50 and SCS), the assumption was made that the count of butterflies has its peak when winter climate conditions were ideal – i.e. the species needs a certain range of temperatures, humidity, and precipitation. The null hypothesis for each model was H_0: "The winter climate element does not affect the abundance of butterflies for the following spring". This null hypothesis was tested in a series of steps:

1) Plot the peak GAM point of butterfly abundance against each climate variable. Consider a log transformation of peak GAM values.
2) Perform a correlation analysis on the data with respect to each climate variable to assess whether regression analyses are merited.
3) If called for, run a simple linear regression on each climate variable and year, with either raw peak GAM or log-transformed peak GAM as the response.
4) Use a model selection approach to assess multiple models (both simple and multiple linear regression models, as deemed reasonable).

If the scatterplots and examination of the plots of the residuals show the climatic variables have a linear relationship to the peak GAM abundance values, the linear regression would give this equation:

$$Y \sim \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \beta_3 x_{i3} + \varepsilon_i$$

Here is the multiple linear regression model for this quadratic relationship, if there is one:

$$Y \sim \beta_0 + \beta_1 x_{i1} + \beta_2 {x_{i1}}^2 + \beta_3 x_{i2} + \varepsilon_i$$

Where

$Y = Butterfly\ count(peak\ abundance\ or\ area\ under\ the\ curve\ for\ each\ season)$

$x_1 = Precipitation$ in mm

$x_2 = Temperature$ in Fahrenheit

$x_3 = Humidity\ in\ VPD(a\ measure\ of\ dryness)$

$i = number\ of\ observations$

Other climate variables (x) could be added to the model, such as wind, number of days below freezing, insolation, heavy flood events, etc., but for the scope of this thesis, the multiple linear regression will be limited to temperature, humidity and precipitation. Furthermore, it will be assumed that the climatic variables used as independent variables in this analysis will be independent *enough* from each other if the correlation coefficient is less than $r = 0.8$.

Modeling the abundance values

The values for abundance data from the three sites that had been compiled by WDFW statisticians and biologists as output from the program "Distance" were used as inputs for the GAM model (Hastie & Tibsirani, 1987) for the purpose of extracting peak abundance values for each site per year. The data for these models needed to have the degrees of freedom calculated due to a low number of observations (from 3-12 in a given year).

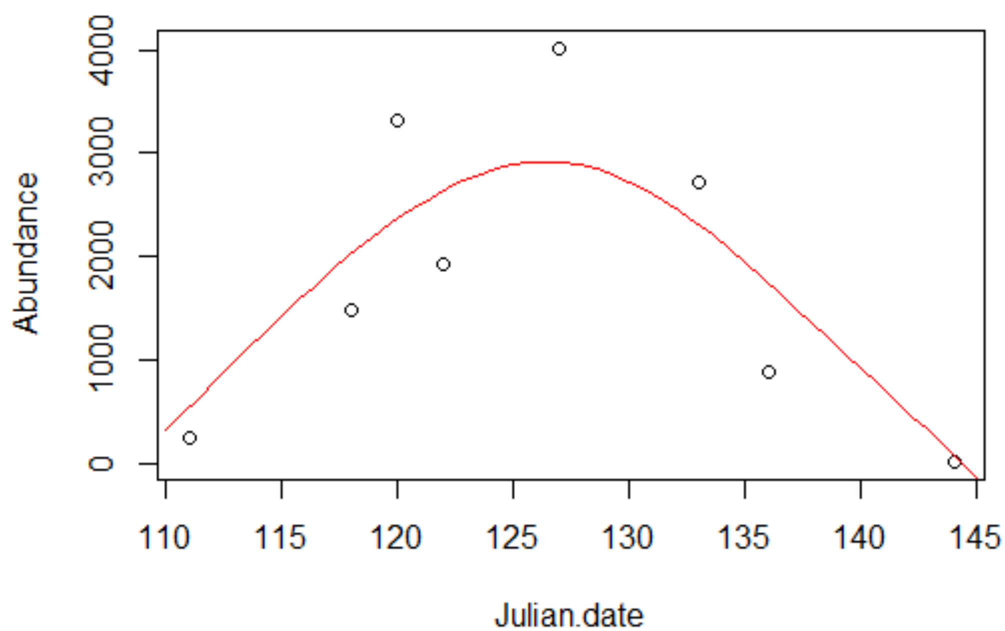


Figure 5: Plot of abundance vs. Julian date for the year 2014 in R76 as a general additive model (GAM). All of these plots are available for inspection in the Appendices.

As an example, the GAM model shown for the Range 76 site in 2014 (Figure 5) yields a peak GAM value of 2919 butterflies (see Appendix A for all individual GAM plots). These yearly maximum values from the GAM models were used in linear regression and correlation models to determine if the winter climatic variables affect the populations of butterflies.

Three climatic variables were tested against the peak GAM values for the three study sites: precipitation in millimeters, temperature in Fahrenheit, and humidity in average maximum vapor pressure deficit (VPD), which is a measurement of dryness (Prenger & Ling, n.d.). An analysis with the peak GAM values as the response was run first with no significant results (See Appendix B).

Regression models were created with log_{10}-transformed peak GAM values as the response variable. All candidate models were evaluated using Akaike's information criterion corrected for small sample sizes (AICc, recommended for cases where $n/K < 40$, Burnham and Anderson 2002) to determine empirical support for the different candidate models. This analysis differed from the raw data analysis in that it also included the year as an independent variable.

RESULTS AND DISCUSSION

R76 data analysis of log-transformed peak GAM data

Correlation of log-transformed peak GAM data from site R76 with winter climate variables was low (Table 1), and there did not appear to be any trend across the years of the data (Figure 6). Therefore, regression analyses were not performed for the R76 peak GAM data.

Table 1: Correlation Matrix for site R76.

Variable	PeakGAM	Log Peak(GAM)	Precipitation	Temperature	Vapor Pressure Deficit	Year
PeakGAM	1	NA	.102	.180	-.357	.074
Log(peakGAM)	NA	1	.122	.245	-.254	.135
Precipitation	.102	.122	1	.431	-.186	-.056
Temperature	.180	.245	.431	1	-.297	.253
Vapor Pressure deficit	-.357	-.254	-.186	-.297	1	-.647
Year	.074	.135	-.056	.253	-.647	1

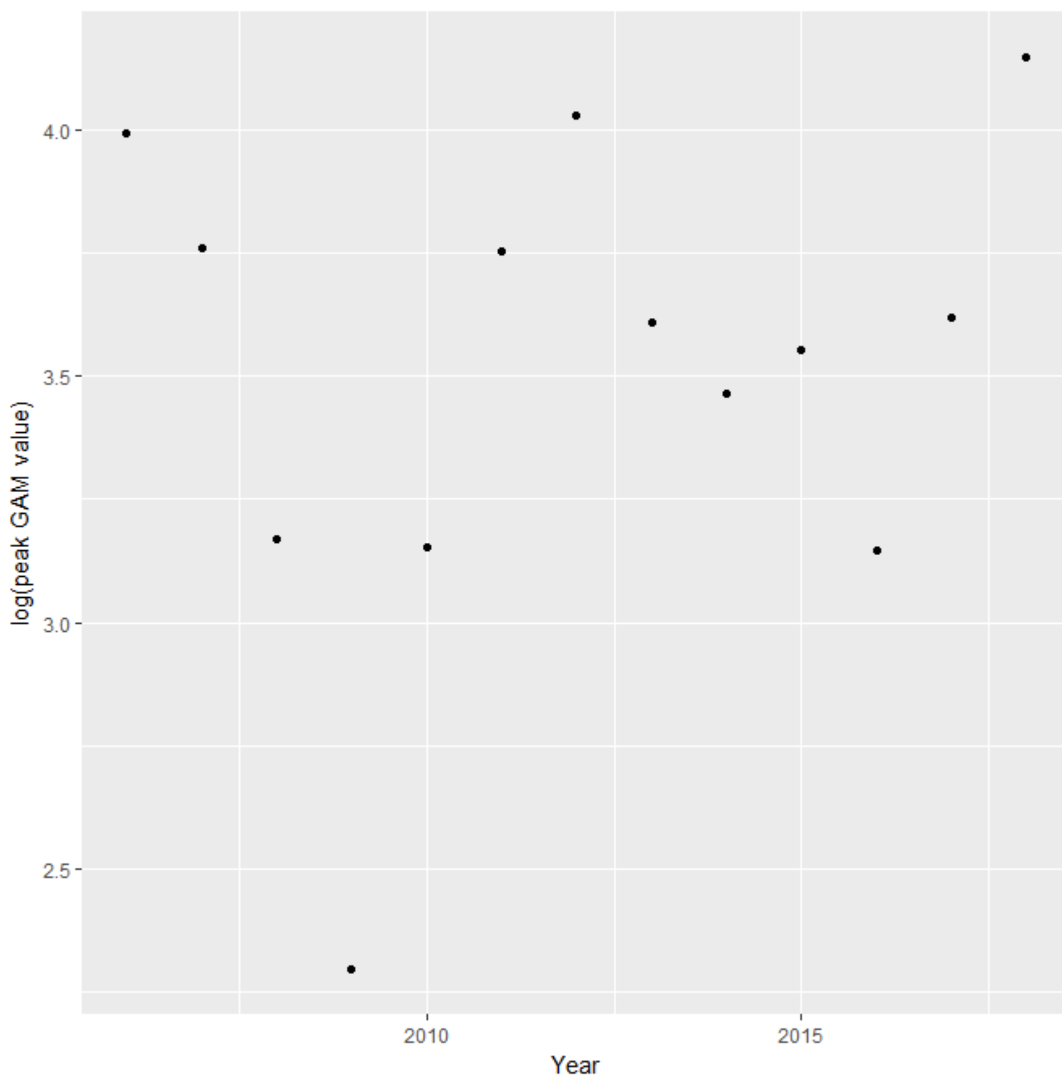


Figure 6: Plot of the log Peak (GAM) vs. year at site R76

R50 data analysis of log-transformed data

Using a model selection approach, a simple linear regression with 'year' as the only independent variable had the best support and year was included in the top four supported models (Table 2, Figure 7). In the best-supported model, year had a coefficient of 0.1684 for an annual average increase of 47% (Figure 7). For illustration, bivariate plots of log-transformed peak GAM from R50 with each climatic variable are also included here (Figures 7-10), but these variables were only part of models with relatively little support (Akaike weights < 0.05). In comparing models using the evidence ratio, the simple regression model with the variable, "Year" is 23.8 times more likely to be a better model than the simple linear regression model with vapor pressure deficit, based on the Akaike weights.

Table 2: Model selection results for site R50 with log-transformed peak GAM values as the response variable. Only models with ΔAICc < 10 and Akaike weights > 0.01 are shown.

Model: $\log_{10}$ (peakGAM) ~	**AICc**	**ΔAICc**	**Akaike weight**	**Adjusted R^2**	**P.Value**	**F-Statistic**
Year	8.20	0.00	0.882	0.78	<0.001	30.19 on 1 and 7 df
vapor pressure deficit + year	14.56	6.36	0.037	0.77	<0.001	14.48 on 2 and 6 df
temperature + year	14.74	6.54	0.033	0.77	0.005	14.15 on 2 and 6 df
precipitation + year	15.39	7.19	0.024	0.75	0.007	12.94 on 2 and 6 df
vapor pressure deficit	16.30	8.10	0.015	0.47	0.025	8.11 on 1 and 7 df

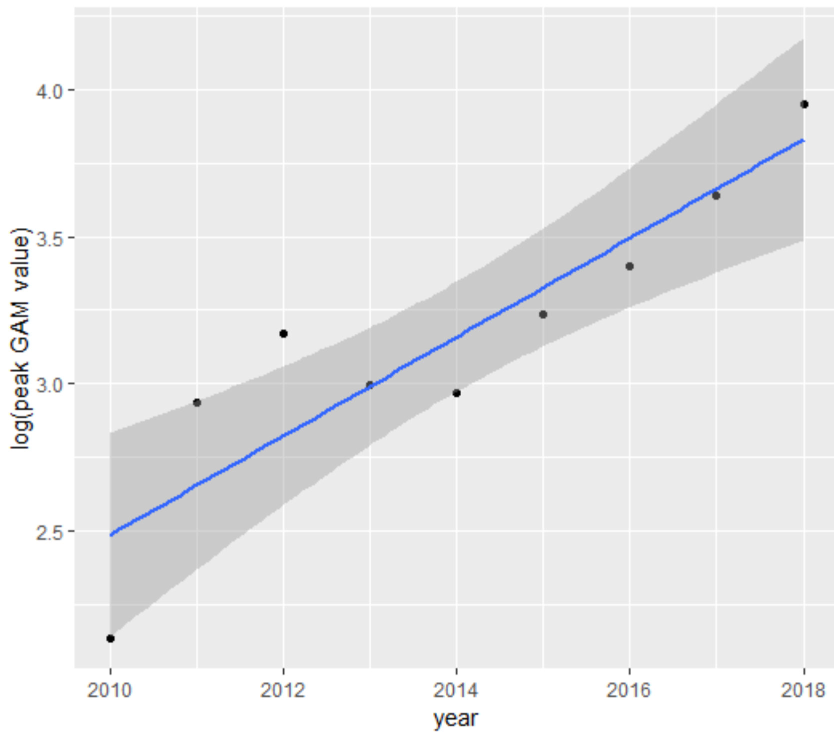


*Figure7: Plot of year vs. log peak (GAM) at site R50. Regression equation is log(peak GAM) = -336 +17 * year.*

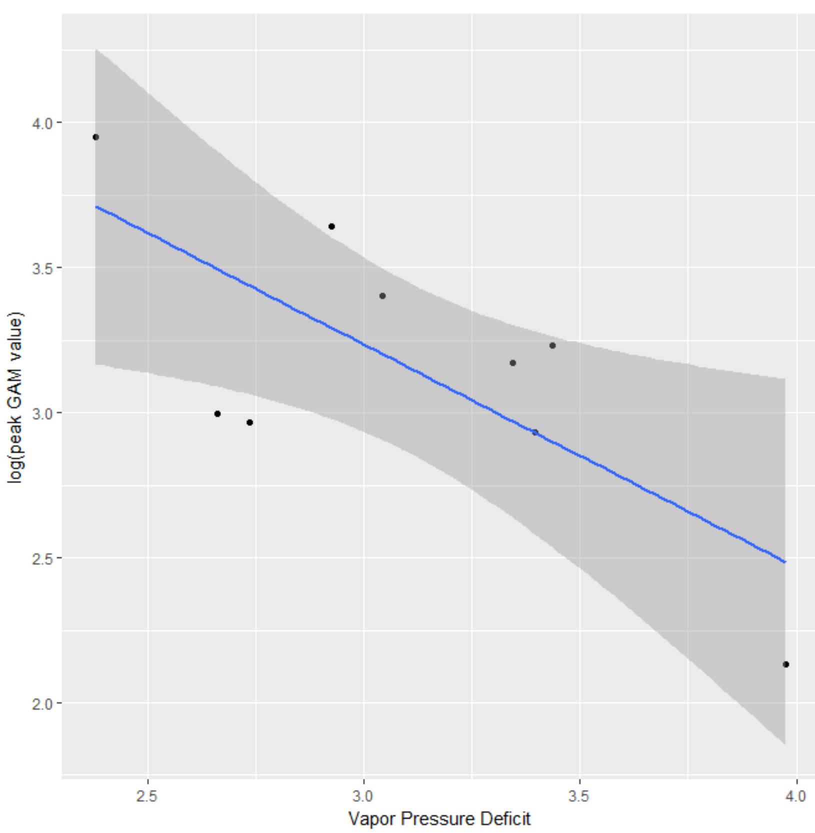


*Figure 8: Plot of max vapor pressure deficit vs. log peak (GAM) at site R50. Regression equation is log(peak GAM) = 5.54-.77*vpd*

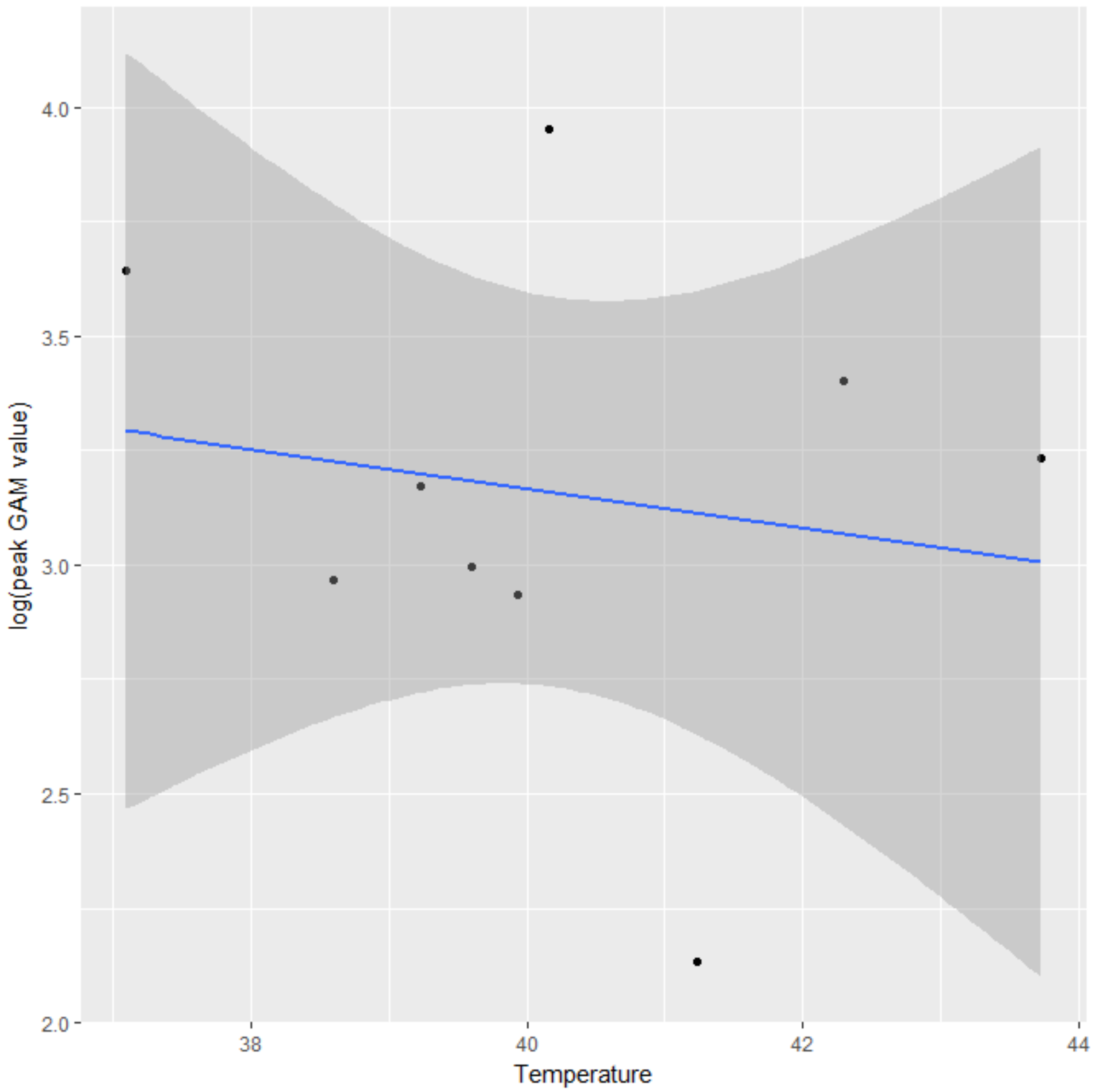


*Figure 9: Plot of Temperature vs. log (peak GAM) at site R50. Regression equation is log peak (GAM) = 4.89-.04*T*

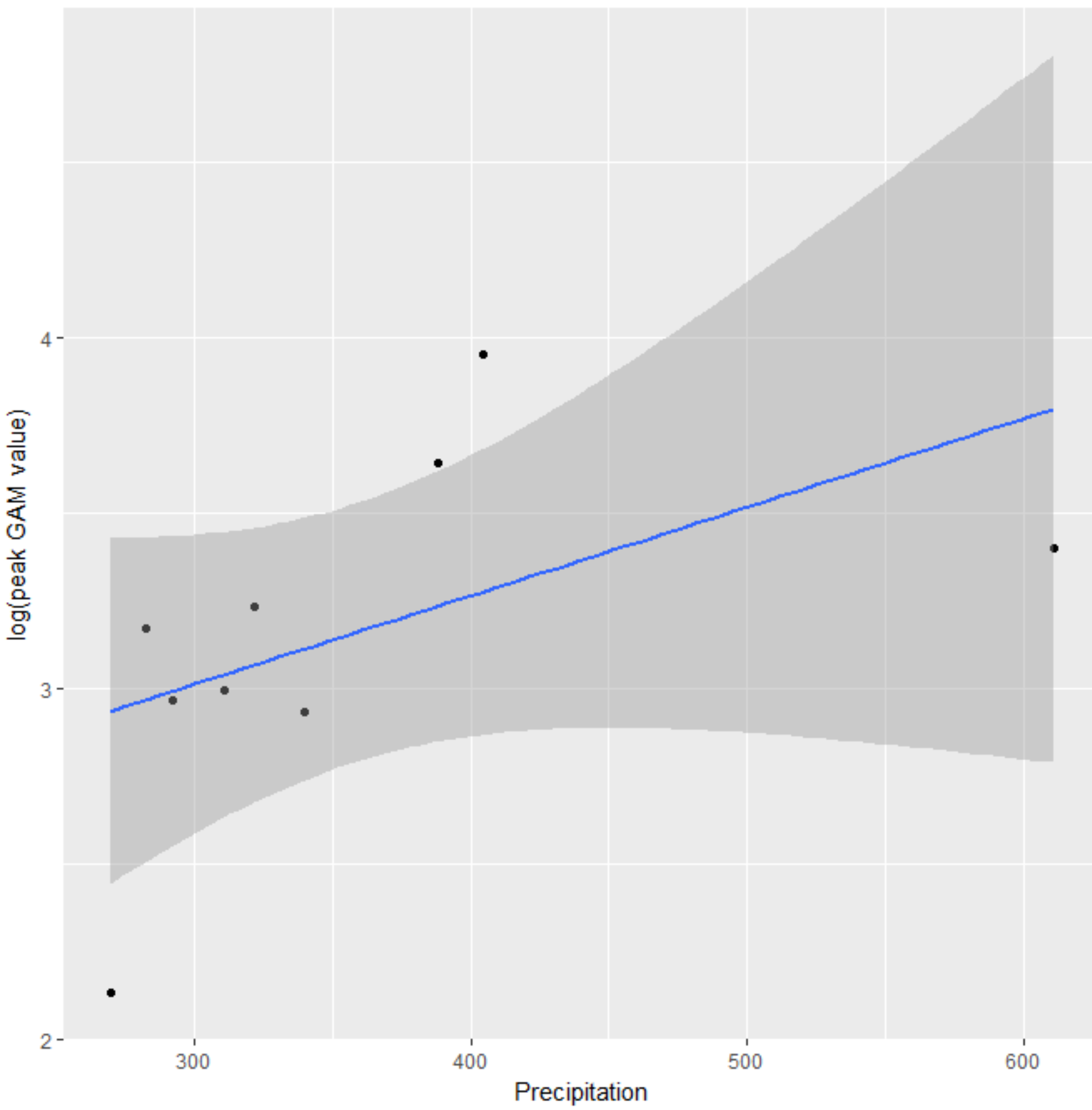


*Figure 10: Plot of Precipitation vs log peak (GAM) at site R50. Equation is log (peak (GAM)=2.25 + .003*ppt*

SCS data analysis of log-transformed peak GAM data

Using a model selection approach, a simple linear regression with year as the only independent variable had the best support, and year was included in all supported models (i.e. with Akaike weight > 0.01, Table 3, Figure 11). In the best-supported model, year had a coefficient of 0.2436, for an annual average increase of 75% (Figure 11). For illustration, bivariate plots of log-transformed peak GAM from SCS with each climatic variable are also included here (Figures 11-14) but these variables were only part of models with relatively little support (Akaike weights < 0.10). In comparing models using the evidence ratio, the simple regression model with the variable, "Year" is 13.9 times more likely to be a better model than the multiple linear regression model with temperature + year, based on the Akaike weights.

Table 3: Model selection results for site SCS with log-transformed peak GAM values as the response variable. Only models with ΔAICc < 10 and Akaike weights > 0.01 are shown.

Model: $\log_{10}$ (peakGAM) ~	**AICc**	**ΔAICc**	**Akaike weight**	**Adjusted R^2**	**P.Value**	**F-Statistic**
Year	13.34	0.00	0.849	0.84	0.000122	47.92 on 1 and 8 df
temperature + year	18.62	5.28	0.061	0.83	0.000861	22.79 on 2 and 7 df
precipitation + year	19.13	5.79	0.047	0.82	0.00103	21.48 on 2 and 7 df
vapor pressure deficit + year	19.26	5.92	0.044	0.82	0.00108	21.14 on 2 and 7 df

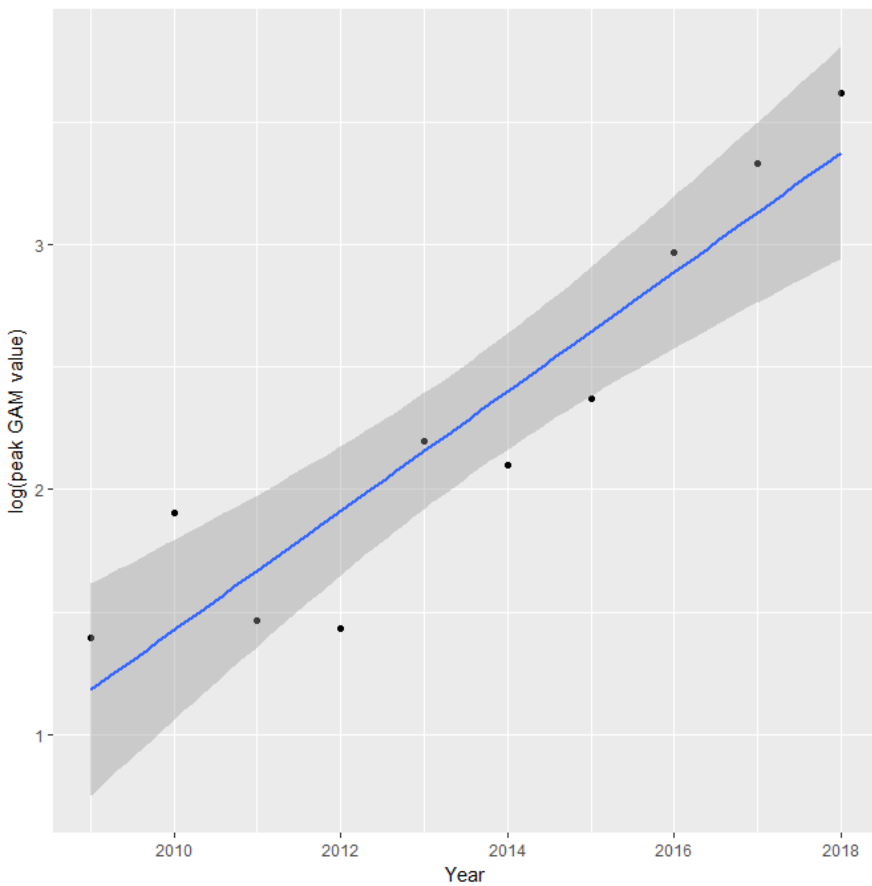


*Figure 11: Scatter Creek South plot of log peak (GAM) vs. Year Regression Equation is log peak(GAM)=-488.19 + .24 * Year*

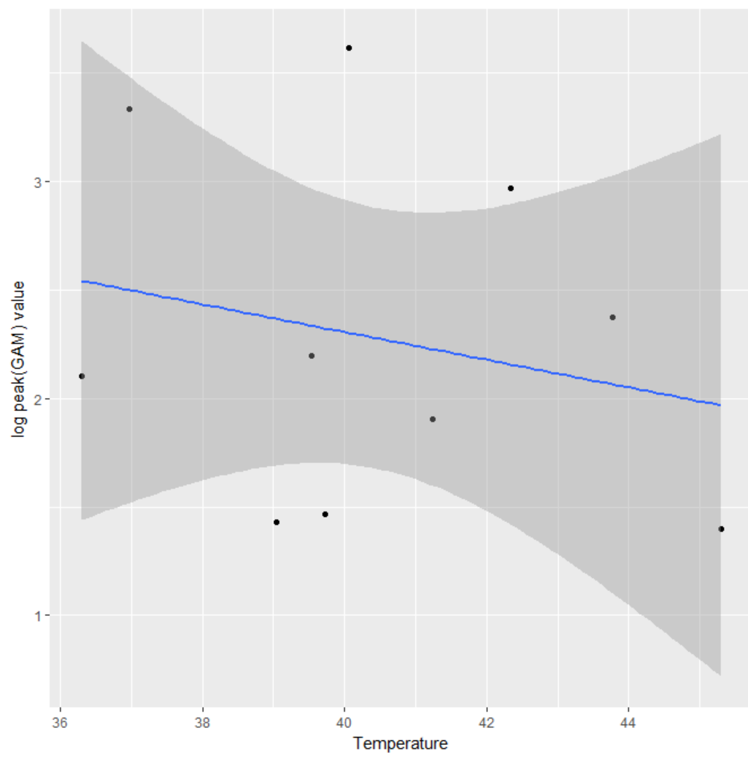


*Figure 12: Scatter Creek South plot of log peak (GAM) vs. Temperature. Regression equation is log peak (GAM) = 4.86 - .06 * T*

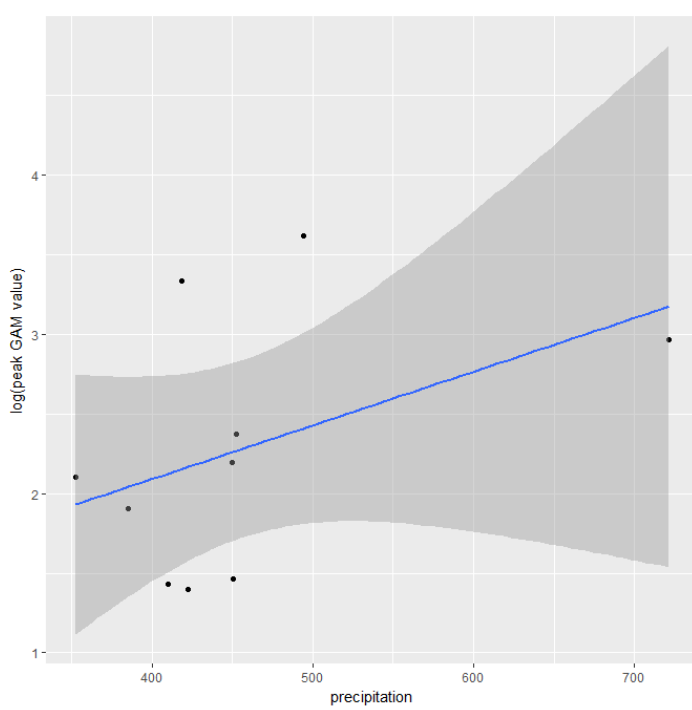


*Figure 73: Plot of Scatter Creek South log peak(GAM) vs. precipitation. Regression equation is log peak(GAM) = 0.74 + .003 * ppt*

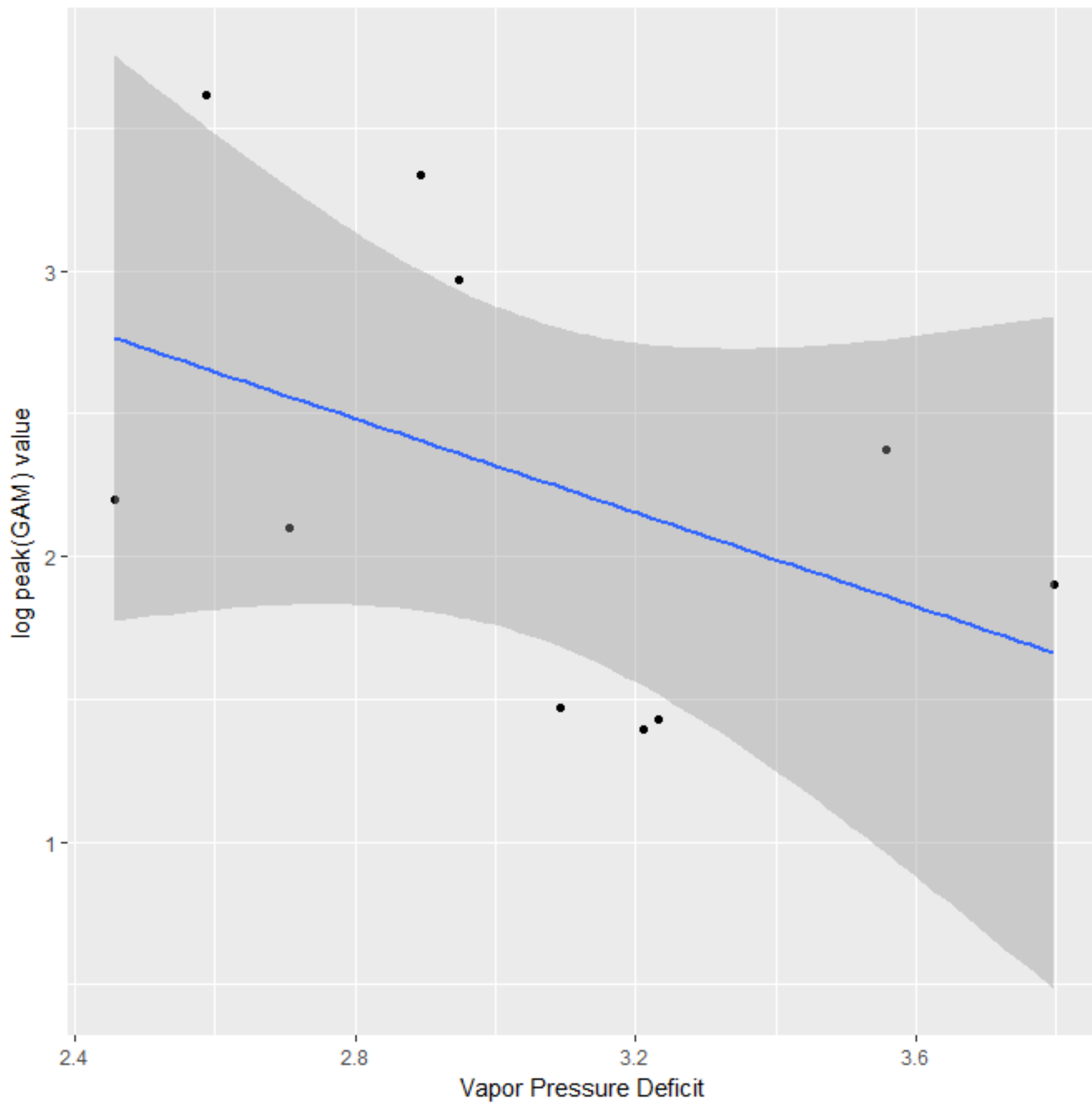


*Figure 14: Plot of Scatter Creek South log peak(GAM) vs. vapor pressure deficit. Regression equation is log peak(GAM) = 4.78 - .82 * vpd*

Discussion

There is an active effort to reintroduce butterflies to several locations, including Scatter Creek South and R50. As these prairies are being improved for habitat and butterflies are reestablishing themselves, the populations may just be naturally increasing due to habitat filling where the butterflies are being returned to their historic ranges, resulting in a significant increase over the past ten years, and reflected in the model selection results for R50 and SCS

Perhaps the population numbers are expanding due to having been introduced to high-quality habitat and could still level off and/or become more subject to variations due to climatic conditions. Abundance of this species is a complex question that involves many different elements besides climate. Additionally, the question of climate is further complicated by the possibility of a lag effect, where the previous year's climatic variables are probably affecting the numbers of the butterflies for the current year. Many studies on the climate should be done to answer the question of climate and its effect on *E. editha taylori* here in the Pacific Northwest.

This thesis was a small-scale examination of the winter climatic variables, but there is the possibility that summer climatic variables are just as, or more important to consider and *should* be the topic of future studies. WDFW biologists working with the Taylor's Checkerspots noted the 2006 July temperature fluctuations were large, varying from around 20-40 degrees. Bay Checkerspots of California are losing the night time cooling effects during the summer, which could have implications for *E. editha* (Arndt 2015). Given the large amount of summer data WDFW has with day and night time fluctuations, we may be able to answer the question about night-time warming as mentioned by Arndt.

Peak GAM points

One important thing to note is that the GAM models needed to have the degrees of freedom calculated and added to the models due to the low number of observations.

This calculation may have added some error to the process. Site R76 needed to have year 2008 excluded due to insufficient data.

These findings in the context of climate change

The choice of following the data for winter climatic variables as a possible effect on the local Taylor's Checkerspot butterflies is due to the phenomenon of climate change. Unfortunately, global climate change has lengthened the "green" season. This could be the reason the humidity values are so important in this data analysis. If the humidity is such that winters are too dry, we may be witnessing the deleterious effects of the unseasonal dryness during the winter. (Miller-Rushing and Primack 2008; Abarca and Lill 2015).

Indeed, studies have shown that the Bay Checkerspot butterflies (*E. editha bayensis*) in California have move north and to higher elevations where the climate is damper and cooler due to the deleterious effects of the dryness brought on by climate change. (Cohen 1996; "Edith's Checkerspot" 2007; Parmesan et al. 2015; Lacy et al. 2017; Parsons 1995; McInnis 1997; Michael C. Singer and Parmesan 2010). Perhaps the increases in butterfly abundance at these sites is due to the fact that the effects of Global Climate change here in the Pacific Northwest may be helpful to the butterfly during the winter months. The Northwest is a cool, wet place, though droughts do occur here. Climate change here in the Pacific Northwest will bring hotter, dryer summers and warmer, wetter winters (Glenn et al. 2011a; Parsons 1995). The worry here in the Pacific Northwest is that the wetter winters will cause the pupae to rot. Pupation does not occur till spring, and the butterflies are in larval stage diapause during the winter, so the humidity values over winter are not the whole picture.

In the context of climate change, the work to save the E. *editha taylori* is not just about that species, it is about the repair of whole ecological systems.

CONCLUSION

This research revealed evidence of winter climate affecting the estimates of peak abundance in the three sites examined. (See tables 2 and 3). The main finding of this thesis was that the two reintroduction sites increased with time, where Scatter Creek South increased an average of 47% over time and Range 50 increased in abundance an average of 75% over time. This phenomenon could simply be a reintroduction effect and not related to climate at all.

Maximum dryness of the air during the winter is possibly to be linked to lower abundances of butterflies the following spring in Range 50 and Scatter Creek South. Range 76 showed no significant correlations between the climate variables and the abundance estimates. Possible links of high vapor pressure deficit to lower abundance estimates hint similar findings from studies on the Bay checkerspot, which show excess dryness in the air to be a detriment.

Funding is being sought here in the Pacific Northwest to explore the effects of climate on the abundance of this endangered species. This work is a small part of a giant project where future researchers can and should explore many angles to help solve the question of what the effects of climate are on *E editha* of the Puget Sound.

BIBLIOGRAPHY

10 Terrific Facts About Trilobites. (2015, September 23). Retrieved November 5, 2017, from http://mentalfloss.com/article/68881/10-terrific-facts-about-trilobites

Abarca, M., & Lill, J. T. (2015). Warming affects hatching time and early season survival of eastern tent caterpillars. *Oecologia*, *179*(3), 901–912. https://doi.org/10.1007/s00442-015-3371-x

Allen, E., Dodero, M., Longcore, T., Murphy, D., Parmesan, C., Pratt, G., … Anderson, A. (2003). *Recovery Plan for the Quino Checkerspot Butterfly* (p. 133) [Recovery Plan]. U.S. Fish and Wildlife Service.

Andrusyszyn, R. (2013). *Using Fire for Butterflies: Soil Characteristics Across a Burn Gradient in Western Washington Prairies* (Master of Environmental Study, Evergreen State College).

Arndt, D. (2015, November 24). Climate change rule of thumb: cold “things” warming faster than warm things. [Blog]. Retrieved October 4, 2017, from National Oceanic and Atmospheric Administration web site website: https://www.climate.gov/news-features/blogs/beyond-data/climate-change-rule-thumb-cold-things-warming-faster-warm-things

Aubrey, D. (2013). *Oviposition Preference in Taylor’s Checkerspot Butterflies (Euphydryas editha taylori): Collaborative Research and Conservation with Incarcerated Women* (Master of Environmental Study, Evergreen State College).

Bennett, V. J., Smith, W. P., & Betts, M. G. (2012). Evidence for Mate Guarding Behavior in the Taylor’s Checkerspot Butterfly. *Journal of Insect Behavior*, *25*(2), 183–196. https://doi.org/10.1007/s10905-011-9289-1

Boersma, D. (1998). *Butter fly Territoriality and Dispersal at Fort Lewis*.

Bonebrake, T. C., Ponisio, L. C., Boggs, C. L., & Ehrlich, P. R. (2010). More than just indicators: A review of tropical butterfly ecology and conservation. *Biological Conservation*, *143*(8), 1831–1841. https://doi.org/10.1016/j.biocon.2010.04.044

Bornad, C. N., Kery, M., Bueche, L., & Fischer, M. (2014). Hide-and-seek in vegetation: time-to-detection is an efficient design for estimating detectability and occurrence. *Methods in Ecology and Evolution*, *5*, 433–442. https://doi.org/10.1111/2041-210X.12171

Boughton, D. A. (1999). Empirical Evidence for Complex Source-Sink Dynamics with Alternative States in a Butterfly Metapopulation. *Ecology*, *80*(8), 2727–2739.

Breuker, C. J., Brakefield, P. M., & Gibbs, M. (n.d.). The association between Wing Morphology and Dispersal is Sex-Specific in the Glanville fritillary Butterfly Meliatea cinxia (Lepidoptera: Nymphalidae). *European Journal of Entomology*, *104*(3), 445–452.

Brown, J., & Boyce, M. S. (1998). Line transect sampling of Karner blue butterflies (Lycaedes melissa samuelis). *Environmental and Ecological Statistics*, *5*, 81–91.

Burlew, D. A. (2010). *The Effects of Pesticide-Contaminated Pollen on Larval Development of the Honey Bee, Apis mellifera* (Master of Environmental Study, Evergreen State College).

Burnham, K. P., Anderson, D. R., & Burnham, K. P. (2002). *Model selection and multimodel inference: a practical information-theoretic approach* (2nd ed). New York: Springer.

Center, N. N. C. D. D. (n.d.). Metadata Standards | National Centers for Environmental Information (NCEI) [Document]. Retrieved October 15, 2017, from https://www.ncddc.noaa.gov/metadata-standards/

Cohen, P. (1996). Edith’s butterfly flees north. *New Scientist*, *151*(2045), 9–9.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., … Pasteris, P. P. (2008). Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology*, *28*(15), 2031–2064. https://doi.org/10.1002/joc.1688

Dempster, J. P., & Hall, M. L. (1980). An attempt at re-establishing the swallowtail butterfly. *Ecological Entomology*, *5*, 327–334.

DeRosa, K. (n.d.). Southern resident killer whales at risk of extinction: study. Retrieved November 1, 2017, from Times Colonist website: http://www.timescolonist.com/news/local/southern-resident-killer-whales-at-risk-of-extinction-study-1.23078363

Dobkin, D. ., Olivieri, I., & Ehrlich, P. R. (1987). Rainfall and the interaction of microclimate with larval resources in the population dynamics of checkerspot butterflies inhabiting serpentine grassia. *Oecologia*, *71*, 161–166. Retrieved from Berlin.

Dodge, J., & Writer. (n.d.). “Just a bug, but a very beautiful bug.” Retrieved October 14, 2017, from the Olympian website: http://www.theolympian.com/news/local/article25254070.html

Dunn, C. D., & Napier, J. A. (1975). An evaluation of factors affecting the in vitro bioassay for erythropoietin. *Experimental Hematology*, *3*(6), 362–374.

Dzurisin, J., Schultz, C. B., & Sheperdson, D. (2004). *Captive rearing of Fender's and Puget blue butterflies: Protocols and conservation consequences* [Report to American Zoo and Aquarium Association Fore project funded by AZA's Conservation Endowment Fund]. Washington State University Vancouver, 14204 NE Salmon Creek Ave, Vancouver, WA 98686 and Oregon Zoo, 4001 SW Canyon Rd. Portland, OR 97221.

Edith's Checkerspot. (2007). *Canadian Wildlife*, *13*(2), 6.

Ehrlich, P. R., & Davidson, S. E. (1960). Techniques for Capture-Recapture Studies of Lepidoptera Populations. *Journal of the Lepidopterists' Society*, *14*(4), 227–229.

Ehrlich, P. R., & Ehrlich, A., H. (2009). The Population Bomb Revisited. *The Electronic Journal of Sustainable Development*, *1*(3), 63–71.

Ehrlich, P. R., & Hanski, I. (2004a). Checkerspot Research. In *On the Wings of Checkerspots a Model System for Population Biology* (pp. 3–16). Oxford : New York: Oxford University Press.

Ehrlich, P. R., & Hanski, I. (Eds.). (2004b). *On the wings of checkerspots: a model system for population biology*. Oxford : New York: Oxford University Press.

Fewster, R. M., Buckland, S. T., Burnham, K. P., Borchers, D. L., Jupp, P. E., Laake, J. L., & Thomas, L. (2009). Estimating the Encounter Rate Variance in Distance Sampling. *Biometrics*, *65*(1), 225–236. https://doi.org/10.1111/j.1541-0420.2008.01018.x

Finlayson et al. (n.d.). *Data Archives for Puget Sound*. Retrieved from https://www.ocean.washington.edu/data/pugetsound/

Ghazoul, J. (2005). Buzziness as usual? Questioning the global pollination crisis. *Trends in Ecology & Evolution*, *20*(7), 367–373. https://doi.org/10.1016/j.tree.2005.04.026

Glenn, E. M., Anthony, R. G., Forsman, E. D., & Olson, G. S. (2011a). Local Weather, Regional Climate, and Annual Survival of The Northern Spotted Owl. *The Condor*, *113*(1), 150–158. https://doi.org/10.1525/cond.2011.100118

Glenn, E. M., Anthony, R. G., Forsman, E. D., & Olson, G. S. (2011b). Reproduction of northern spotted owls: The role of local weather and regional climate. *The Journal of Wildlife Management*, *75*(6), 1279–1294. https://doi.org/10.1002/jwmg.177

Grosboll, D. (2011). *Taylor's Checkerspot (Euphydryas Editha Taylori) Oviposition Habitat Selection and Larval Hostplant Use in Washington State* (Master of Environmental Study, Evergreen State College).

Gross, K., Kalendra, E. J., Hudgens, B. R., & Haddad, N. M. (2007). Robustness and uncertainty in estimates of butterfly abundance from transect counts. *Population Ecology*, *49*(3), 191–200. https://doi.org/10.1007/s10144-007-0034-8

Grüss, A., Chagaris, D. D., Babcock, E. A., & Tarnecki, J. H. (2018). Assisting Ecosystem-Based Fisheries Management Efforts Using a Comprehensive Survey Database, a Large Environmental Database, and Generalized Additive Models. *Marine and Coastal Fisheries*, *10*(1), 40–70. https://doi.org/10.1002/mcf2.10002

Hanski, I., Ehrlich, P. R., Nieminen, M., Murphy, D., D., Hellmann, J., J., Boggs, C., L., & McLaughlin, J. F. (2004). Checkerspots and Conservation Biology. In *On the Wings of Checkerspots: A Model System for Population Biology* (pp. 264–287). Oxford : New York: Oxford University Press.

Hastie, T., & Tibsirani, R. (1987). General Additive Models: Some Applications. *Journal of the American Statistical Association*, *82*(398), 371–386.

Hellmann, J., J. (2005). *Distribution, abundance, and adaptation of butterflies at their northern range limit 2005 Research Summary Report-- Washington DFW* (p. 7) [Research Summary Report]. Washington State: Washington State Department of Fish and Wildlife.

Hetrick, W. ., Rich, P. ., Barnes, F. ., & Weiss, S. B. (n.d.). GIS-Based Solar Radiation Flux Models American Society for Photogrammetry and Remote Sensing Technical Papers. *GIS. Photogrammetry and Modeling*, *3*, 132–143.

Husby, J. F. (2012). *Pollinators May Not Limit Native Seed Viability for Puget Lowland Prairie Restoration* (Master of Environmental Study, Evergreen State College).

James, D. G., Nunnallee, D., & Pyle, R. M. (2011). *Life histories of Cascadia butterflies*. Corvallis, Or: Oregon State University Press.

Jarvis, B. (2018, November 27). The Insect Apocalypse is Here. *The New York Times*, p. 41. Retrieved from https://www.nytimes.com/2018/11/27/magazine/insect-apocalypse.html

Koh, L. P., Sodhi, N. S., Hugh Tiang Wah Tan, & Kelvin S.-H. Peh. (2002). Factors Affecting the Distribution of Vascular Plants, Springtails, Butterflies and Birds on Small Tropical Islands. *Journal of Biogeography*, *29*(1), 93–108.

Konvicka, M., Hula, V., & Fric, Z. (2003). Habitat of pre-hibernating larvae of the endangered butterfly Eupydryas aurinia (Lepidoptera: Nymphailidae): What can be learned from vegetation composition and architecture? *European Journal of Entomology*, *100*, 313–322.

Kuefler, D., & Haddad, N. M. (2006). Local versus landscape determinants of butterfly movement behaviors. *Echography*, *29*(4), 549–560.

Lacy, R. C., Williams, R., Ashe, E., Iii, K. C. B., Brent, L. J. N., Clark, C. W., … Paquet, P. C. (2017). Evaluating anthropogenic threats to endangered killer whales to inform effective recovery plans. *Scientific Reports*, *7*(1), 14119. https://doi.org/10.1038/s41598-017-14471-0

Linders, M. J. (2013, February 25). *WeatherDataDocumentation_25Feb2013*.

Linders, M. J., & Olson, G. S. (2014, January). *Taylor's checkerspot monitoring South Puget Sound, Washington, methodology of the Washington State Department of Fish and Wildlife*. Unpublished.

Linders, M., Lewis, K., & Curry, K. (2016). *Taylor's checkerspot (Euphydryas editha taylori) Captive Rearing and Reintroduction: South Puget Sound, Washington, 2016-2017* (p. 49) [2017 Final Annual Report to US Fish and Wildlife Service, Joint Base Lewis-McChord, ACUB Technical Review Committee]. Washington State Department of Fish and Wildlife, Oregon Zoo, and The Evergreen State College.

Linders, M., Lewis, K., & Dorman, S. (2016). *Taylor's checkerspot (Euphydryas editha taylori) Captive Rearing and Reintroduction: South Puget Sound, Washington, 2015-2016* (p. 61) [2016 Annual Report to US Fish and Wildlife Service, Joint Base Lewis-McChord, ACUB Technical Review Committee]. Washington State Department of Fish and Wildlife, Oregon Zoo, and The Evergreen State College.

Liu, H., Feng, C.-L., Chen, B.-S., Wang, Z.-S., Xie, X.-Q., Deng, Z.-H., … Luo, Y.-B. (2012). Overcoming extreme weather challenges: Successful but variable assisted colonization of wild orchids in southwestern China. *Biological Conservation*, *150*(1), 68–75. https://doi.org/10.1016/j.biocon.2012.02.018

Marques, T. A., Thomas, L., Fancy, S. G., & Buckland, S. T. (2007). Improving Estimates of Bird Density using Multiple-Covariate Distance Sampling. *The Auk*, *124*(4), 1229–1243.

McInnis, D. (1997). Go north, young checkerspot. *Earth (1056148X)*, *6*(1), 16.

McIntyer, J. (2010). *Habitat Variables, Mammal Interactions and Recovery Approaches Important to a Rare, New Mexican Butterfly, Euphydrias anicia cloudcrofti (Lepidoptera: Nyphalidae)* (Doctor of Philosophy Biology). University of New Mexico, Albuquerque, New Mexico.

Miller-Rushing, A. ., & Primack, R. (2008). Global warming and flowering times in Thoreau's Concord. *Ecology*, *89*, 332–341.

Morrison, M. L., Smallwood, S., & Hall, L. S. (2003). Creating Habitat through Plant Relocation. *Ecological Restoration*, *21*(2), 95–100.

Murphy, D. D., & Weiss, S. B. (1988). A Long-Term Monitoring Plan for a Threatened Butterfly. *Conservation Biology*, *2*(4), 367–374.

Olson, G. S. (2011, Spring). *Distance Sampling Field Techniques*.

Olson, G. S. (2017a). *DISTANCE Sampling Training 2017*. PowerPoint presented at the WDFW. WDFW.

Olson, G. S. (2017b). Modeling the Effects of Weather on Taylor's Checkerspot Abundance. *Population Estimate*, 10. Oregon Zoo: Washington State Department of Fish and Wildlife.

Ovaskainen, O., Skorokhodava, S., Yakovleva, M., Sukhov, A., Kutenkov, A., Kutenkova, N., … Delgado, M. del M. (2013). Community-level phenological response to climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(33), 13434–13439.

Parmesan, C., Williams-Anderson, A., Moskwik, M., Mikheyev, A. S., & Singer, M. C. (2015). Endangered Quino checkerspot butterfly and climate change: Short-term success but long-term vulnerability? *Journal of Insect Conservation*, *19*(2), 185–204. https://doi.org/10.1007/s10841-014-9743-4

Parsons, P. A. (1995). Evolutionary Response to Drought Stress: Conservation Implications. *Biological Conservation*, *74*, 21–27.

Penuelas, J., Rutishauser, T., & Filella, I. (2009). Phenology Feedbacks on Climate Change. *Science*, *324*(5929), 887–888. https://doi.org/10.1126/science.1173004

Pietras, M., & Netzel, P. (2012). The method of assessment of solar potential for selected area with use Geographical Information Systems. *EPJ Web of Conferences*, *33*, 1010. https://doi.org/10.1051/epjconf/20123301010

Pollard, E. (1988). Temperature, Rainfall and Butterfly Numbers. *Journal of Applied Ecology*, *25*(3), 819–828. https://doi.org/10.2307/2403748

Prenger, J. J., & Ling, P., P. (n.d.). *Greenhouse Condensation Control: Understanding and Using Vapor Pressure Deficit (VPD) AEX-804-01*. Retrieved from http://www.ecaa.ntu.edu.tw/weifang/class-cea/Greenhouse%20Condensation%20Control%20VPD,%20AEX-804-01.htm

Pyle, R. M. (2002). *The butterflies of Cascadia: a field guide to all the species of Washington, Oregon, and surrounding territories*. Seattle: Seattle Audubon Society.

Raloff, J. (1996). Butterfly Displaced by Climate Change? *Science News*, *150*(9), 135–135.

Rausher, M. (1982). Population Differentiation in Euphydryas Editha Butterflies: Larval Adaptation to Different Hosts. *Evolution*, *36*(3), 581–590.

Rusty Patched Bumble Bee [US Fish and Wildlife Service]. (n.d.). Retrieved from https://www.fws.gov/midwest/endangered/insects/rpbb/

Schoonmaker, P. K., & Foster, D. R. (1991). Some Implications of Paleoecology for Contemporary Ecology. *Botanical Review*, *57*(3), 204–245.

Severns, P. M., & Breed, G. A. (2014). Behavioral consequences of exotic host plant adoption and the differing roles of male harassment on female movement in two checkerspot butterflies. *Behavioral Ecology and Sociobiology*, *68*(5), 805–814. https://doi.org/10.1007/s00265-014-1693-z

Singer, M. C., & Lee, J., R. (2000). *Discrimination within and between host species by a butterfly: implications for design of preference experiments* (No. 3; pp. 101–105). Section of Integrative Biology, University of Texas, Austin Texas 78712, USA.

Singer, M. C., & Parmesan, C. (2010). Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? *Philosophical Transactions: Biological Sciences*, *365*(1555), 3161–3176.

Singer, M. C., & Parmesan, C. (2010). Phenological asynchrony between herbivorous insects and their hosts: signal of climate change or pre-existing adaptive strategy? *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1555), 3161–3176. https://doi.org/10.1098/rstb.2010.0144

Singer, M. C., & Wee, B. (2005). Spatial pattern in checkerspot butterfly-host plant association at local, metapopulation and regional scales. *Ann. Zool. Fennici*, *42*, 347–361.

Sugarbaker, D. (2017, November). *GIS day 2017 Keynote*. Keynote presented at the GIS day, DES Building. Retrieved from http://www.wsdot.wa.gov/mapsdata/gisday.htm

Szymanski, J., Smith, T., Horton, A., Parkin, M., Ragan, L., Masson, G., … Hill, L. (2016). *Rusty Patched Bumble Bee (Bombus affinis) Species Status Assessment Final Report Version 1* (p. 100). Retrieved from U.S. Fish and Wildlife Service website: https://www.fws.gov/midwest/endangered/insects/rpbb/pdf/SSAReportRPBBwAdd.pdf

Thomas, J. A., Simcox, D. J., & Hovestadt, T. (2011). Evidence based conservation of butterflies. *Journal of Insect Conservation*, *15*(1–2), 241–258. https://doi.org/10.1007/s10841-010-9341-z

Thomas, L., Buckland, S. T., Rexstad, E. A., Laake, J. L., Strindberg, S., Hedley, S. L., … Burnham, K. P. (2010). Distance software: design and analysis of distance sampling surveys for estimating population size. *Journal of Applied Ecology*, *47*(1), 5–14. https://doi.org/10.1111/j.1365-2664.2009.01737.x

Trilobites and Cambrian Utah – Utah Geological Survey. (n.d.). Retrieved November 5, 2017, from https://geology.utah.gov/map-pub/survey-notes/glad-you-asked/trilobites-and-cambrian-utah/

Wallis DeVries, M. F., Baxter, W., & Van Vliet, A. J. H. (2011). Beyond climate envelopes: effects of weather on regional population trends in butterflies. *Oecologia*, *167*(2), 559–571. https://doi.org/10.1007/s00442-011-2007-z

Weiss, S. B., Murphy, D. D., Ehrlich, P. R., & Metzler, C. F. (1993). Adult emergence phenology in checkerspot butterflies: the effects of macroclimate, topoclimate, and population history. *Oecologia*, *96*, 261–270.

Weiss, S. B., Murphy, D. D., & White, R. (1988). Sun, Slope, and Butterflies: Topographic Determinants of Habitat Quality For Euphydryas Editha. *Ecology*, *69*(5), 1486–1496.

Weiss, S. B., & Weiss, A. D. (1998). Landscape-Level Phenology of a Threatened Butterfly: A GIS-Based Modeling Approach. *Ecosystems*, *1*(3), 299–309.

White, R., & Singer, M. C. (1987). Marking Technique for Larvae. *Pan-Pacific Entomologist*, *63*(4), 341–345.

APPENDIX A

Final Data used for the Linear Regressions:

Butterfly abundance data:

- PeakGamPoint: Each year butterfly counts were recorded and analyzed to get density estimates, which was then used to calculate the total abundance of butterflies in each study site, R76, R50, and Scatter Creek South. The count data was fitted to a model. The model was then used to generate an approximation of each day's abundance over time for that year, and the maximum approximation from that model was then used for the regression analyses. Site R76 had too few data abundance points to model a peak GAM point for the year 2008.

Weather data: The winter's precipitation data was downloaded from the point source data available from the PRISM website maintained and managed by the University of Washington's School of Oceanography. Furthermore, only precipitation, humidity, and temperature will be used as the independent variables for the analysis.

- Precip.mm: This represents the sum total of all the precipitation for each year's winter values.
- Temperature Degrees Fahrenheit: This field represents each year's average winter temperature.

- Average Max Vapor Pressure Deficit (VPD): This field represents each year's average winter humidity, or in the case of vapor pressure deficit it should be called, dryness.

R76 (excludes year 2008 due to lack of data)

Year	PeakGamPoint	Precip.mm	Temperature Degrees Fahrenheit	Average Max Vapor Pressure Deficit (VPD)
2006	9825.97	518.41	39.57	3.10
2007	5736.80	472.44	39.57	3.22
2009	197.81	320.04	37.77	3.10
2010	1420.88	300.48	34.40	3.89
2011	5658.57	363.98	39.63	3.39
2012	10681.72	311.40	38.90	3.28
2013	4055.43	315.21	39.23	2.62
2014	2918.96	304.55	38.33	2.58
2015	3567.57	327.66	43.40	3.20
2016	1401.09	621.28	42.03	2.75
2017	4153.43	383.29	36.90	2.65
2018	14040.73	398.78	39.93	1.99

R50

Year	PeakGamPoint	Precip.mm	Temperature Degrees Fahrenheit	Average Max Vapor Pressure Deficit (VPD)
2010	135.54	269.75	41.23	3.98
2011	856.91	339.60	39.93	3.40
2012	1484.32	282.45	39.23	3.34
2013	987.59	310.64	39.60	2.66
2014	924.43	292.35	38.60	2.73
2015	1710.68	321.56	43.73	3.44
2016	2520.72	610.87	42.30	3.04
2017	4382.89	387.86	37.10	2.92
2018	8948.88	404.37	40.17	2.38

SCS

Year	PeakGamPoint	Precip.mm	Temperature Degrees Fahrenheit	Average Max Vapor Pressure Deficit (VPD)
2009	24.90	422.66	45.30	3.21
2010	80.17	385.06	41.23	3.80
2011	29.33	450.60	39.73	3.09
2012	26.96	409.96	39.03	3.23
2013	157.20	450.09	39.53	2.46
2014	126.44	352.55	36.30	2.71
2015	235.38	452.63	43.77	3.56
2016	923.91	721.36	42.33	2.95
2017	2151.40	418.34	36.97	2.89
2018	4123.85	494.03	40.07	2.59

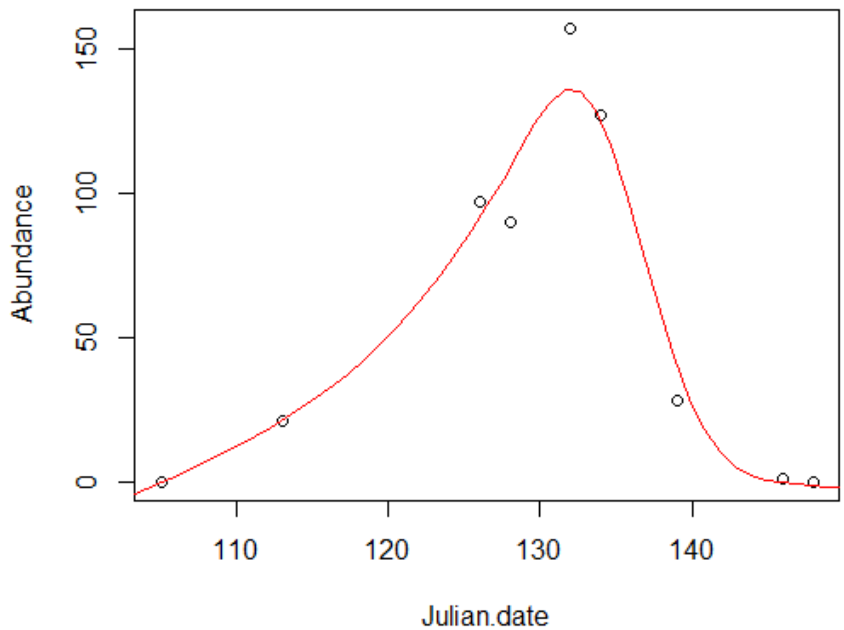
GAM Plots

The abundance calculations are derived from the density calculations that had been computed from the “Distance” software by the data scientists at WDFW were used for the general additive models (GAM) to estimate the peak abundance values for each study year.

The red lines in the plots below represent estimations of the abundance at each site throughout each year derived from a general additive model (GAM). The time (julian date) is the date measured in days for each year. For instance, day 1(julian date =1) is January first. A GAM could not be modeled for the year 2008 in site R76 due to a lack of abundance data.

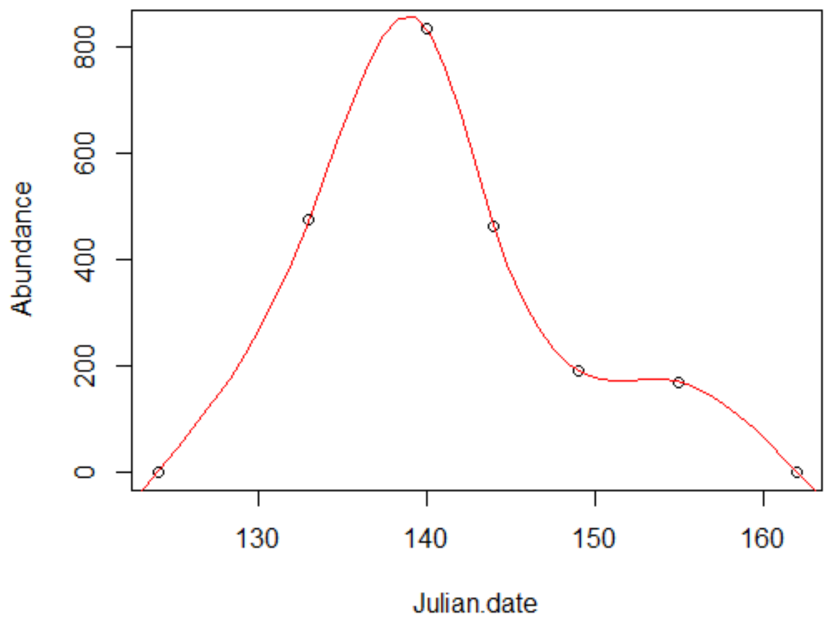
Site R50

R50-2010

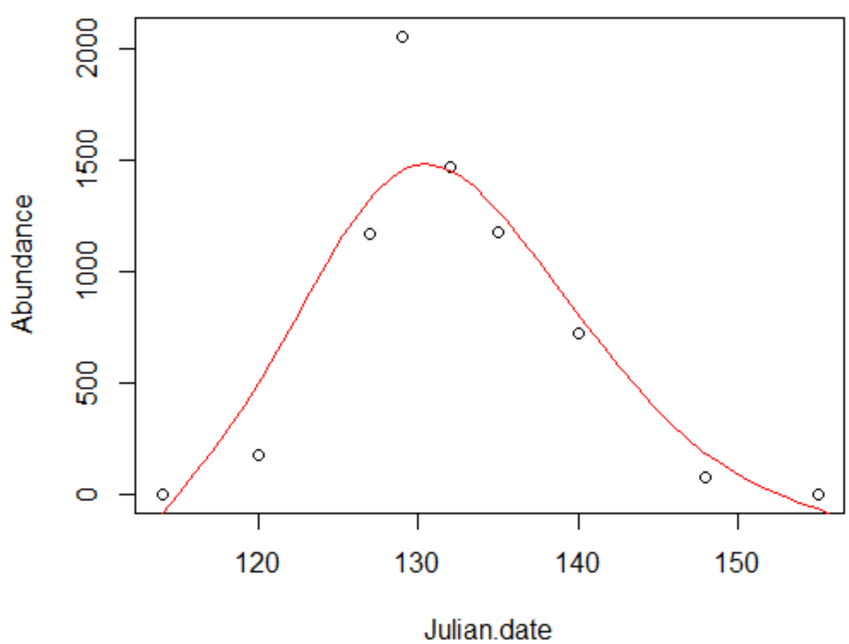


Abundance
0
50
100
150
110
120
130
140
Julian.date

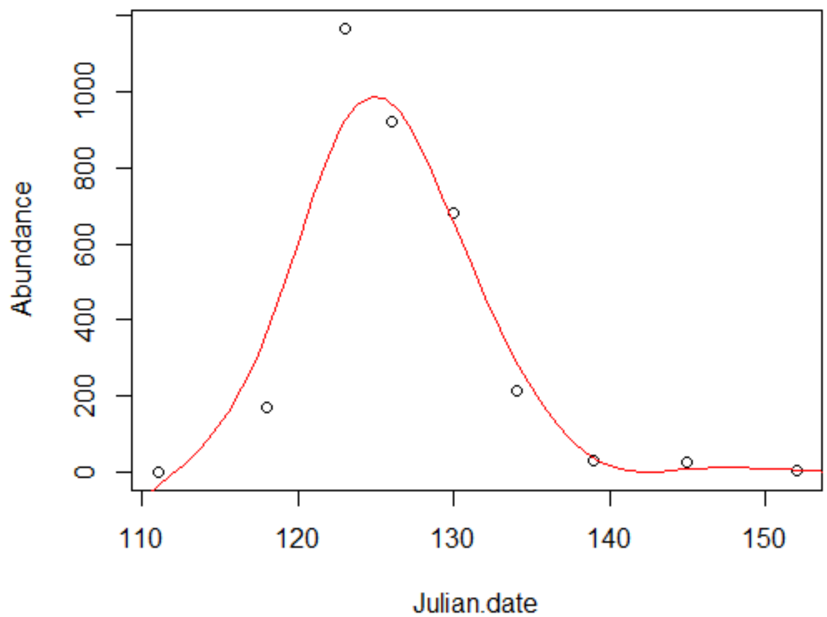
R50-2011



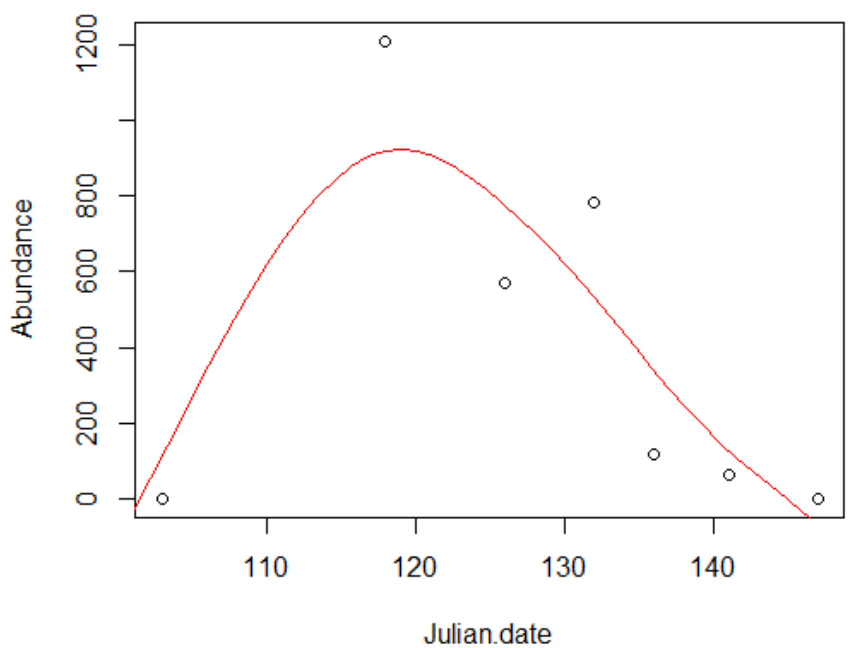
R50-2012



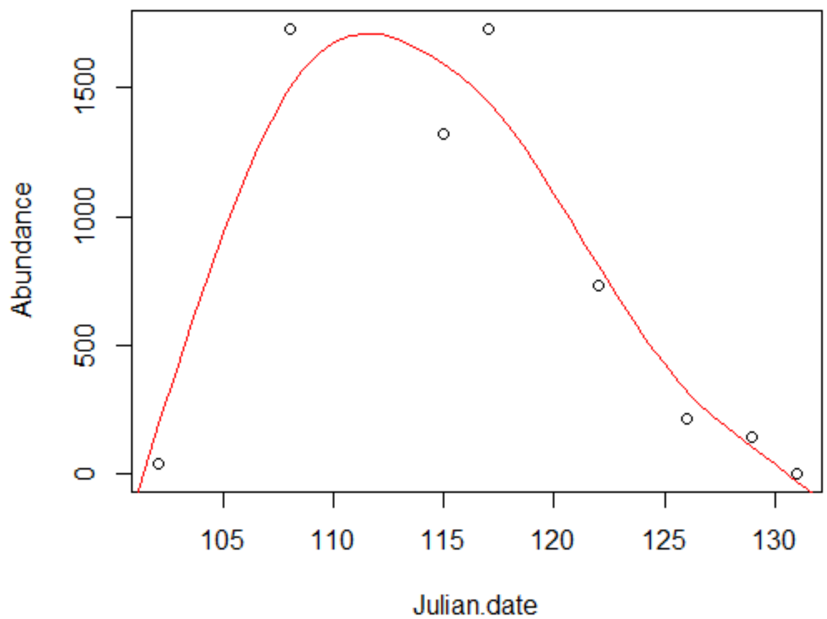
R50-2013



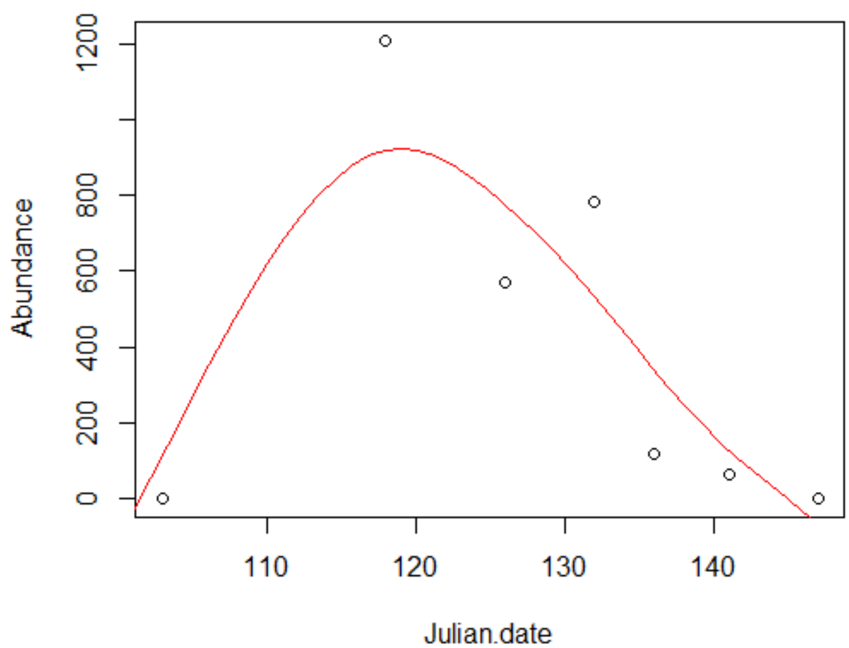
R50-2014



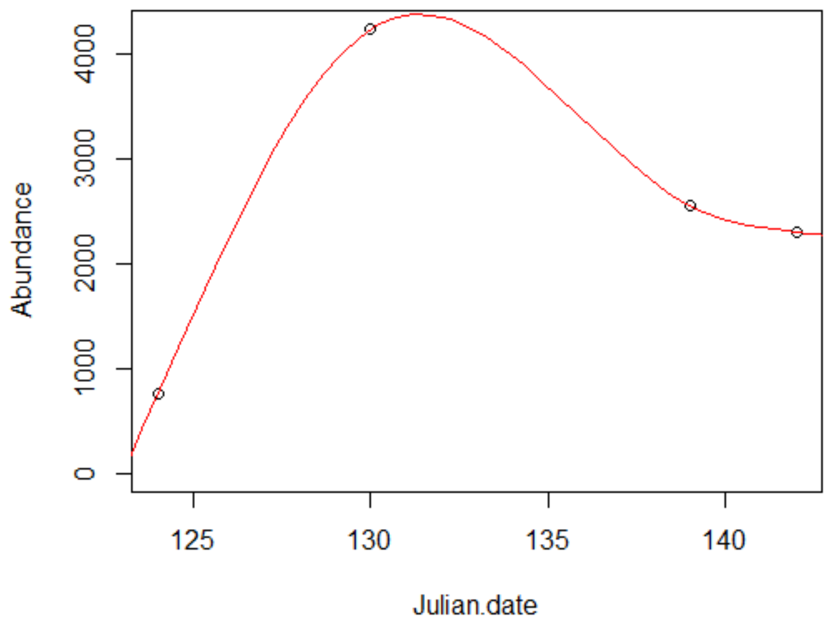
R50-2015



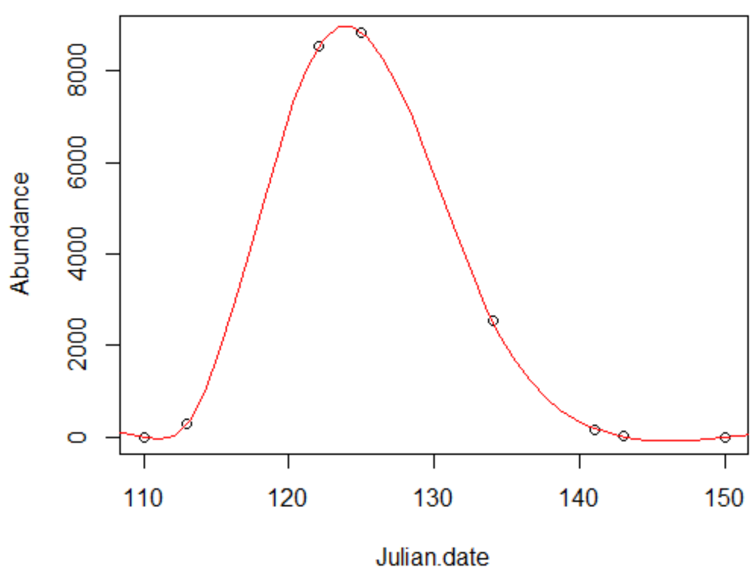
R50-2016



R50-2017

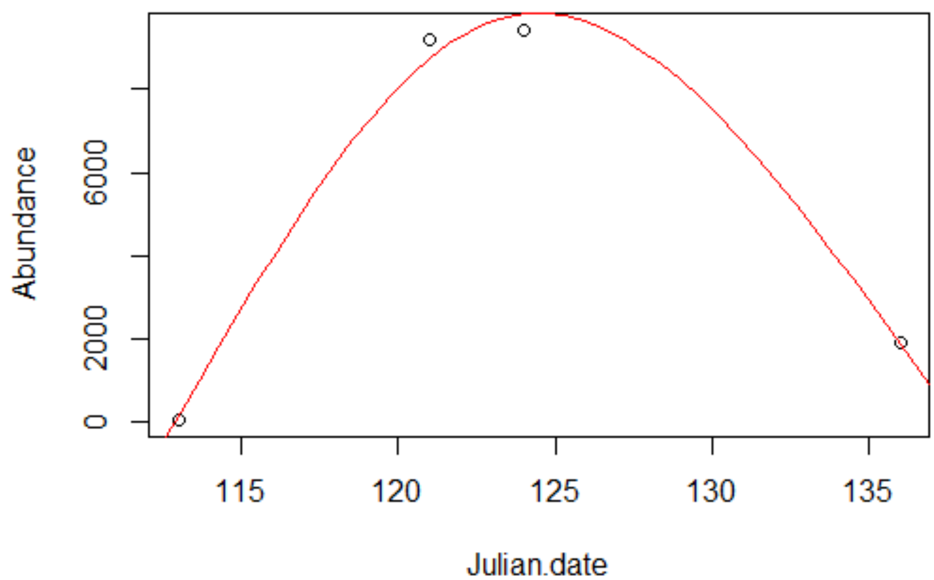


R50-2018

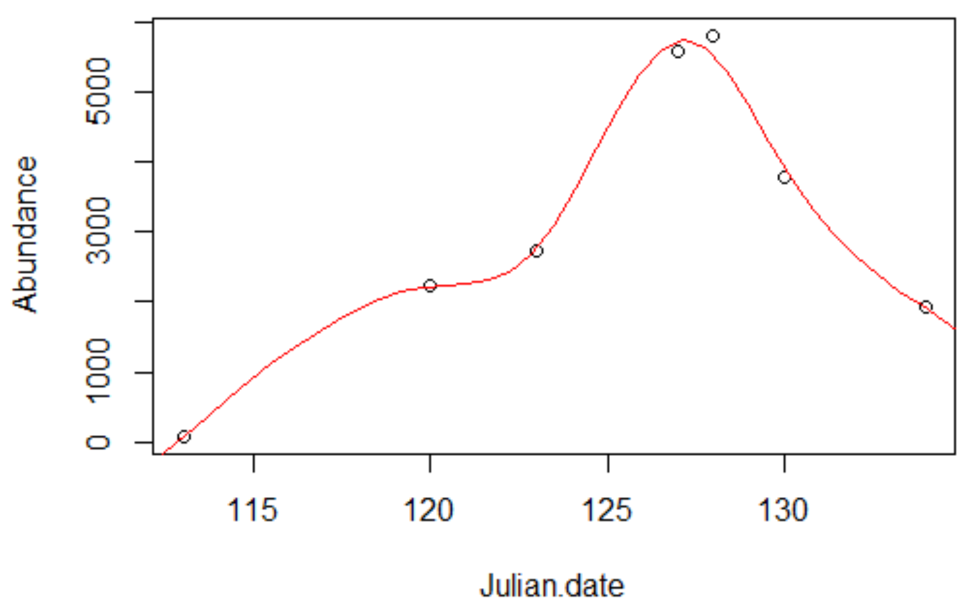


Site R76

R76-2006

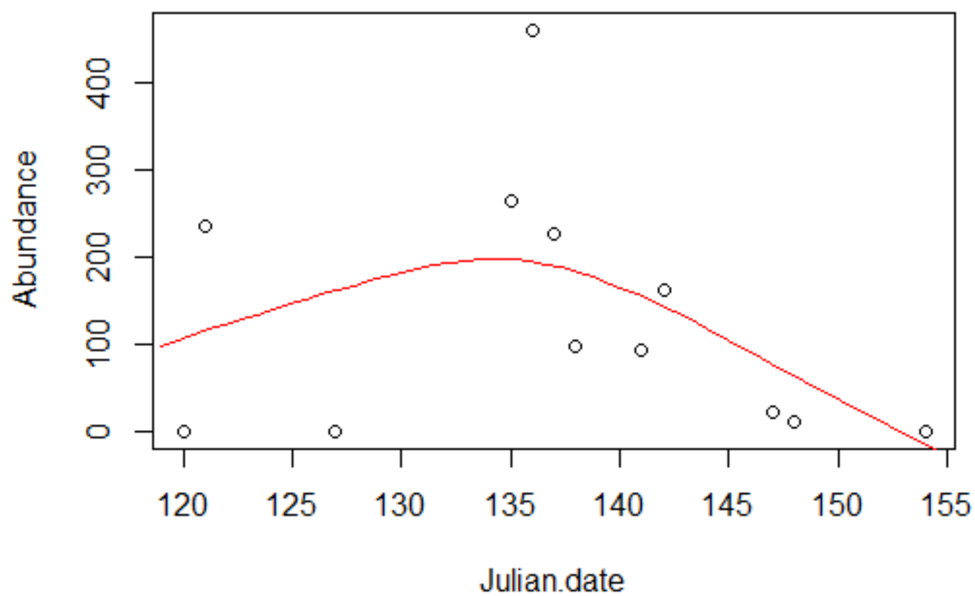


R76-2007

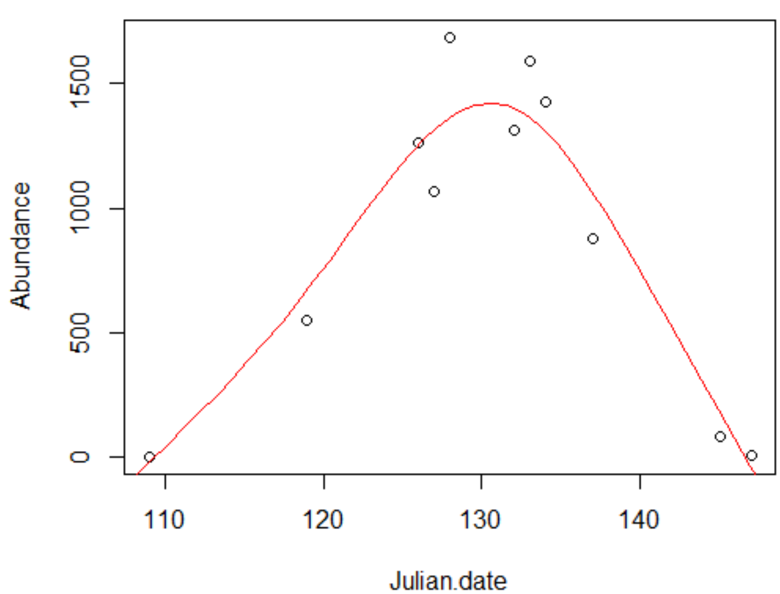


R76-2008: This year had only three data points; not enough for a GAM.

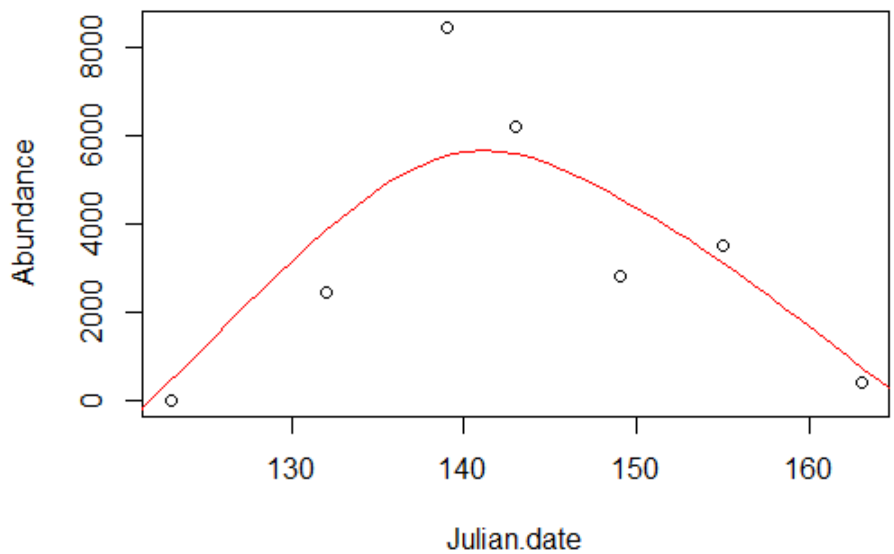
R76-2009



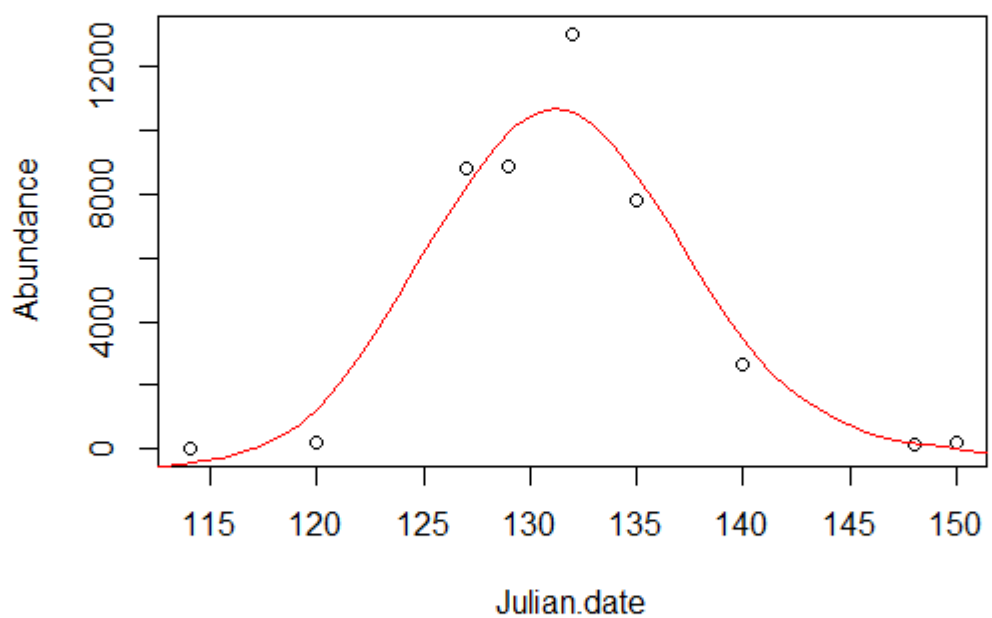
R76: 2010



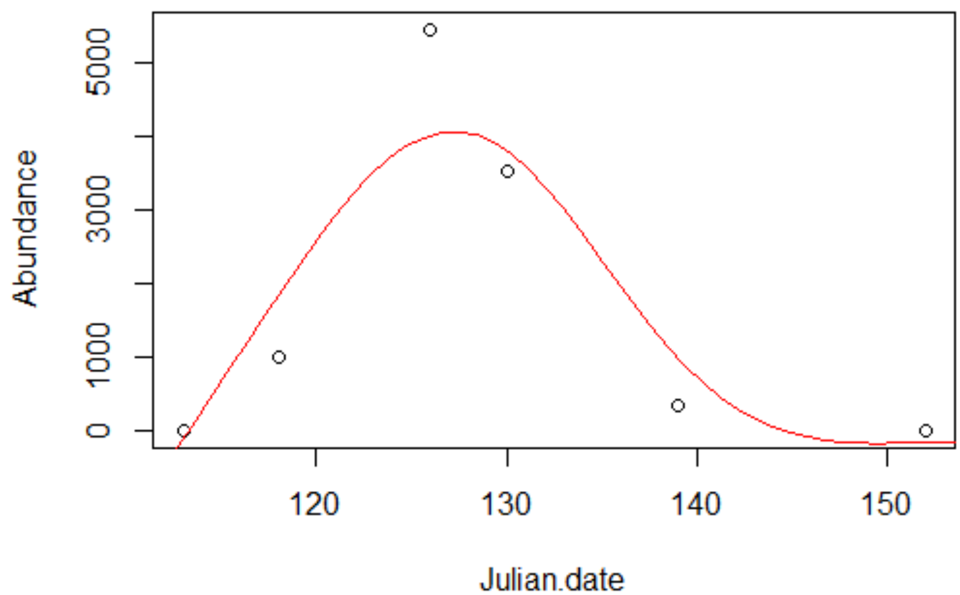
R76-2011



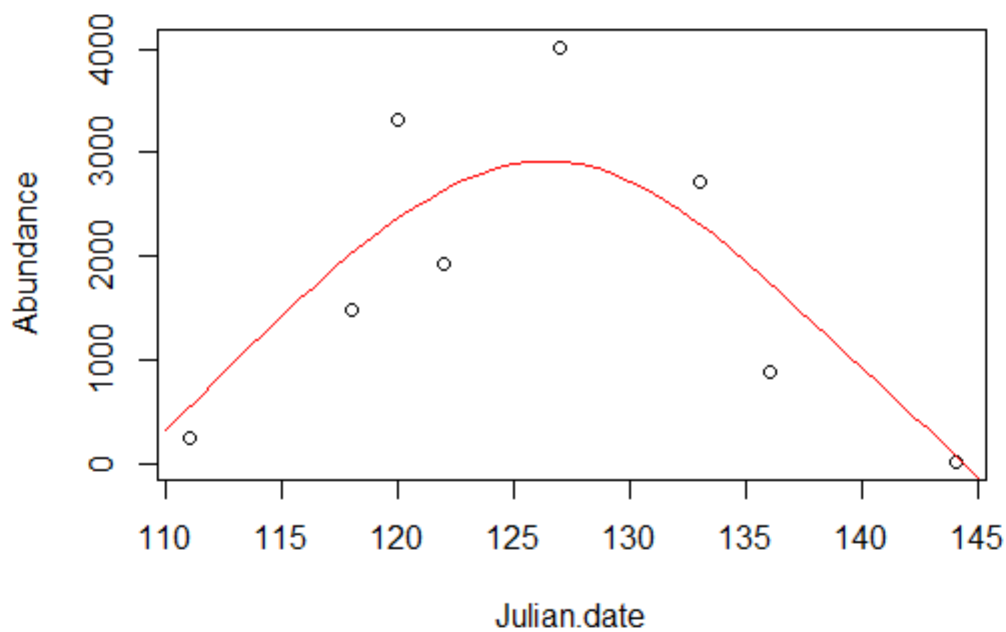
R76-2012



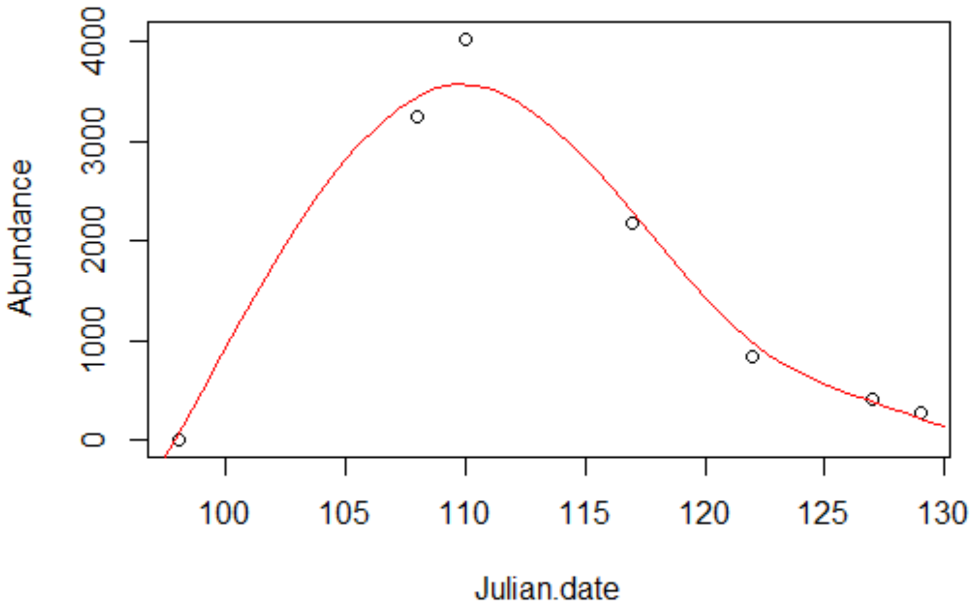
R76-2013



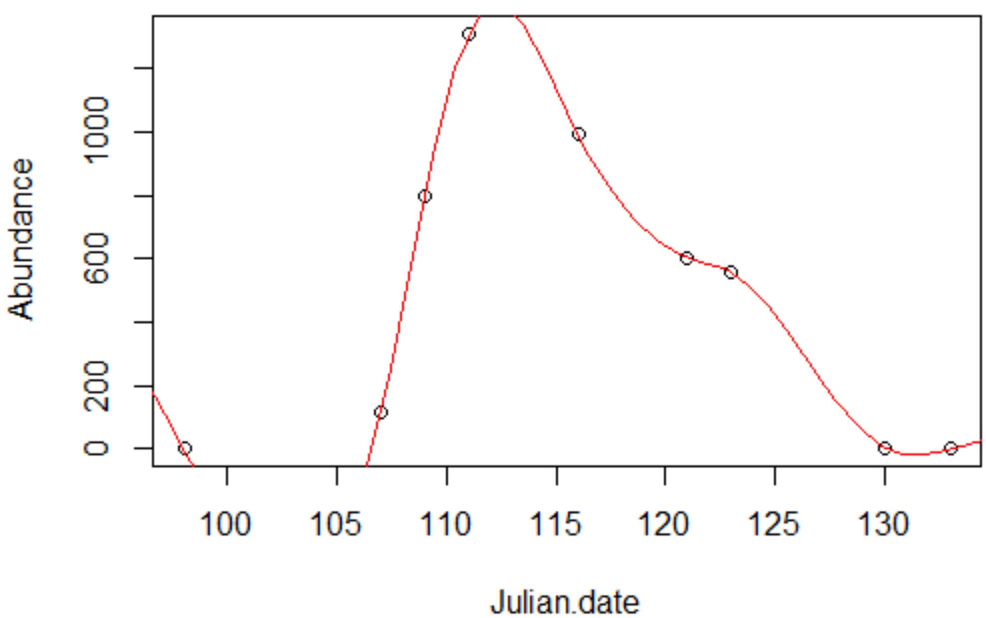
R76-2014



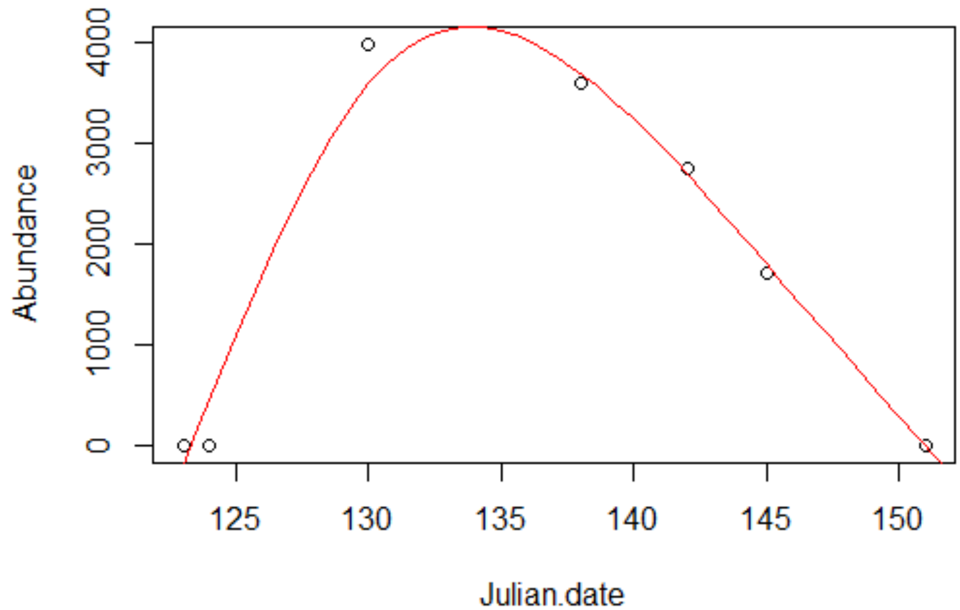
R76-2015



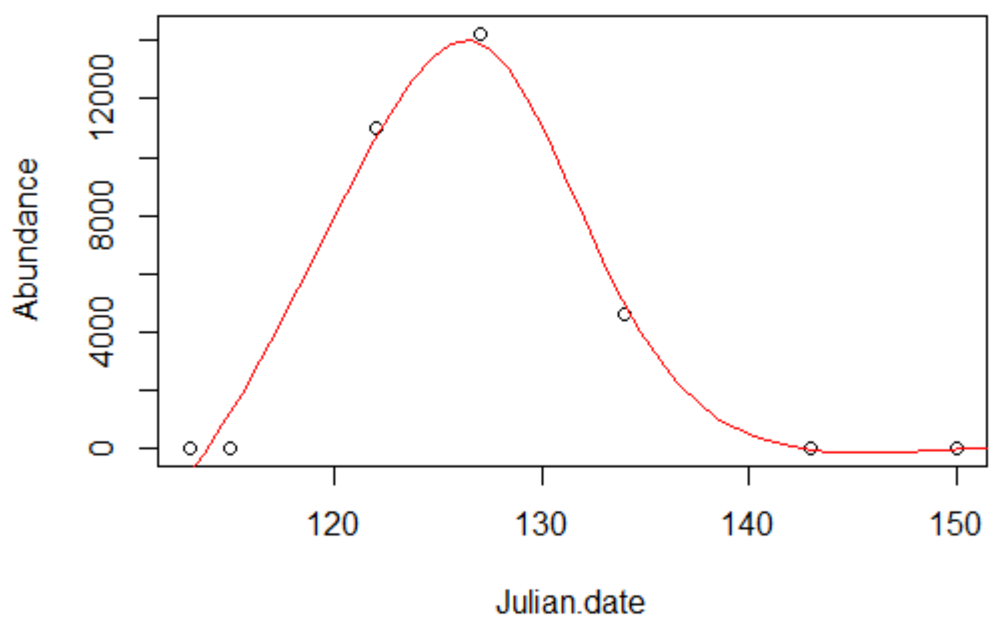
R76-2016



R76-2017

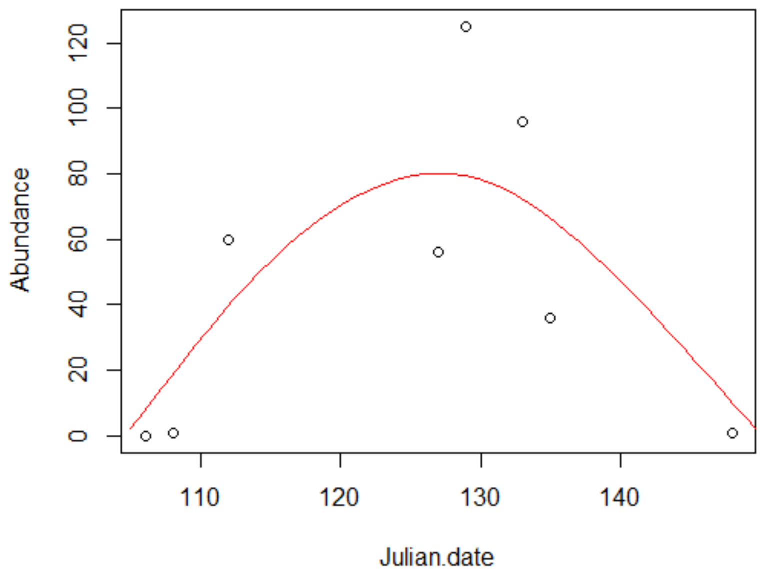


R76-2018

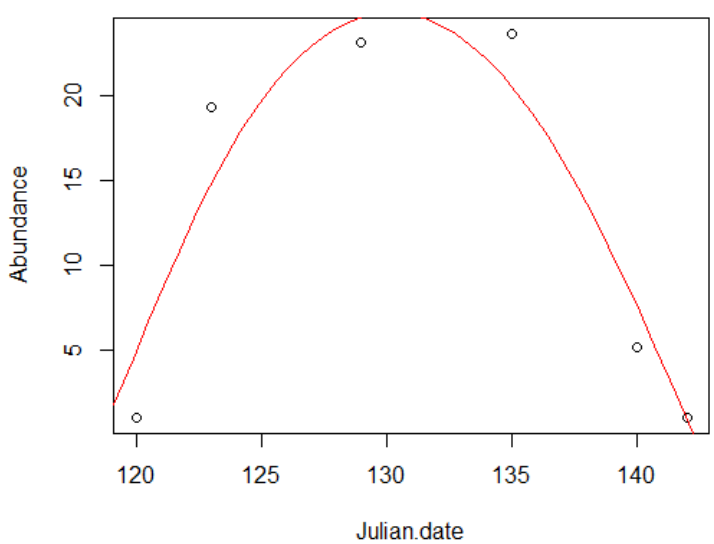


Scatter Creek South site

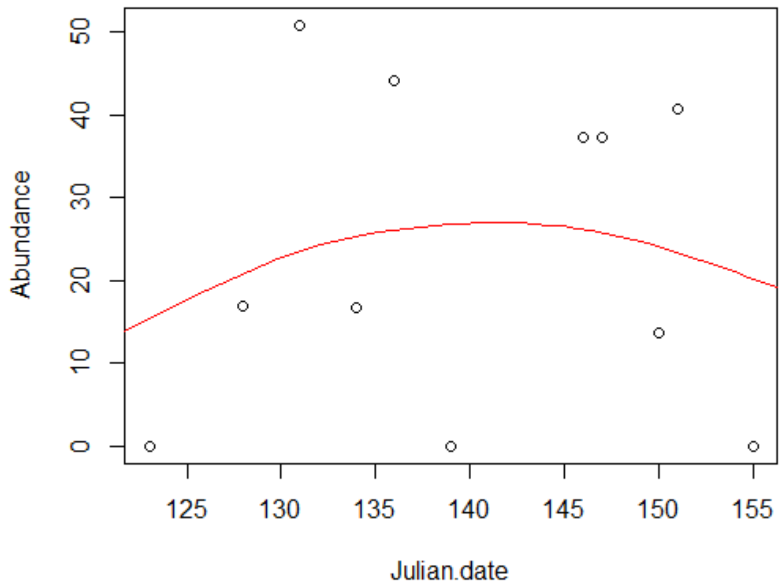
SCS-2009



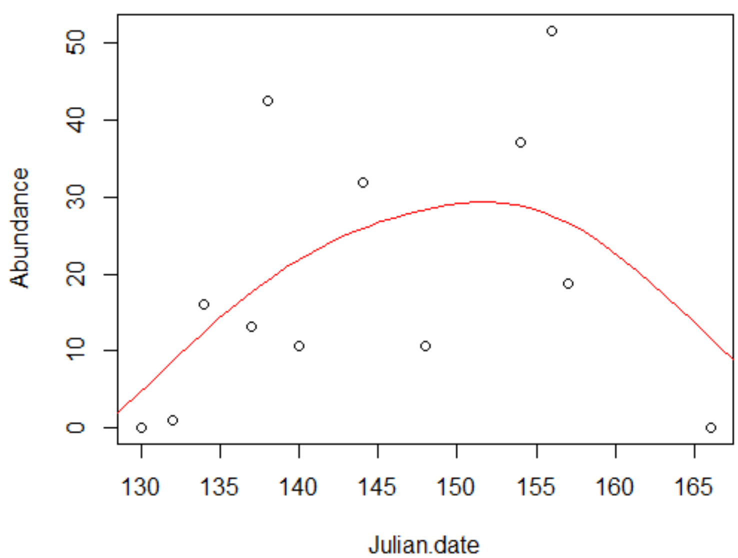
SCS-2010



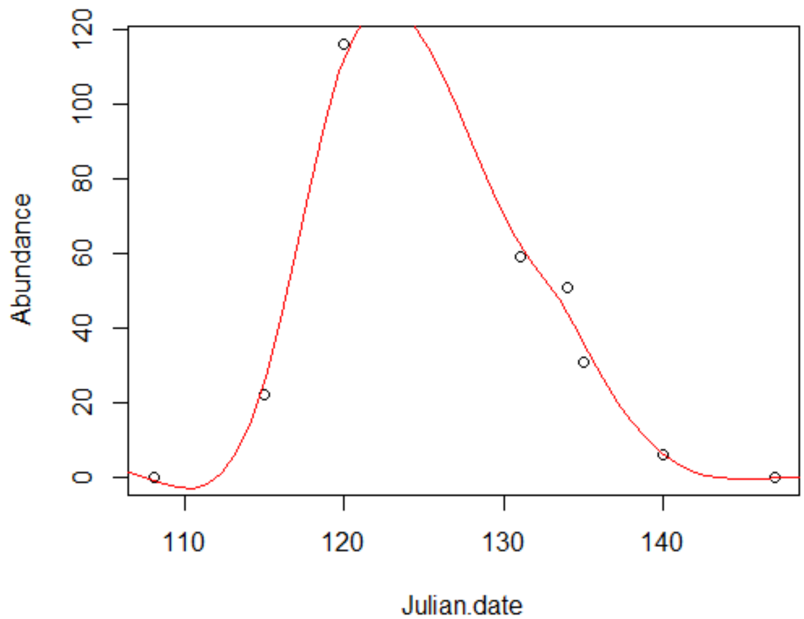
SCS-2011



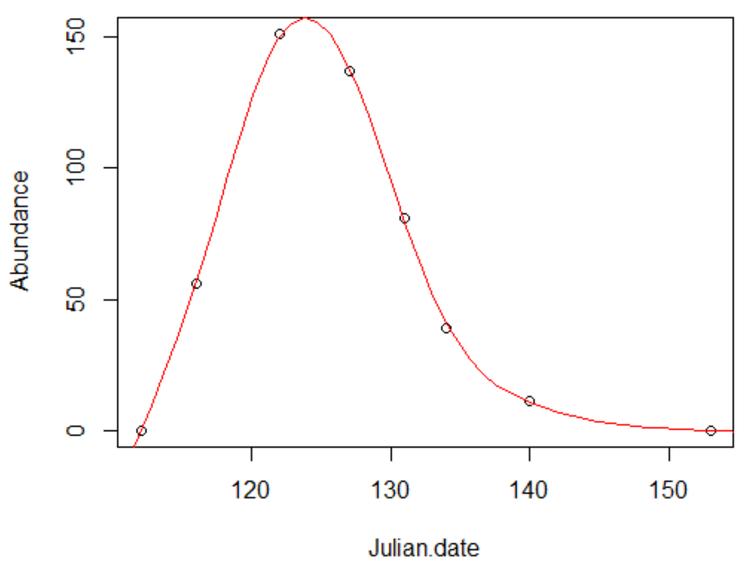
SCS-2012



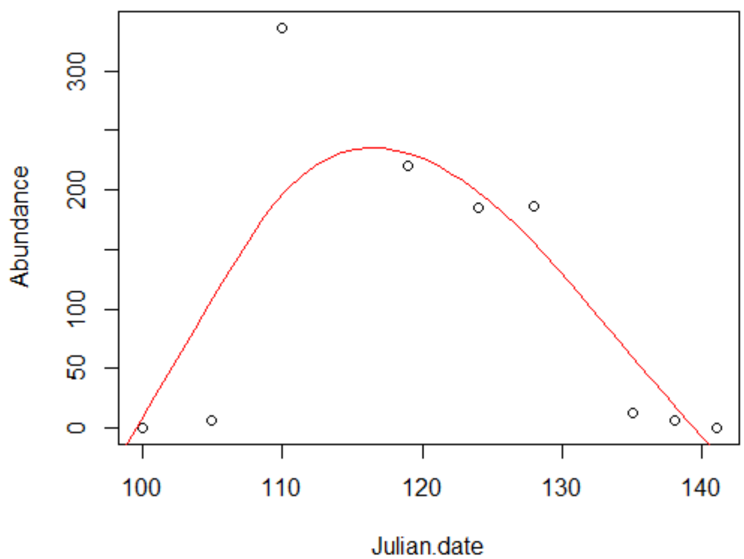
SCS-2013



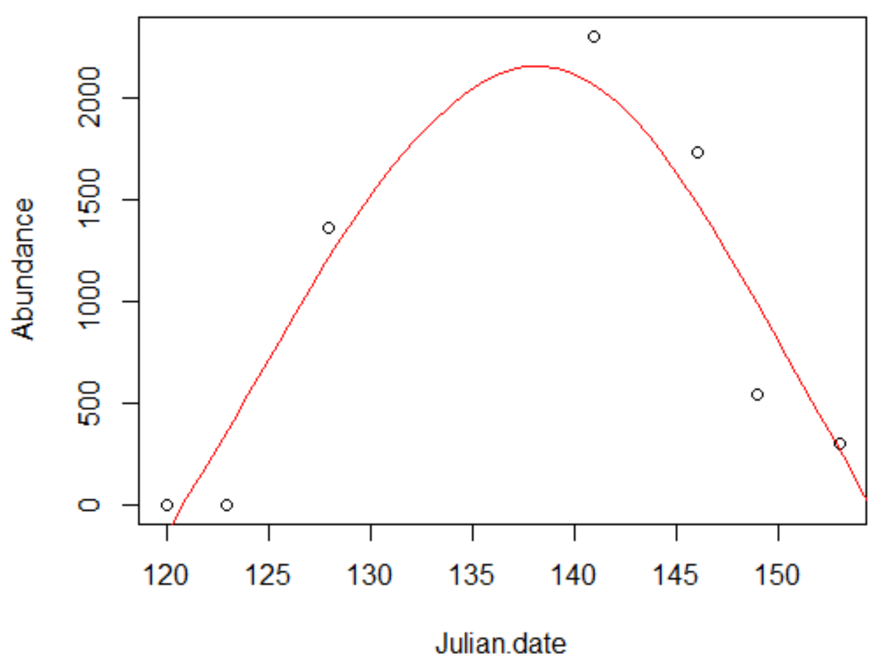
SCS-2014



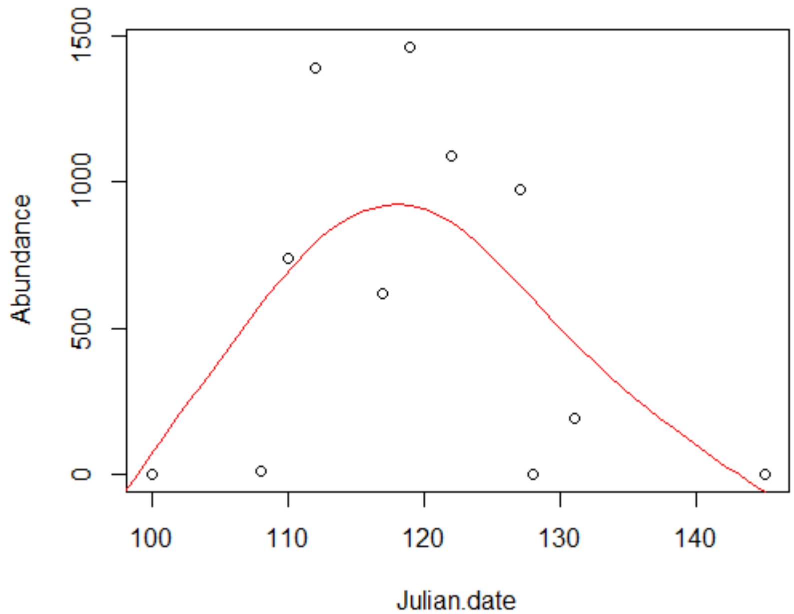
SCS-2015



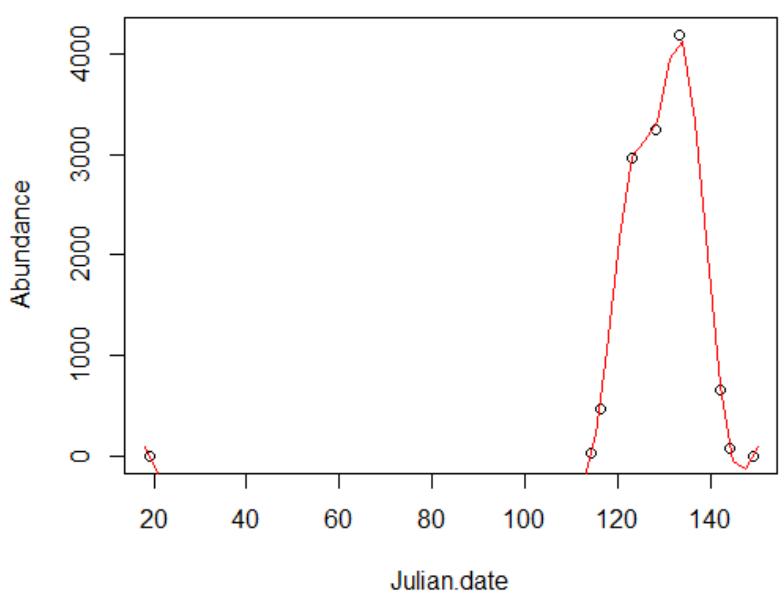
SCS-2016



SCS-2017



SCS-2018



APPENDIX B

Results of raw data without transformations

Three climatic variables were tested against the peak GAM values for the three study sites: precipitation in millimeters, temperature in Fahrenheit, and humidity in average maximum vapor pressure deficit (VPD), which is a measurement of dryness (Prenger & Ling, n.d.). The results of the simple and multiple linear regression models in all three sites show the need for further weather modeling due to the low correlations. An examination of all the plots of the residuals for the data indicated that the model of choice is a linear model.

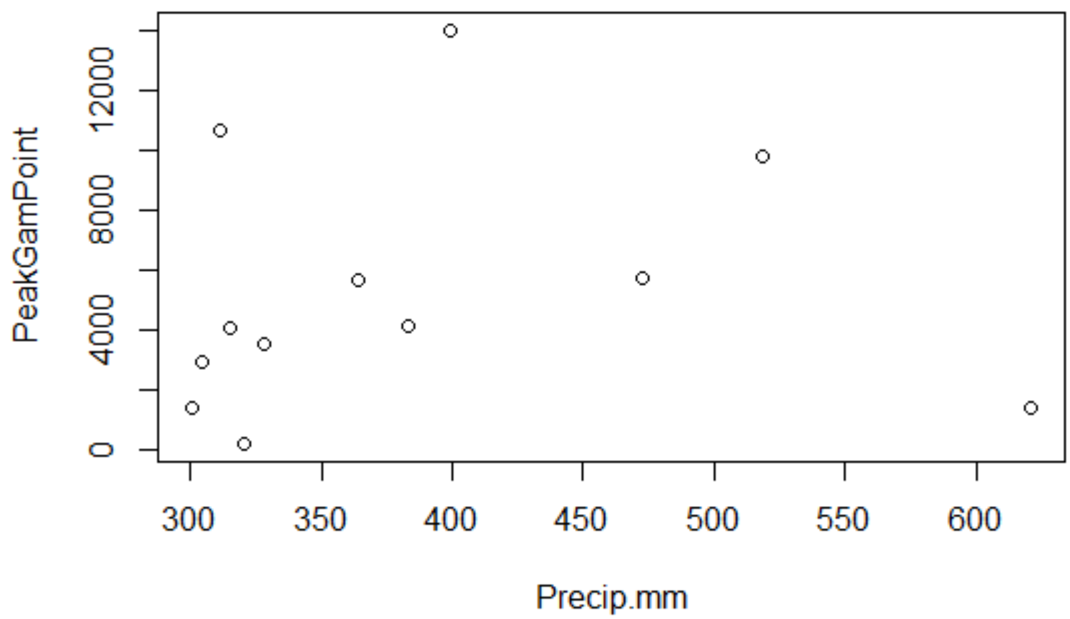
The null hypothesis was H_0: "The winter weather element does not affect the populations of butterflies." The simple and multiple linear regression model proved the null hypotheses to be true. However, there was a higher correlation of peak abundance estimates with respect to humidity.

R76 data analysis:

Because the year 2008 had only three observations, there were not enough data points to model a peak GAM abundance value. Because of this, the year 2008 was left out of the analysis for site R76.

Precipitation

The analysis used linear regression models where the maximum value of the fitted general additive model (GAM) of the abundance estimates was the dependent variable and the sum of the total winter precipitation in millimeters was the independent variable.

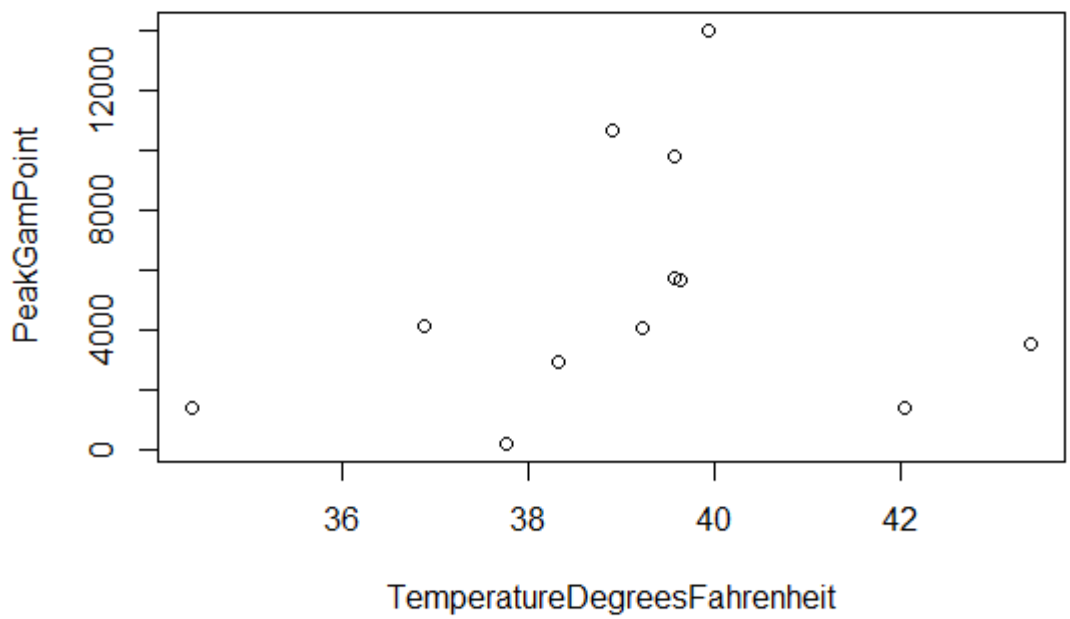


Plot of total winter precipitation plotted against abundance at site R76

The correlation coefficient between precipitation and peak GAM values of the abundance data is 0.10. Because of this, no simple linear regression is needed

Temperature

The correlation coefficient of temperature with respect to abundance is r=0.18, too low to run a simple linear model.

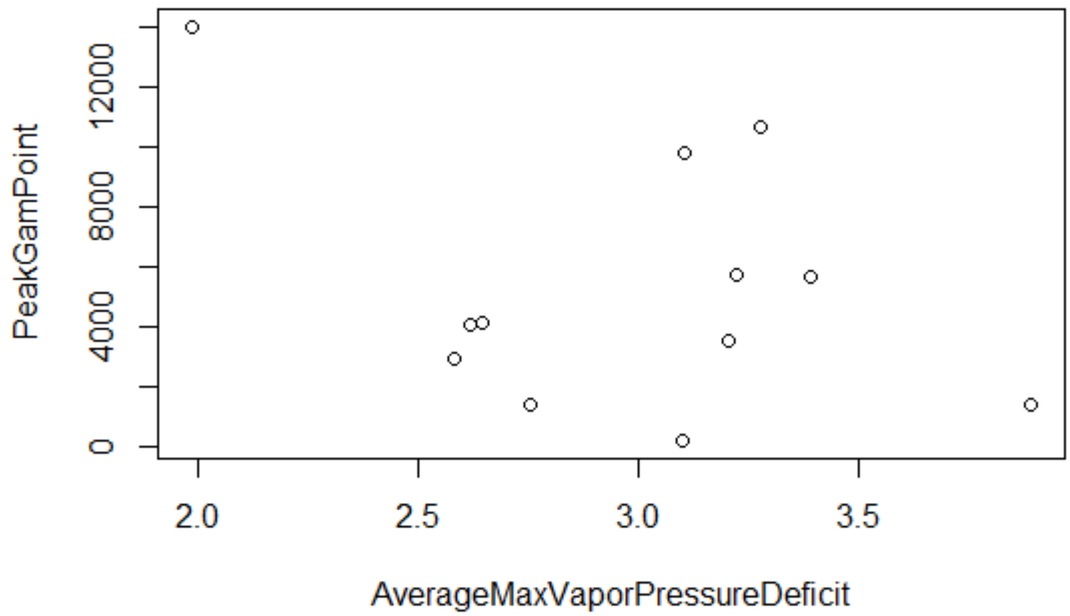


Winter average temperature(˚F) plotted against peak GAM butterfly abundance values from site R76

Humidity

Winter dryness may have a deleterious effect on the populations of butterflies, but not enough to reject the null hypothesis, which was, H_0: "The populations of butterflies in the site, R76 are not affected by humidity".

There is a sufficient correlation between vapor pressure deficit and peak GAM abundance values to run a linear regression model. The correlation coefficient is -0.36, showing that dryness and populations of butterflies may be negatively correlated.



Winter average of max dryness measured in vapor pressure deficit (Vpd) plotted against the peak GAM points for butterfly abundance at R76

The simple linear regression showed the coefficient of correlation, the adjusted R^2 to be 0.04. The F-statistic (with 1 and 10 d.f.) was 1.47 with a p-value of 0.254. These values show an effect, but not enough to determine that humidity alone is affecting the butterfly populations. Higher winter humidity is associated with greater spring abundance of butterflies in R76.

Multivariate analysis in R76

Before running the multiple linear regression on the peak GAM estimates for site R76 and the three climatic variables, a correlation model was run to avoid including the independent variables that are highly correlated. In R76, the climatic variables precipitation and temperature had a correlation coefficient of 0.42. The multiple linear regression model did not include these two variables together. Due to low number of data points for abundance in the year 2008, that year was not included.

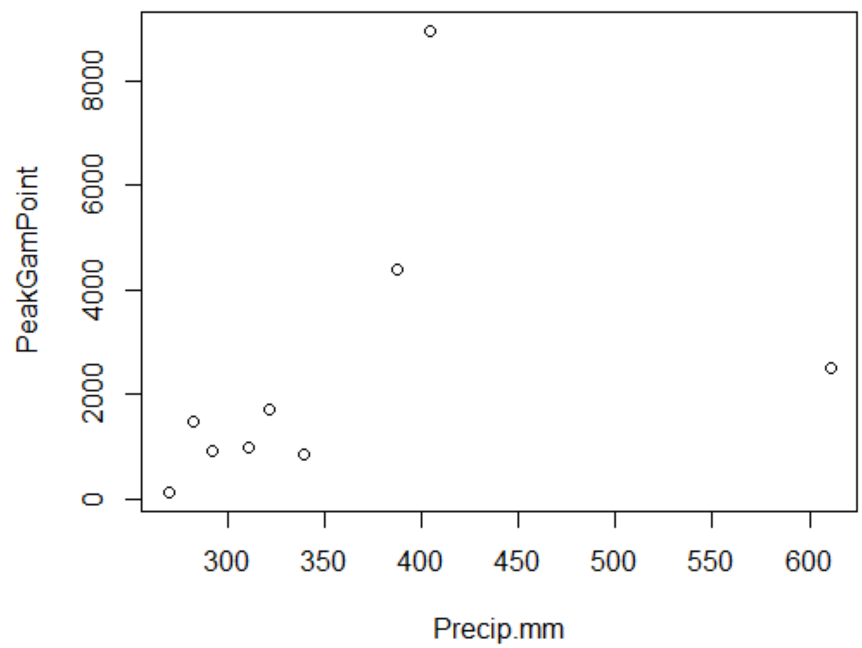
A run of the multiple linear regression model of the peak GAM abundance points with respect to precipitation and humidity returned an adjusted R^2 value of -.06. The F-statistic (with 2 and 9 d.f.) was 0.67 with a p-value of 0.536. This model is not a good fit.

A second model was run looking at the values of temperature and humidity with respect to the peak GAM values. This model returned an adjusted R^2 value of -0.06. The F-statistic (with 2 and 9 d.f.) was 0.70 with a p-value of 0.523. This model is not a good fit either.

R50 data analysis

Precipitation

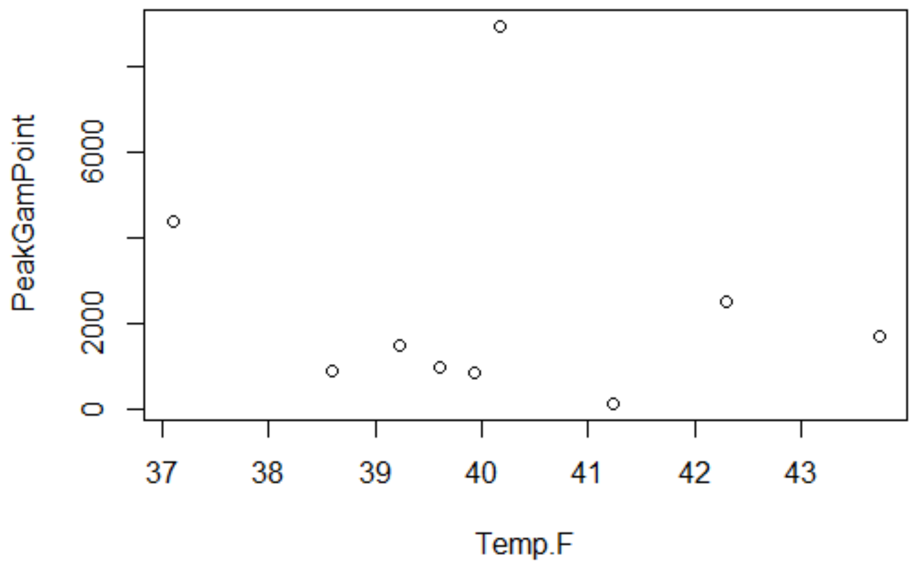
The correlation coefficient between precipitation and peak GAM values is 0.38. This small amount of correlation indicated the need for a simple linear regression model. The value for the adjusted R^2 is 0.02. The F statistic in this regression model (with 1 and 7 d.f.) is 1.2 and the p-value is 0.310. There may be an effect here, but the p-value is too large to reject the null hypothesis, further indicating that there may be other weather or confounding variables affecting the butterfly abundance in this site.



Total winter precipitation plotted against peak GAM values at site R50

Temperature

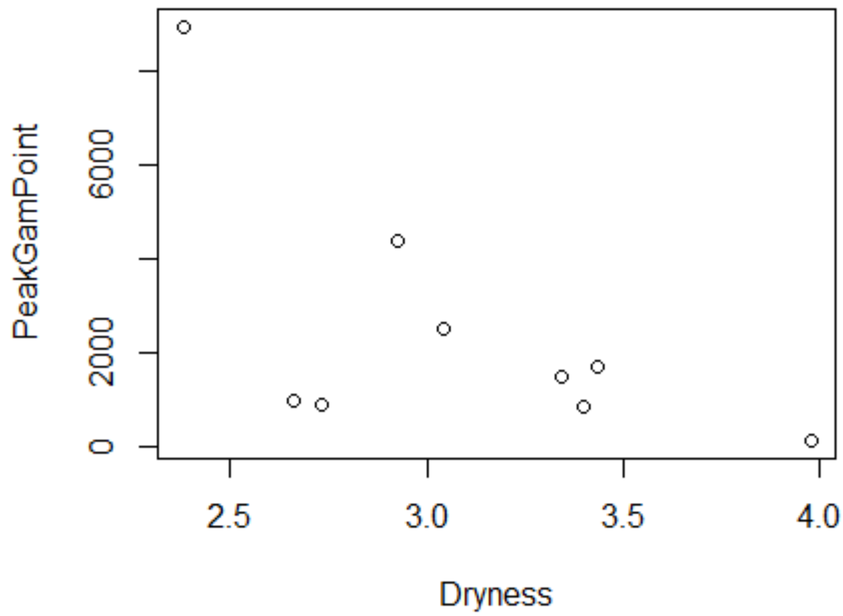
The correlation between the peak GAM abundance values and temperature was negative showing r=-0.15. There is not much correlation, so no linear model was needed for abundance values with respect to average winter temperature at this site.



Plot of peak GAM abundance values against the average winter temperature for site R50

Humidity

There was a negative correlation between the peak GAM points for abundance in this site and the humidity values measured in vapor pressure deficit. The correlation coefficient is r= -0.64, indicating a need for a linear model to be run. The linear model returned an adjusted R^2=0.32. The F-statistic (with 1 and 7 d.f.) was 4.8, with a p-value of 0.065. Higher winter humidity is somewhat associated with greater abundance of butterflies in R50 during the following spring.



Plot of winter average max vapor pressure deficit (Vpd) plotted against the peak GAM abundance values at site R50

Multivariate analysis at R50

A correlation analysis of all the weather variables for R50 showed the two variables, humidity and precipitation to be somewhat correlated, where r=.30. Additionally, humidity and temperature were also correlated at r= 0.40. Because of these correlations, humidity was not included in any of the models.

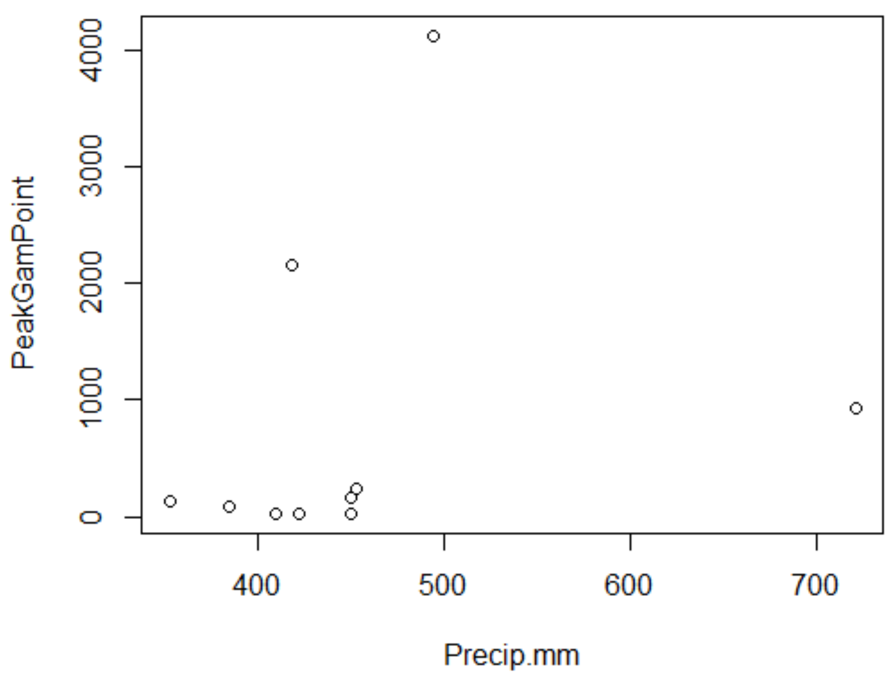
Upon looking at the multiple linear regression model of temperature and precipitation and how it affects the peak GAM points, an adjusted R^2 value was returned as -0.5. The F-statistic (with 2 and 6 d.f.) was 0.80 with a p-value of 0.493. This model is not a good fit.

Scatter Creek South

Precipitation

There is not much effect that the sum of total winter precipitation is having on the abundance numbers of butterflies at Scatter Creek South. The correlation coefficient is r= 0.24. There seems to be some correlation, indicating a need for a linear regression model.

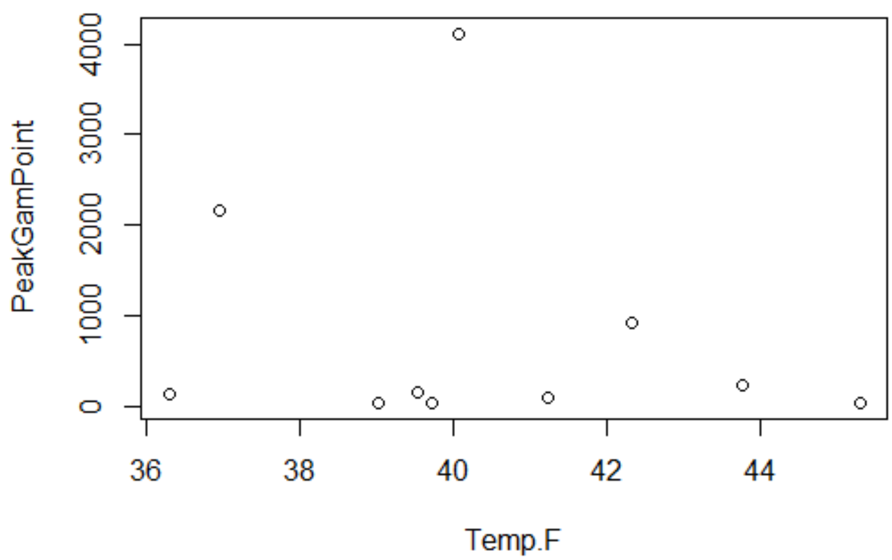
The adjusted R^2 is -.06. The F statistic (with 1 and 8 d.f.) in this regression is 0.51 and the p-value is 0.496. This indicates that winter precipitation does not affect the populations of butterflies. There may be an effect here, however the p-value is too large to reject the null hypothesis, further indicating that there may be other weather or confounding variables.



Plot of peak GAM abundance values against total winter precipitation values at Scatter Creek South

Temperature

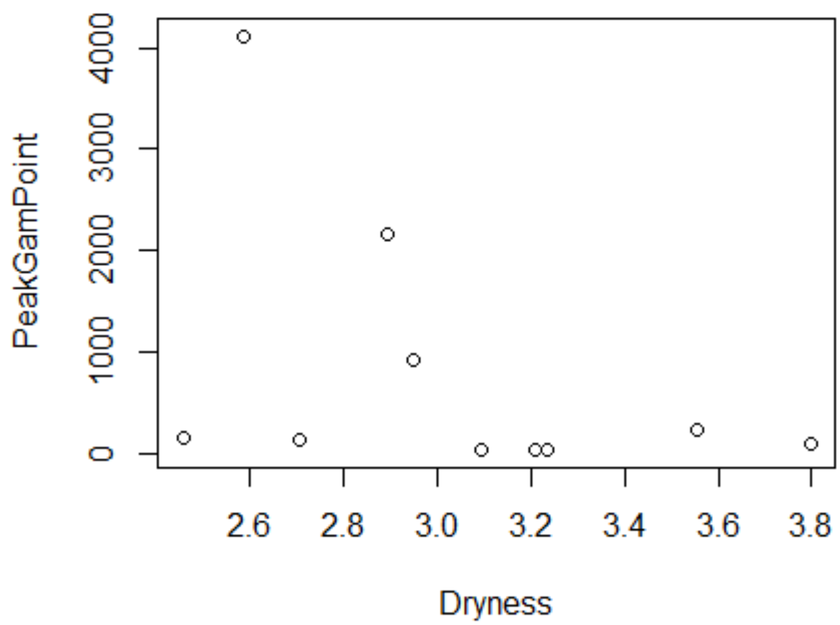
The return of a low correlation coefficient of r=-.20 indicates no need to run a linear regression model of temperature as it affects the values of peak GAM abundance values at Scatter Creek South.



Plot of average winter temperature against peak GAM values of abundance at the Scatter Creek South study site

Humidity

Though not as strong a correlation as site R50, there is still a negative correlation between the measure of vapor pressure deficit and the peak GAM values for butterfly abundance at this site. The correlation coefficient, r = -0.44, is a large enough correlation to run a linear regression model. The model returns an adjusted R^2 of 0.1. There is an F-statistic (with 1 and 8 d.f.) of 2.0 with a p-value of .198. This shows a pretty strong effect, but not enough to reject the null hypothesis.



Plot of the average max winter vapor pressure deficit (Vpd) against the peak GAM abundance values of butterflies at Scatter Creek South

Multivariate analysis at SCS

The correlation analysis of the independent variables (winter climatic variables) showed some correlation between humidity and temperature (r=0.49), as well as correlation between precipitation and temperature (r=0.35). For this reason, the only reasonable multiple linear regression model is that of precipitation and humidity that has a correlation value of r= (-0.18).

This multiple linear regression model returned an adjusted R^2 of -0.005. The F-statistic (with 2 and 7 d.f.) is 1.0 with a p-value of 0.408. This is not a good model fit.

Plots of the residuals:

All the plots of the residuals performed on the data show the appropriateness of the linear model as a model of choice for this data analysis.

The statistics program, R has the function of displaying the plots of the residuals. These plots help measure how far the data points are off the regression line, or in other words, how much the regression line misses the data point.

Plots of the residuals explained in detail:

The most common plot is the Residuals vs. Fitted plot. The residuals are plotted against the fitted value. Lots of scatter and no patterns indicate that the linear models are appropriate for this data.

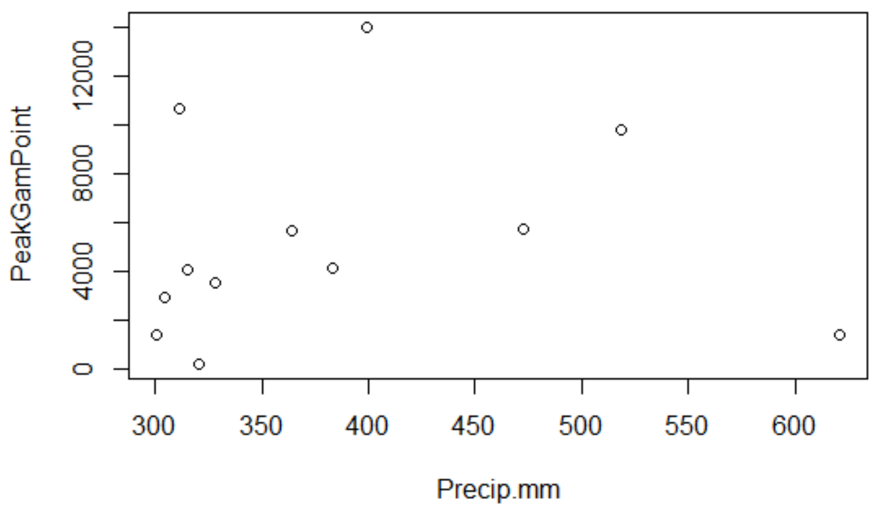
The Normal Q-Q plot tells us from the straight line that the errors in this data set are normally distributed. This data shows that the linear model is appropriate and we do need to use a non-linear model for the regression.

The Residuals vs Leverage plot lets us know if the variance of all the residuals is constant. Leverage is the measure of the influence of the points. The higher the influence, the farther from the mean value (the regression line). If the variance (value of the distance each point is from the regression line) get larger as the dependent variable (PeakGamPoint) increases, it will show that our assumption for using the linear regression that the variance of these residuals are constant is actually false and a different model other than linear regression should be used.

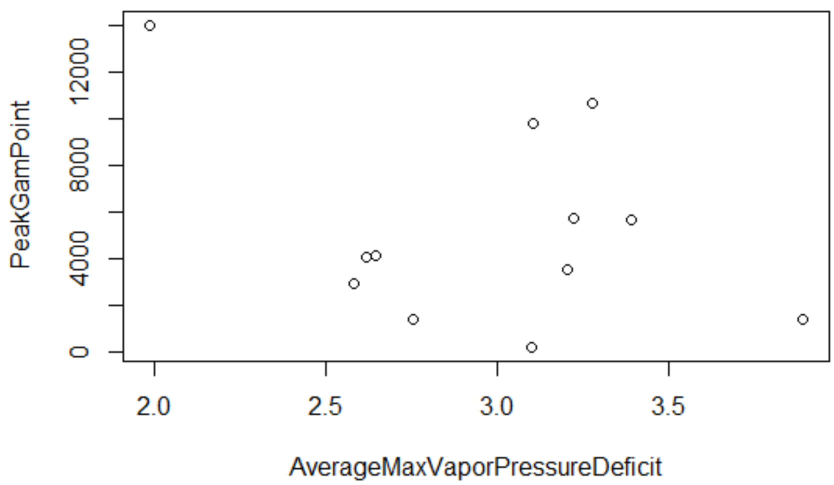
The Scale-Location plot is a measure of what the predicted values are plotted against the square root of the residuals for the linear model of the data. We would have to consider a different statistical model if the data showed a pattern of residual increase as the predicted values increase.

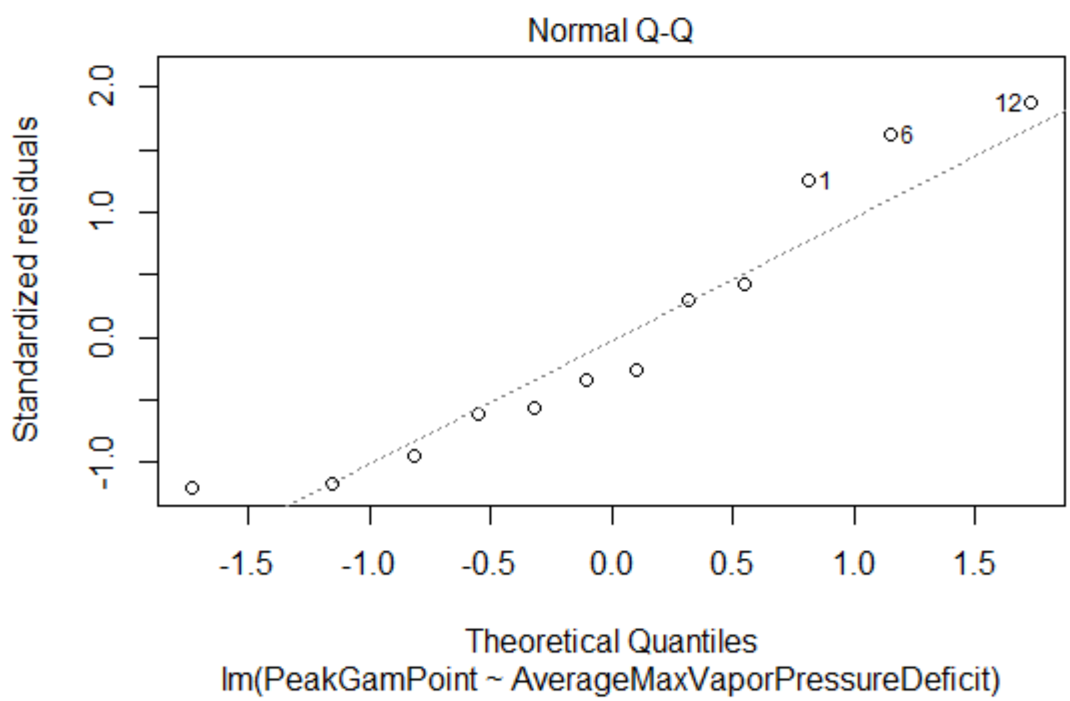
R76 Precipitation Data:

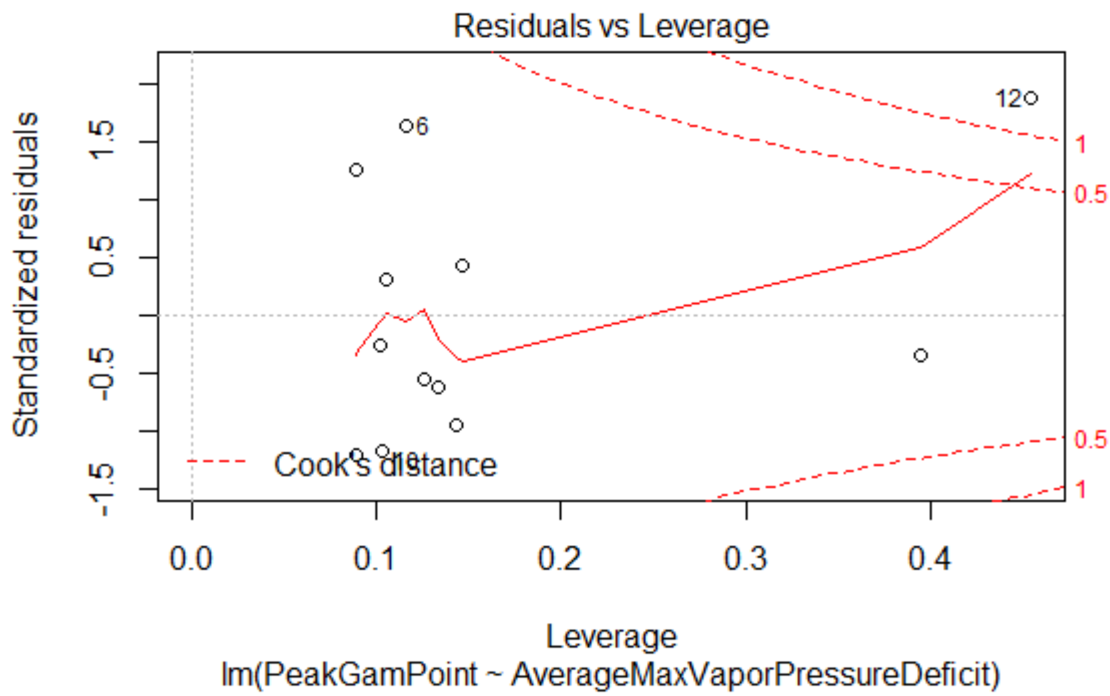
Low correlation for R76 precipitation data and peak GAM points indicated no linear model was needed.

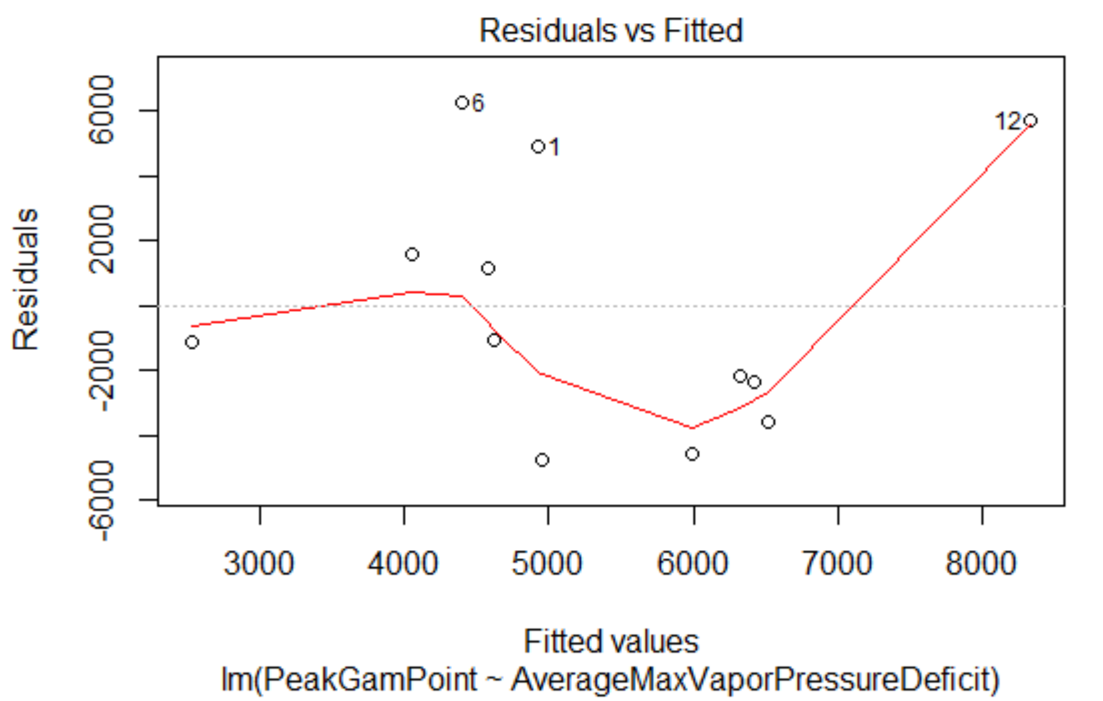


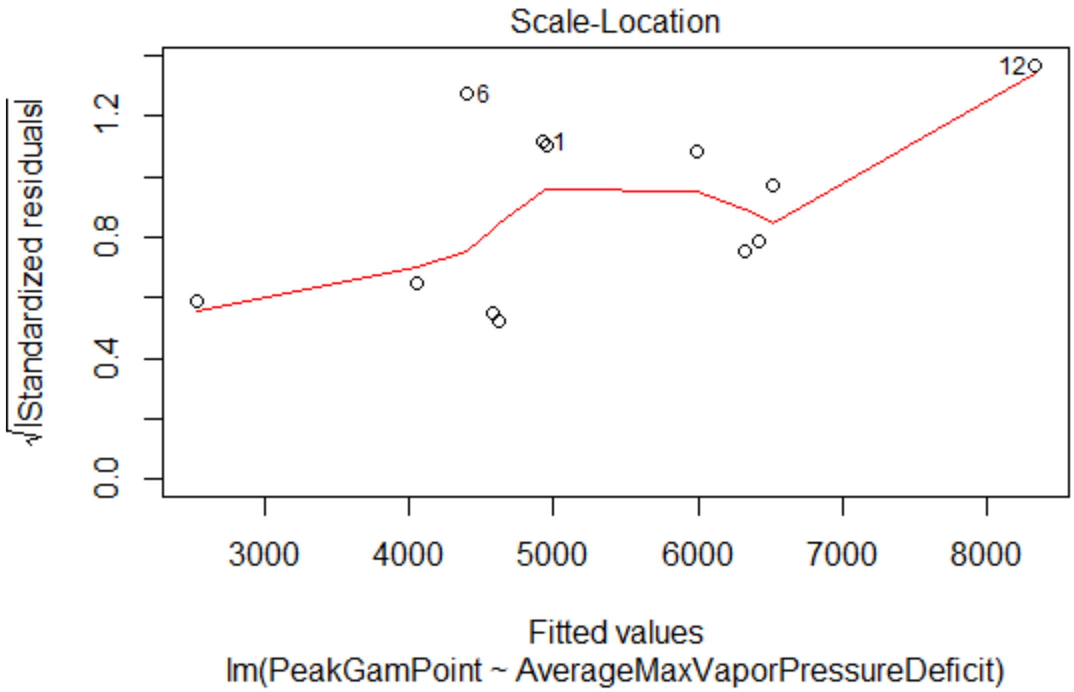
R76 Humidity Data





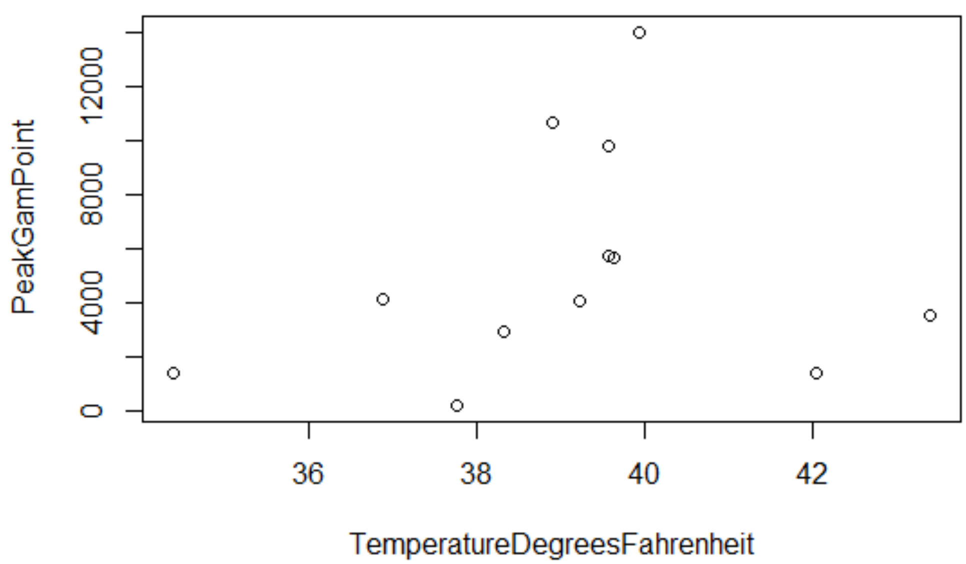

Residuals vs Leverage
Standardized residuals
1.5
0.5
-0.5
-1.5
0.0
0.1
0.2
0.3
0.4
Leverage
lm(PeakGamPoint ~ AverageMaxVaporPressureDeficit)
Cook's distance
12
6
1
0.5
0.5
1


Residuals vs Fitted
Residuals
6000
2000
-2000
-6000
3000
4000
5000
6000
7000
8000
Fitted values
lm(PeakGamPoint ~ AverageMaxVaporPressureDeficit)
6
1
12

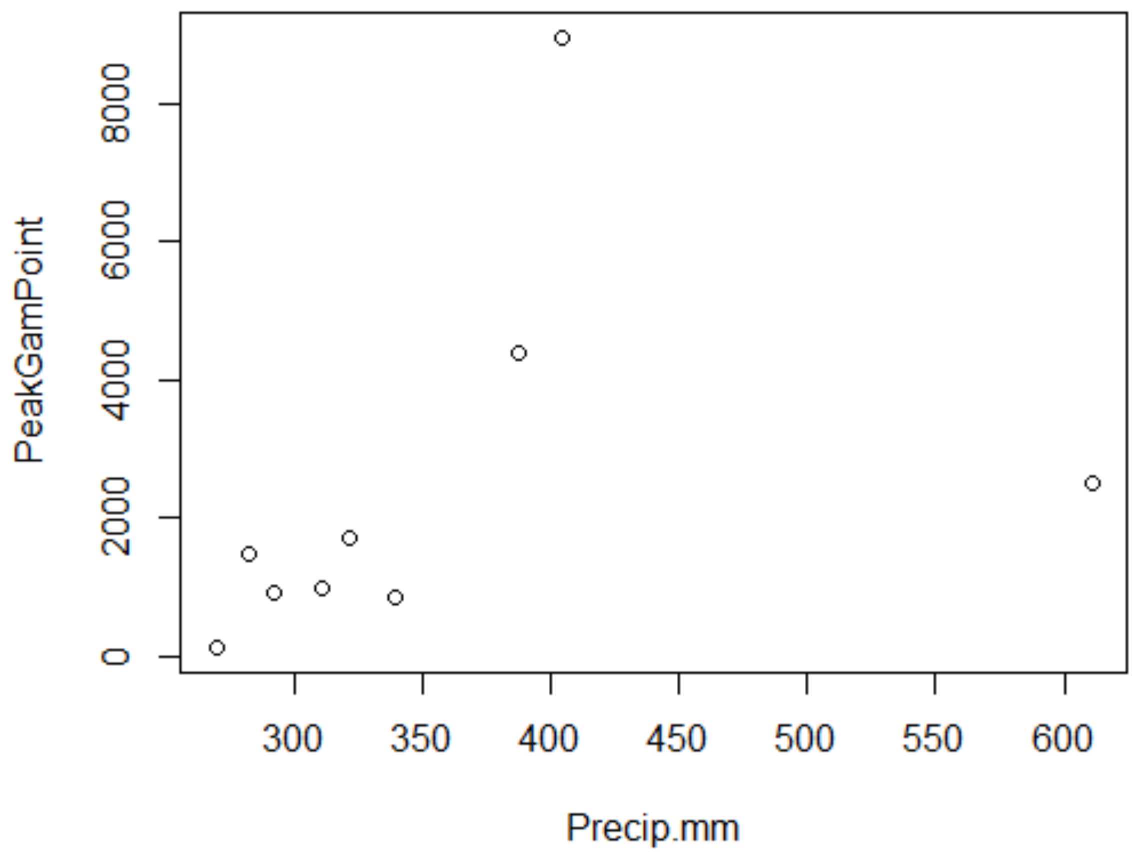


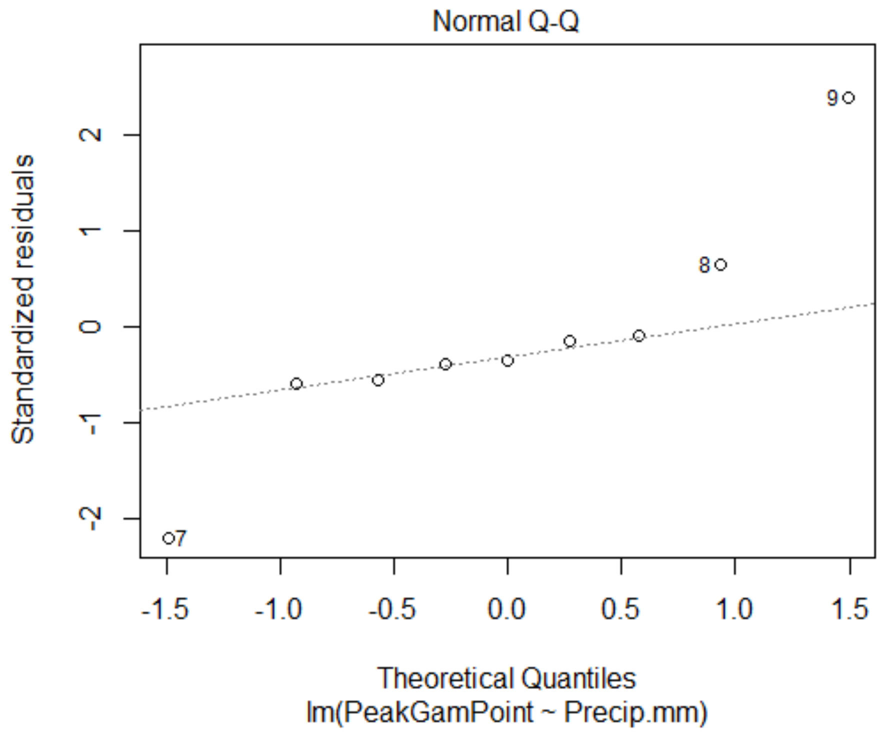
R76 Temperature Data:

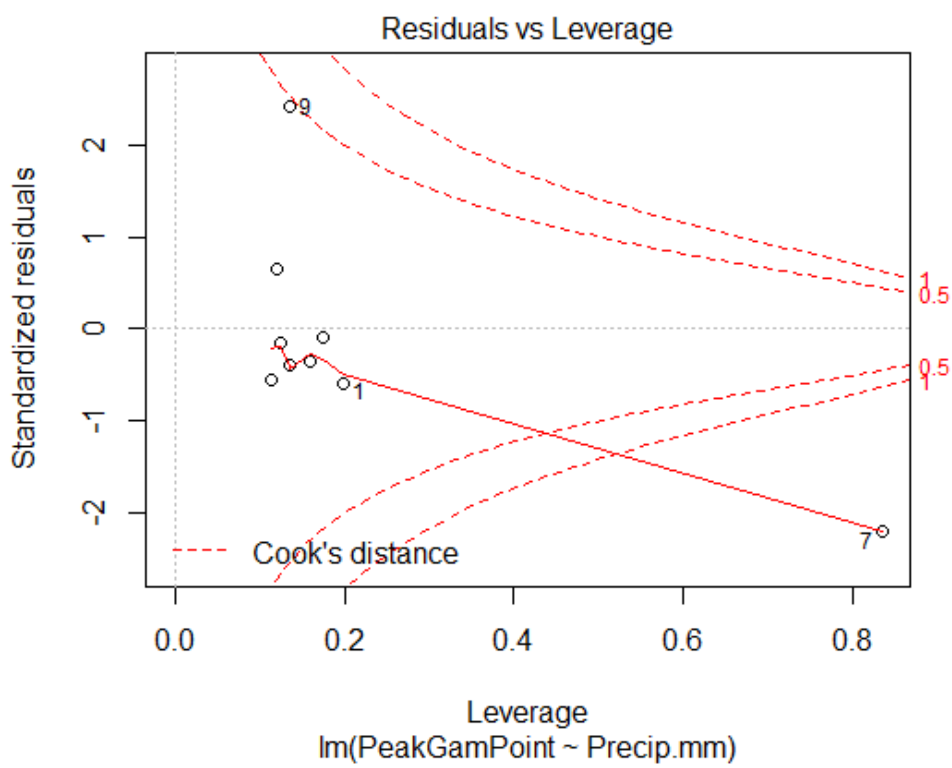
R76 Temperature data was not modeled due to low correlation

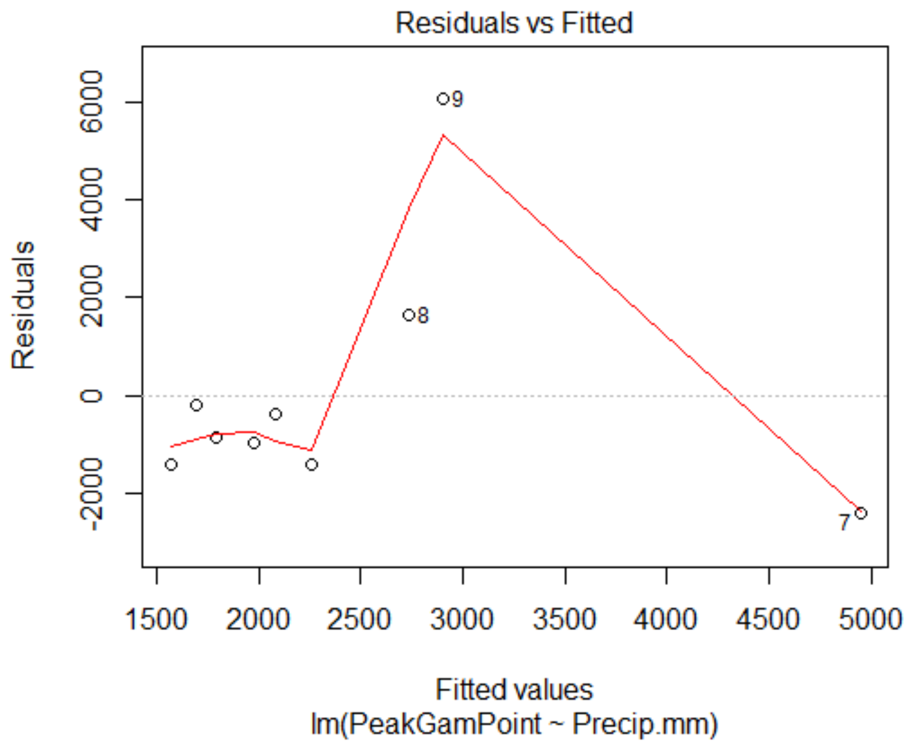


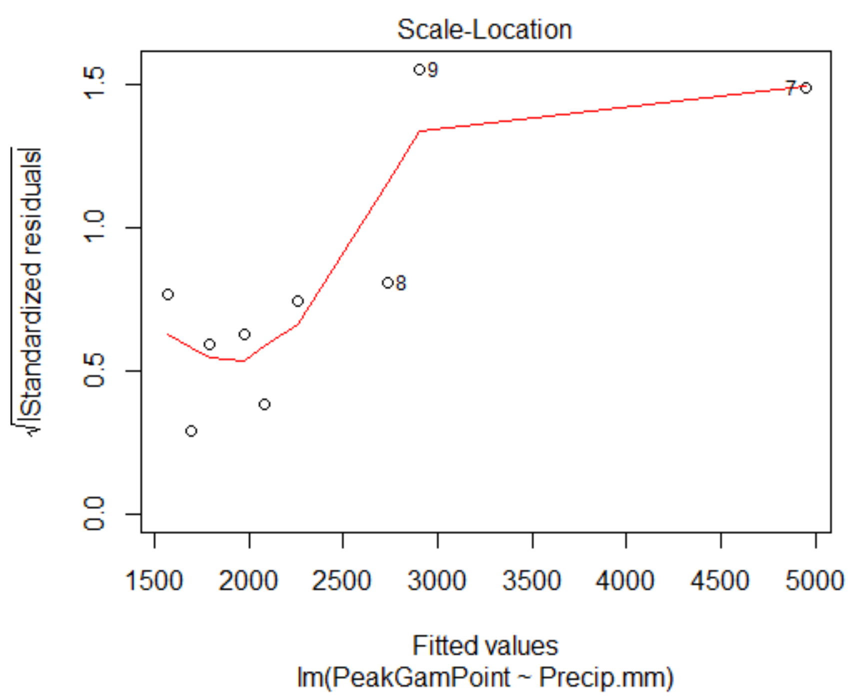
R50 Precipitation Data:




Normal Q-Q
Standardized residuals
Theoretical Quantiles
lm(PeakGamPoint ~ Precip.mm)

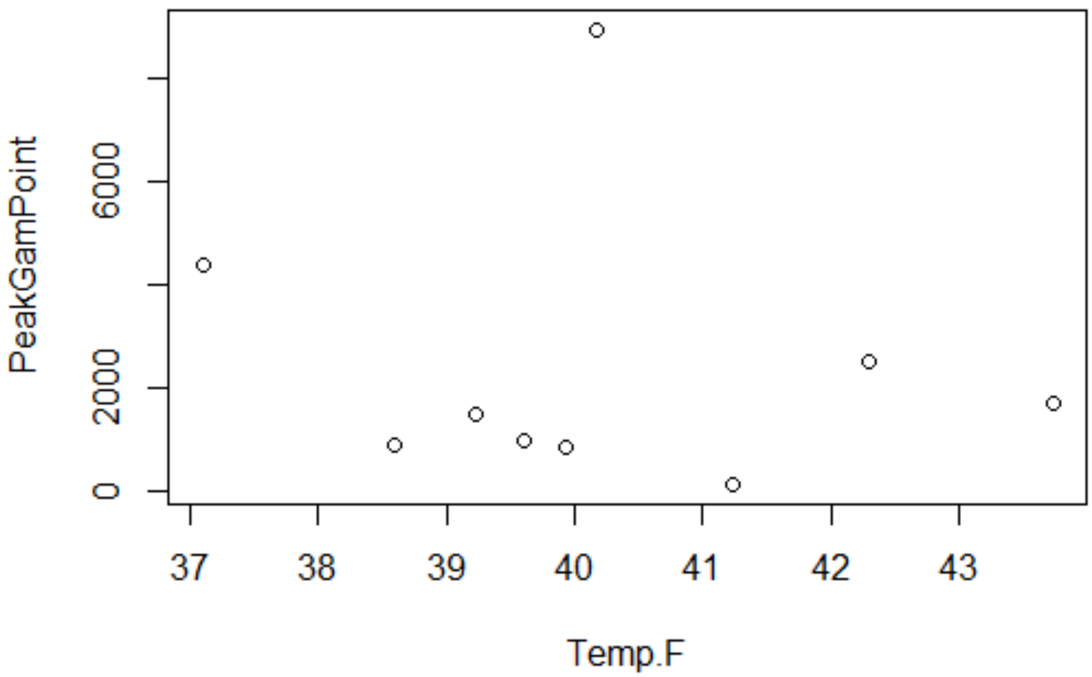

Residuals vs Leverage
Standardized residuals
Cook's distance
Leverage
lm(PeakGamPoint ~ Precip.mm)



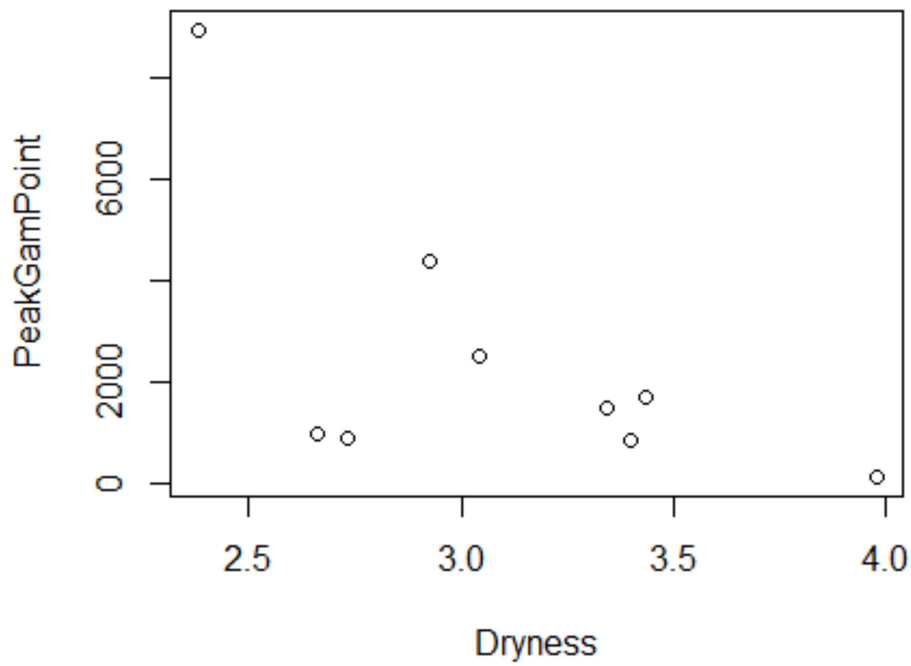


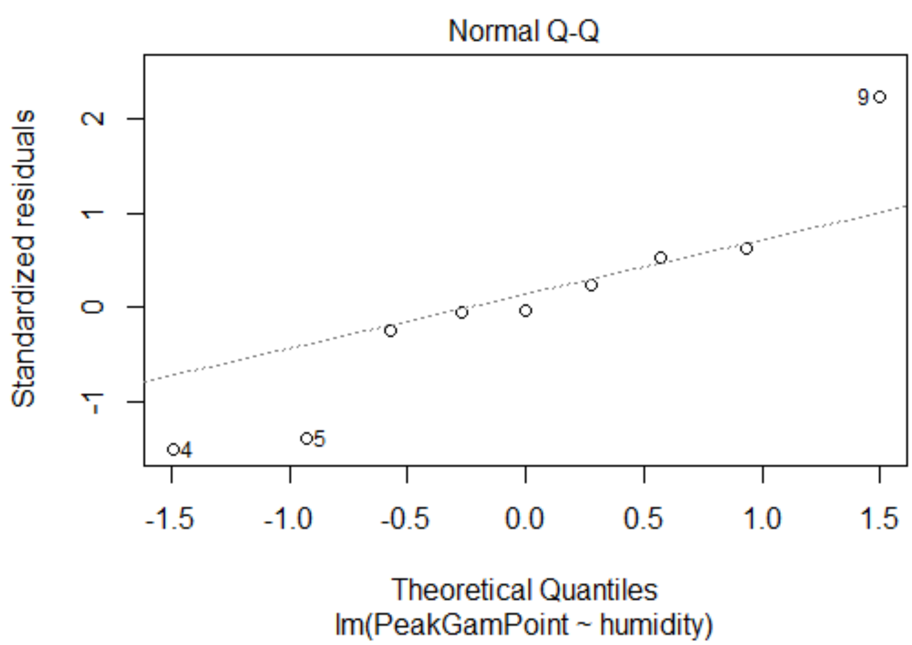
R50 Temperature Data:

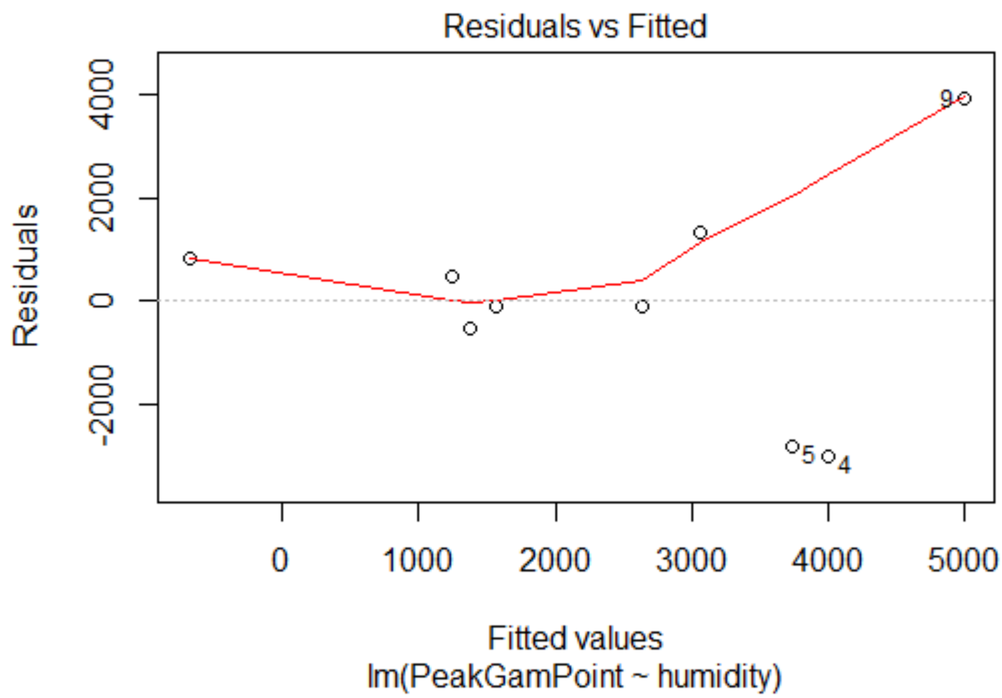
R50 Temperature data was not modeled due to low correlation

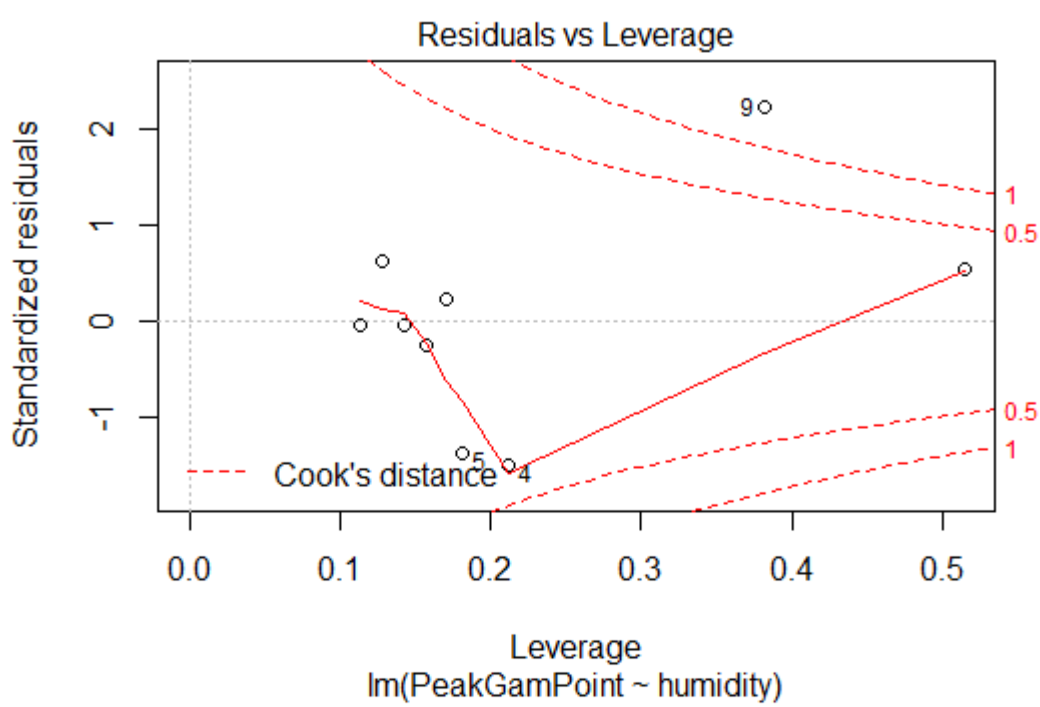

PeakGamPoint
0
2000
6000
37
38
39
40
41
42
43
Temp.F

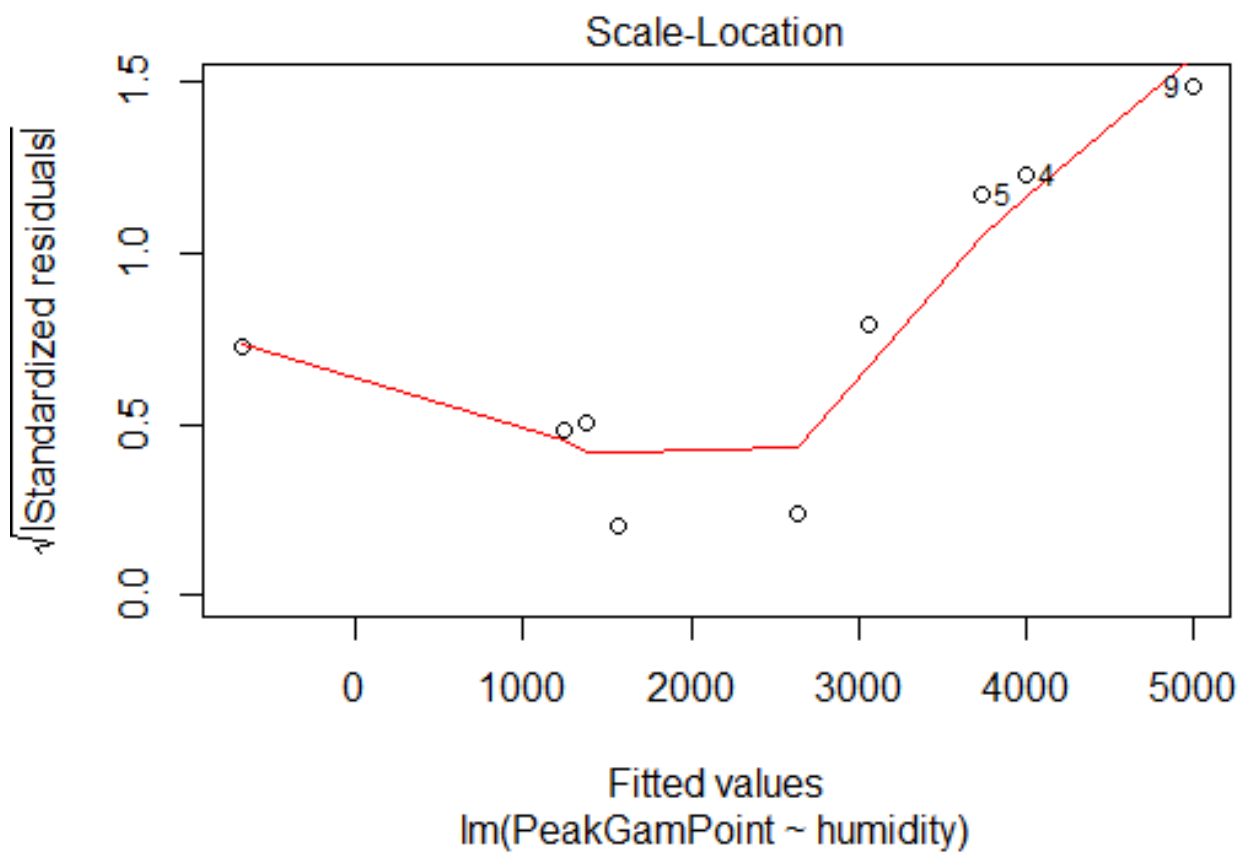
R50 Humidity Data:



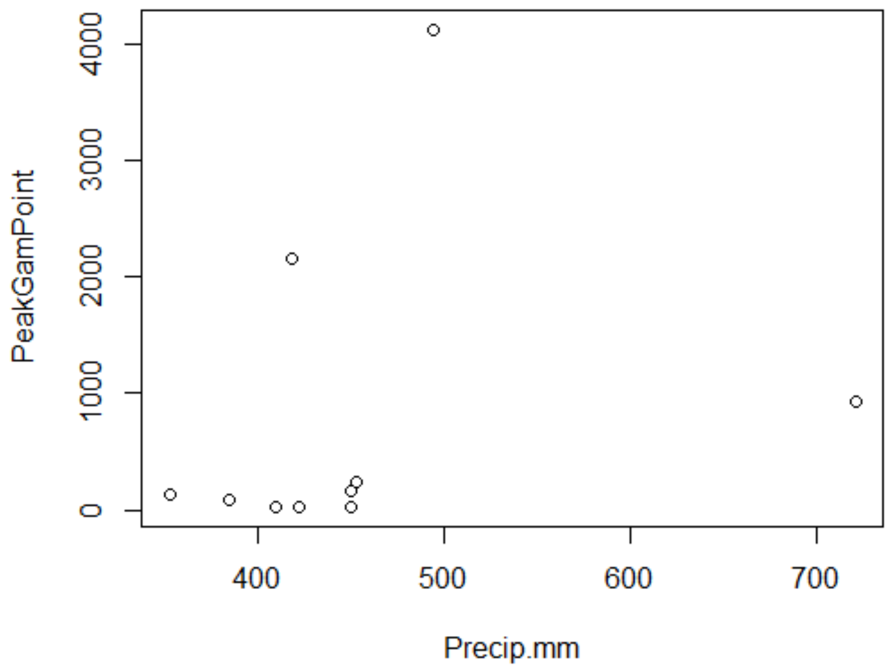


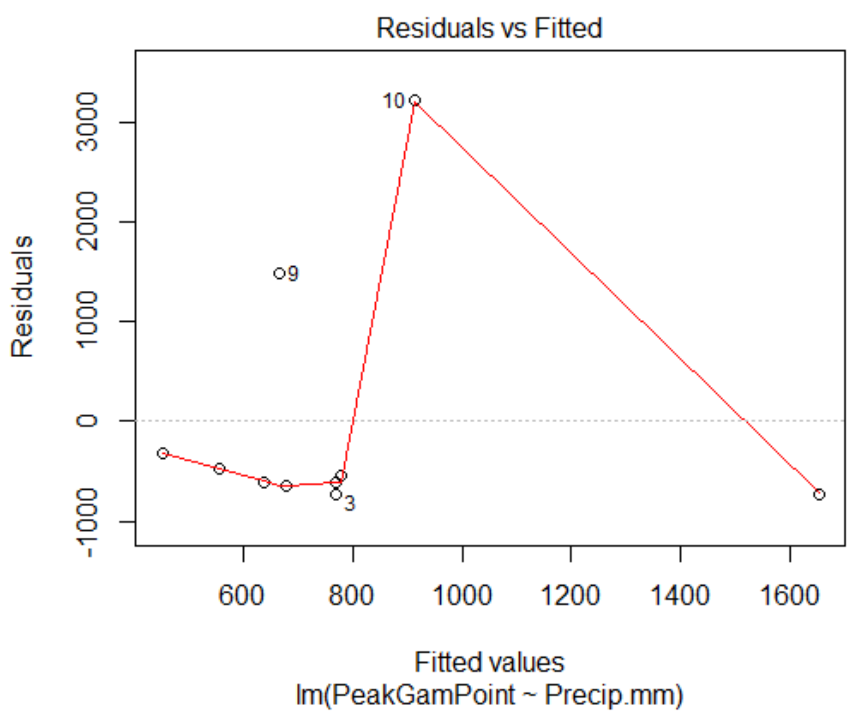

Residuals vs Fitted
Residuals
4000
2000
0
-2000
9
5
4
0
1000
2000
3000
4000
5000
Fitted values
lm(PeakGamPoint ~ humidity)

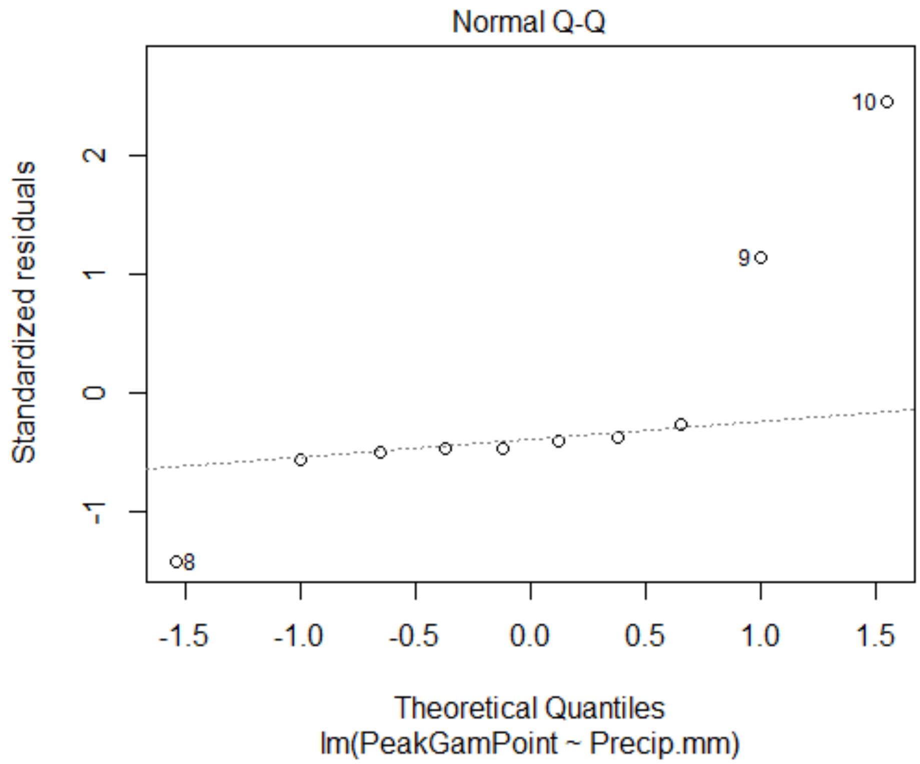

Residuals vs Leverage
Standardized residuals
2
1
0
-1
9
1
0.5
0.5
1
5
4
Cook's distance
0.0
0.1
0.2
0.3
0.4
0.5
Leverage
lm(PeakGamPoint ~ humidity)

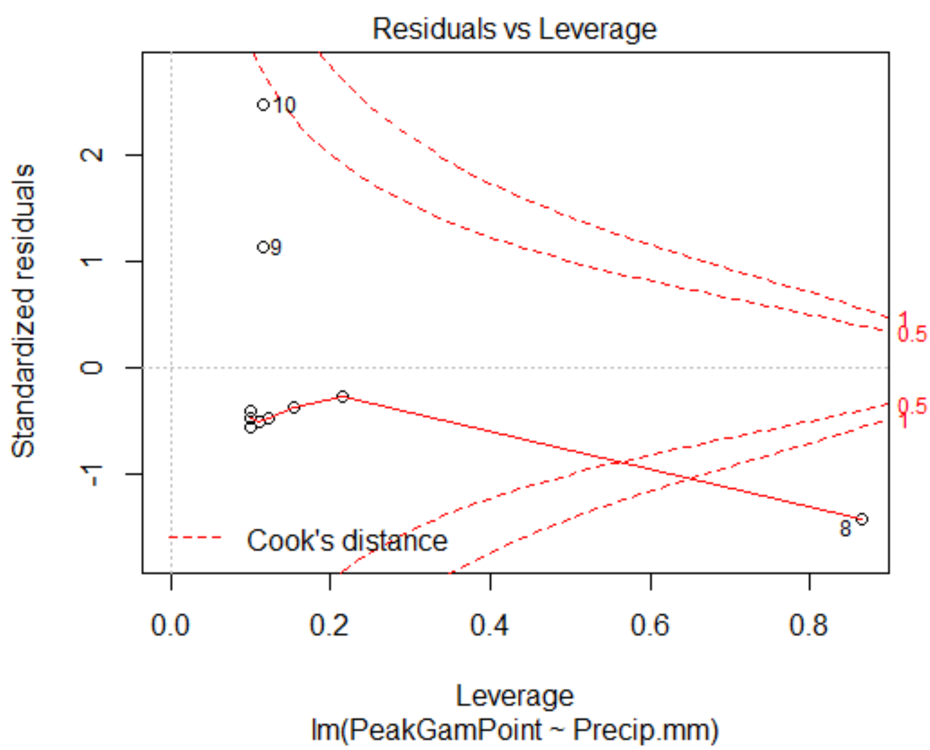

Scale-Location
√|Standardized residuals|
0.0
0.5
1.0
1.5
0
1000
2000
3000
4000
5000
Fitted values
lm(PeakGamPoint ~ humidity)
9
4
5

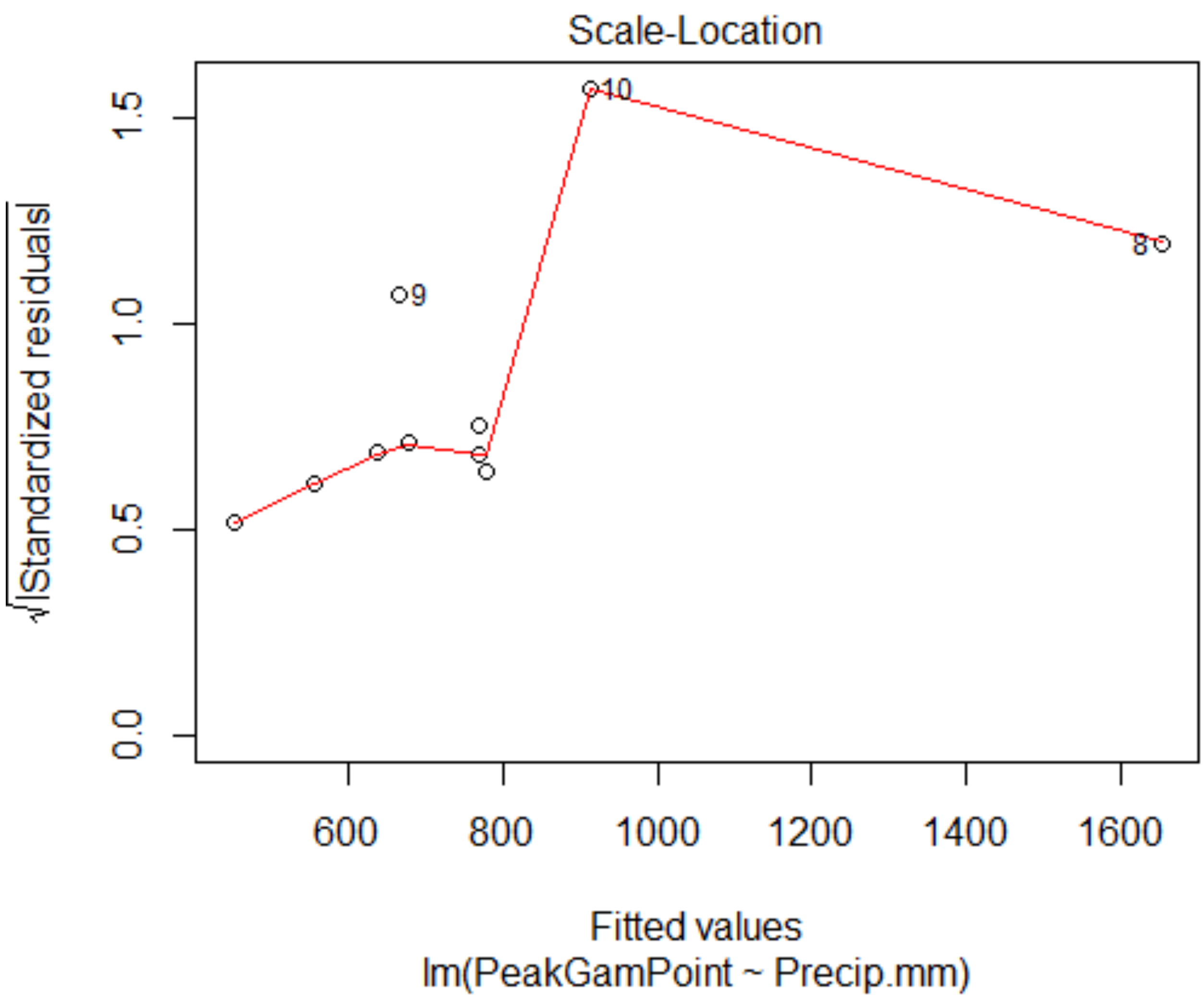
Scatter Creek South Precipitation Data:





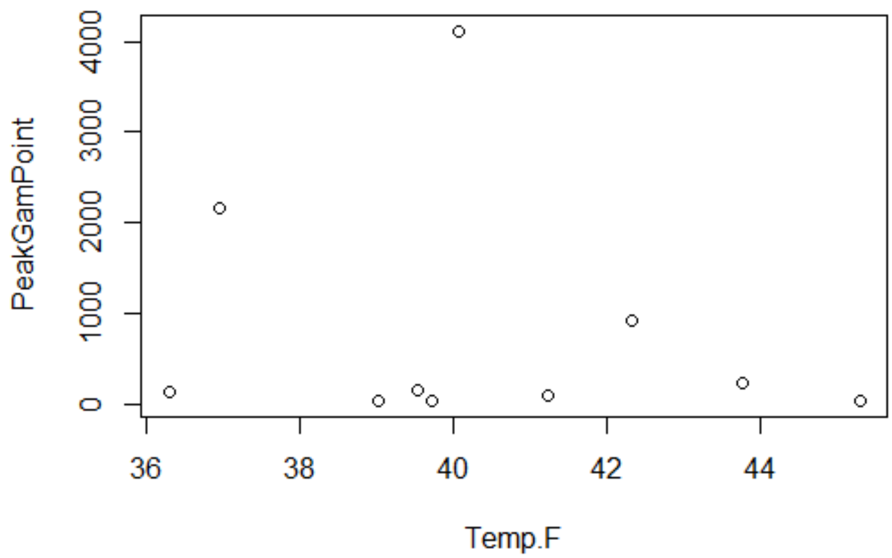

Normal Q-Q
Standardized residuals
Theoretical Quantiles
lm(PeakGamPoint ~ Precip.mm)
10
9
8
-1
0
1
2
-1.5
-1.0
-0.5
0.0
0.5
1.0
1.5


Residuals vs Leverage
Standardized residuals
Leverage
lm(PeakGamPoint ~ Precip.mm)
Cook's distance
10
9
8
1
0.5
0.5
1
-1
0
1
2
0.0
0.2
0.4
0.6
0.8

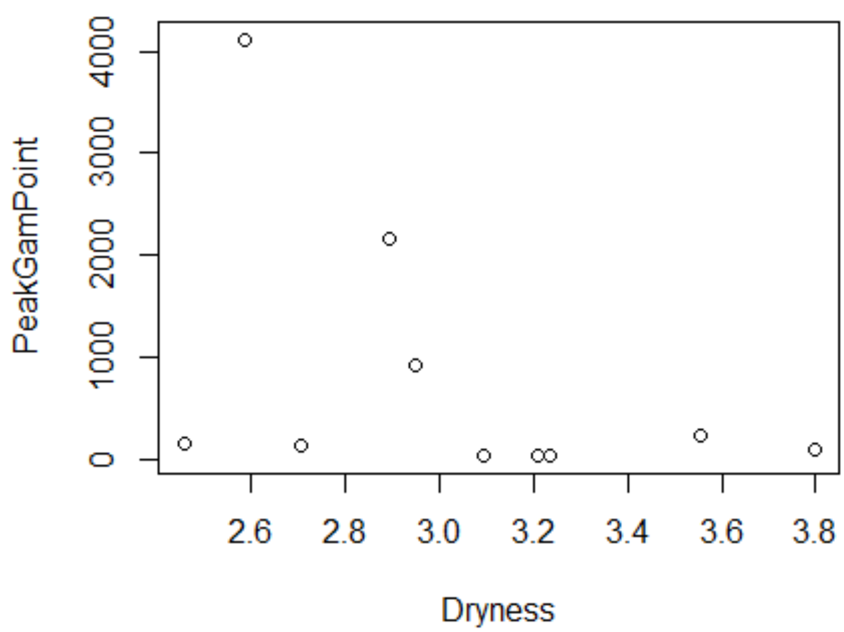

Scale-Location
√|Standardized residuals|
0.0
0.5
1.0
1.5
600
800
1000
1200
1400
1600
Fitted values
lm(PeakGamPoint ~ Precip.mm)
10
9
8

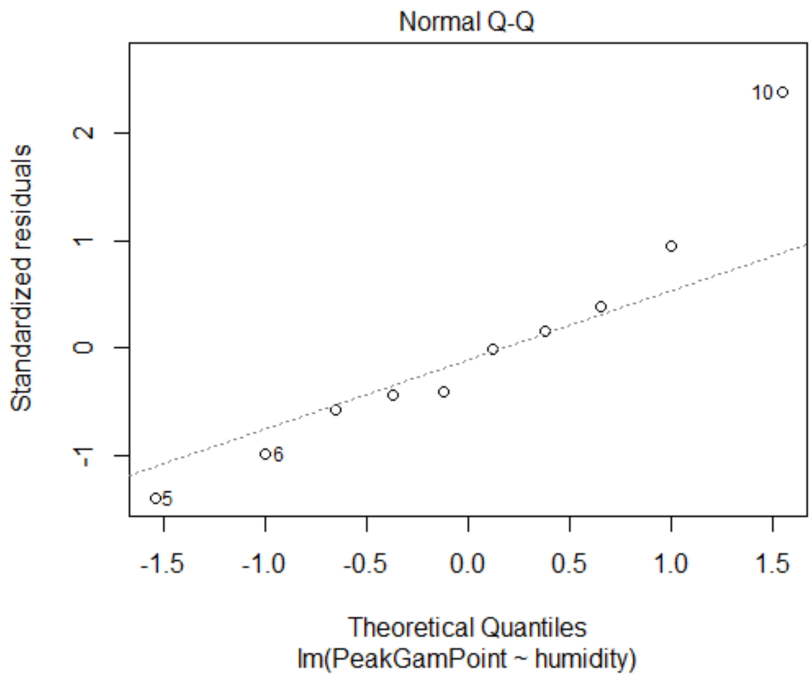
Scatter Creek South Temperature Data:

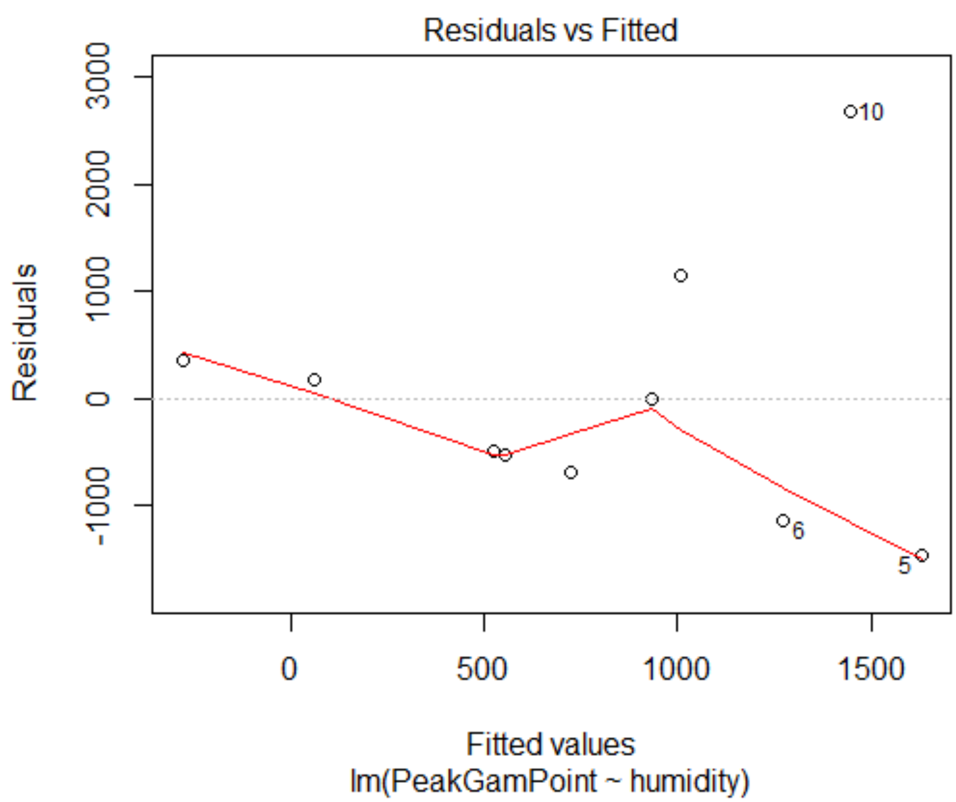
Scatter Creek South did not get modeled for temperature due to low correlation

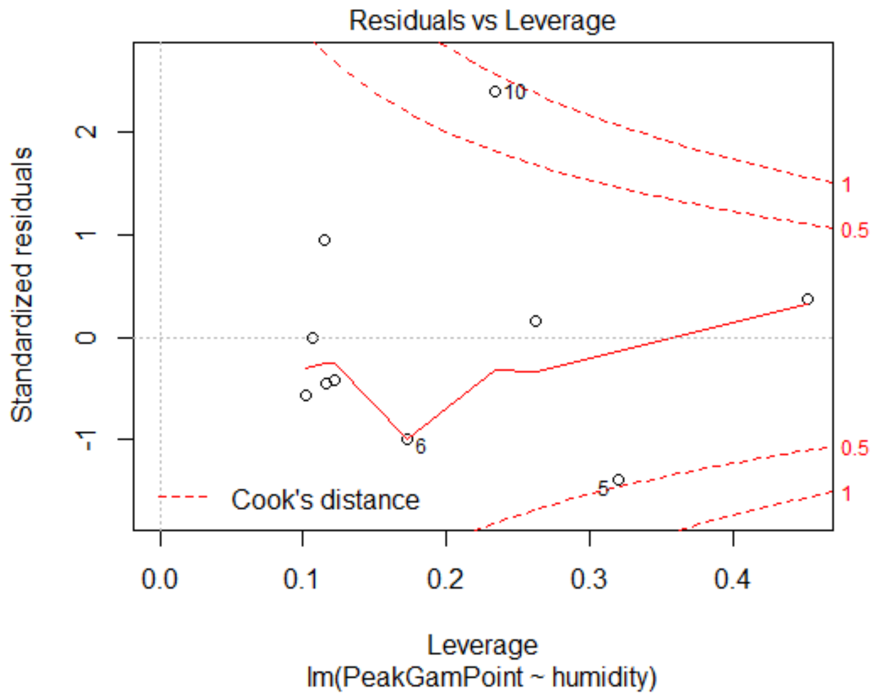


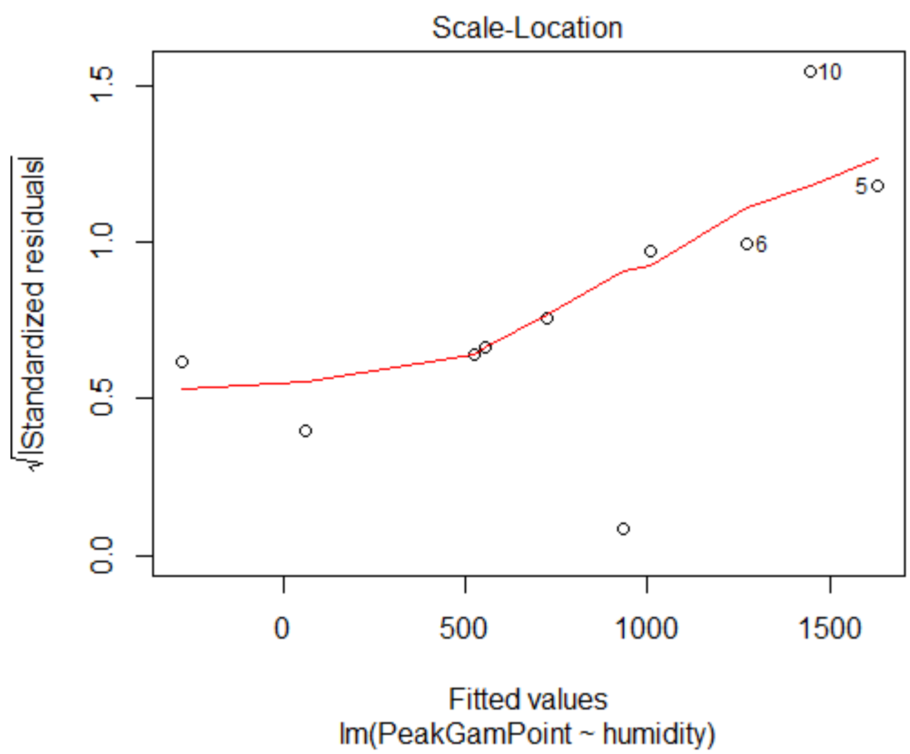
SCS Humidity Data:




Normal Q-Q
Standardized residuals
Theoretical Quantiles
lm(PeakGamPoint ~ humidity)
-1.5 -1.0 -0.5 0.0 0.5 1.0 1.5
-1 0 1 2
10
6
5


Residuals vs Fitted
Residuals
Fitted values
lm(PeakGamPoint ~ humidity)
0 500 1000 1500
-1000 0 1000 2000 3000
10
6
5





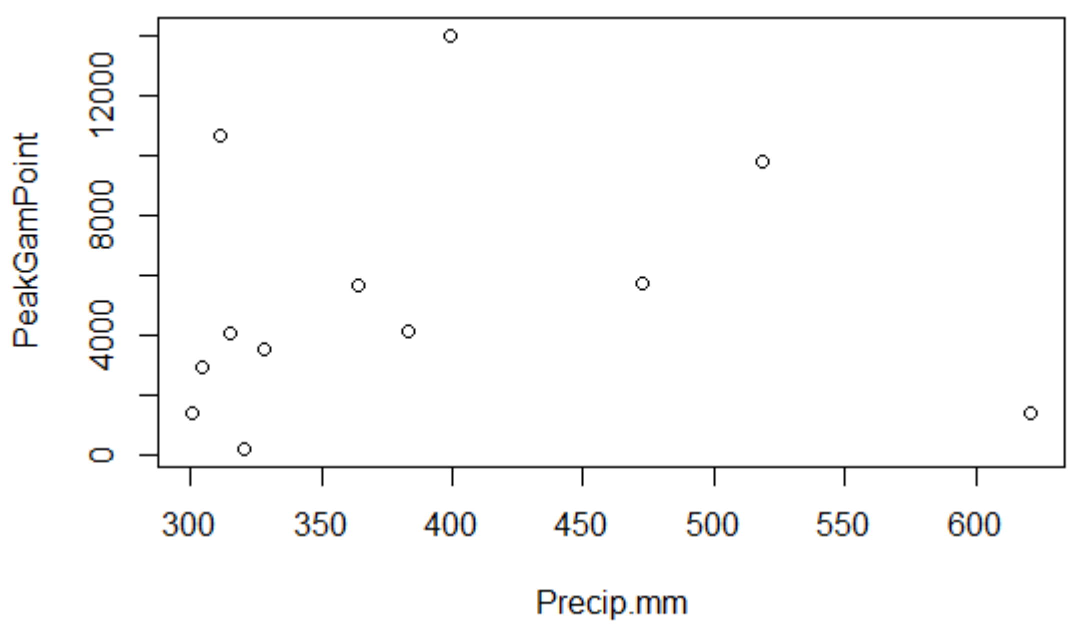
Scatter Creek South Temperature was not modeled due to low correlation

R76 data analysis of raw data:

Because the year 2008 had only three observations, there were not enough data points to model a peak GAM abundance value. Because of this, the year 2008 was left out of the analysis for site R76.

Precipitation

The analysis used linear regression models where the maximum value of the fitted general additive model (GAM) of the abundance estimates was the dependent variable and the sum of the total winter precipitation in millimeters was the independent variable.

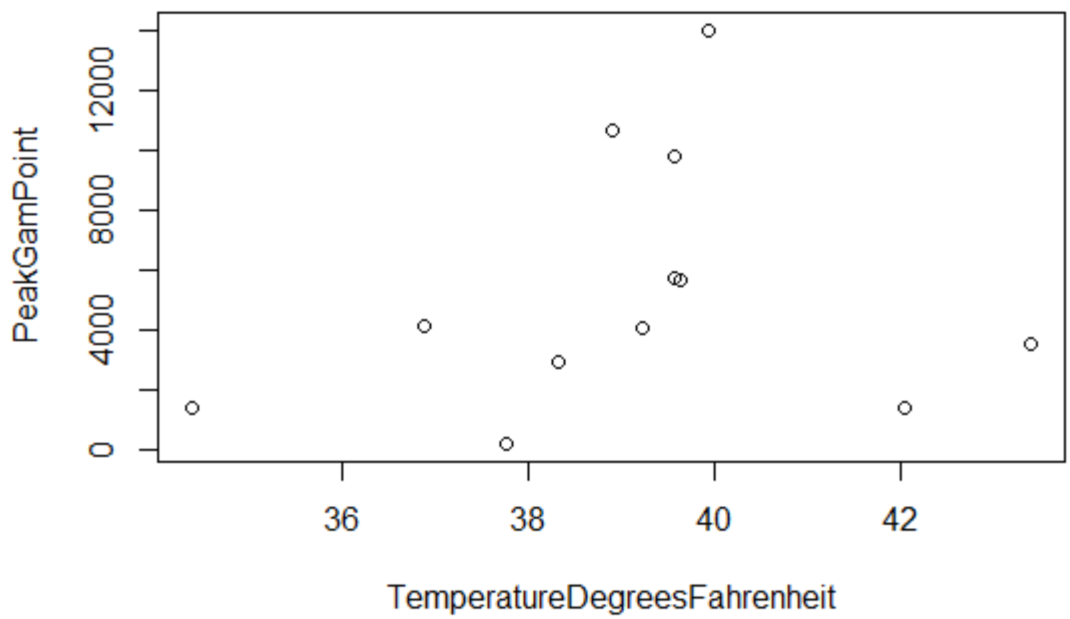


Plot of total winter precipitation plotted against abundance at site R76

The correlation coefficient between precipitation and peak GAM values of the abundance data is 0.10. Because of this, no simple linear regression is needed

Temperature

The correlation coefficient of temperature with respect to abundance is r=0.18, too low to run a simple linear model.

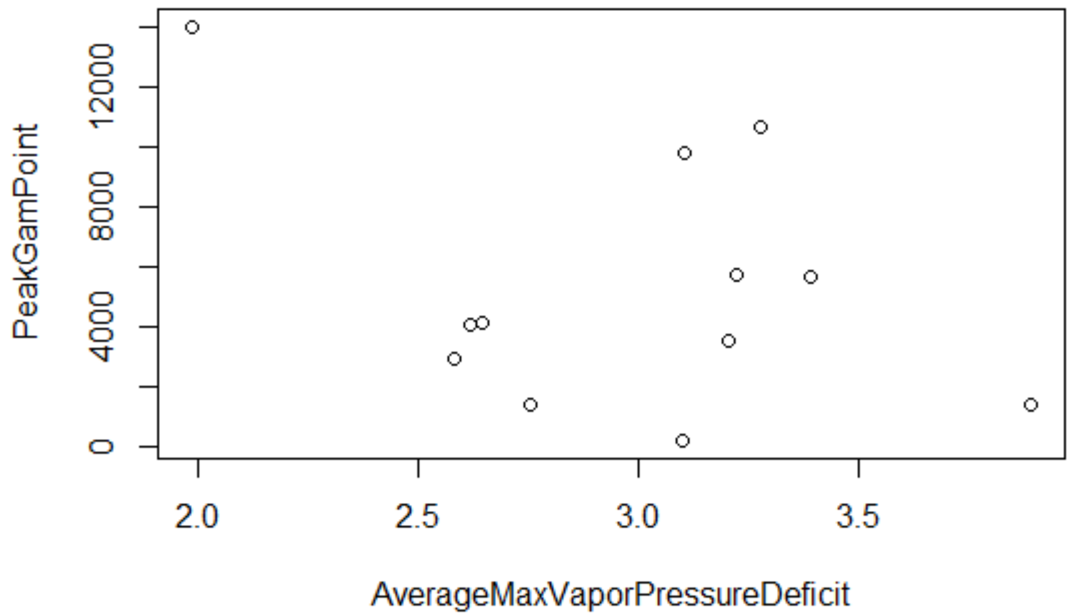


Winter average temperature (˚F) plotted against peak GAM butterfly abundance values from site R76

Humidity

Winter dryness may have a deleterious effect on the populations of butterflies, but not enough to reject the null hypothesis, which was, H_0: "The populations of butterflies in the site, R76 are not affected by humidity".

There is a sufficient correlation between vapor pressure deficit and peak GAM abundance values to run a linear regression model. The correlation coefficient is -0.36, showing that dryness and populations of butterflies may be negatively correlated.



Winter average of max dryness measured in vapor pressure deficit (Vpd) plotted against the peak GAM points for butterfly abundance at R76

The simple linear regression showed the coefficient of correlation, the adjusted R^2 to be 0.04. The F-statistic (with 1 and 10 d.f.) was 1.47 with a p-value of 0.254. These values show an effect, but not enough to determine that humidity alone is affecting the butterfly populations. Higher winter humidity is associated with greater spring abundance of butterflies in R76.

Multivariate analysis in R76

Before running the multiple linear regression on the peak GAM estimates for site R76 and the three climatic variables, a correlation model was run to avoid including the independent variables that are highly correlated. In R76, the climatic variables precipitation and temperature had a correlation coefficient of 0.42. The multiple linear regression model did not include these two variables together. Due to low number of data points for abundance in the year 2008, that year was not included.

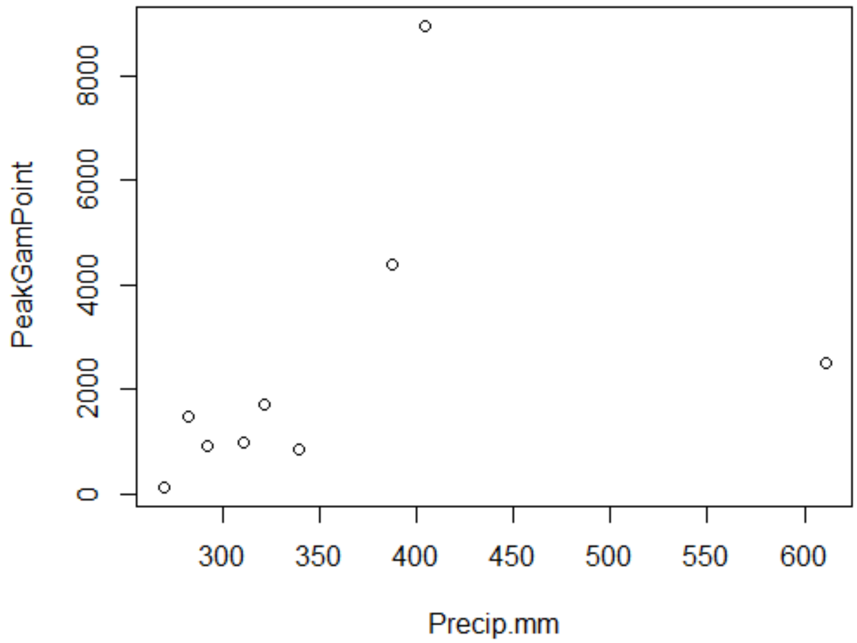
A run of the multiple linear regression model of the peak GAM abundance points with respect to precipitation and humidity returned an adjusted R^2 value of -.06. The F-statistic (with 2 and 9 d.f.) was 0.67 with a p-value of 0.536. This model is not a good fit.

A second model was run looking at the values of temperature and humidity with respect to the peak GAM values. This model returned an adjusted R^2 value of -0.06. The F-statistic (with 2 and 9 d.f.) was 0.70 with a p-value of 0.523. This model is not a good fit either.

R50 data analysis of raw data

Precipitation

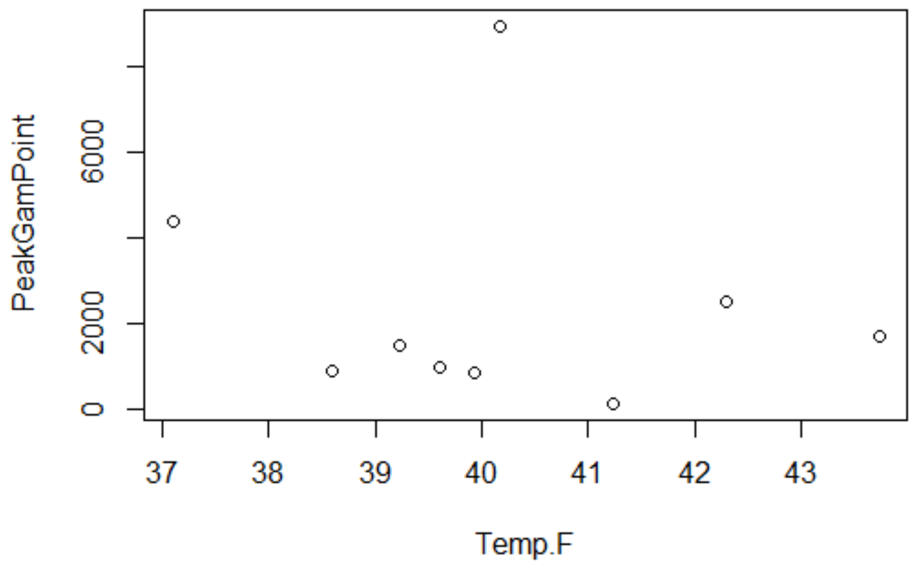
The correlation coefficient between precipitation and peak GAM values is 0.38. This small amount of correlation indicated the need for a simple linear regression model. The value for the adjusted R^2 is 0.02. The F statistic in this regression model (with 1 and 7 d.f.) is 1.2 and the p-value is 0.310. There may be an effect here, but the p-value is too large to reject the null hypothesis, further indicating that there may be other weather or confounding variables affecting the butterfly abundance in this site.



Total winter precipitation plotted against peak GAM values at site R50

Temperature

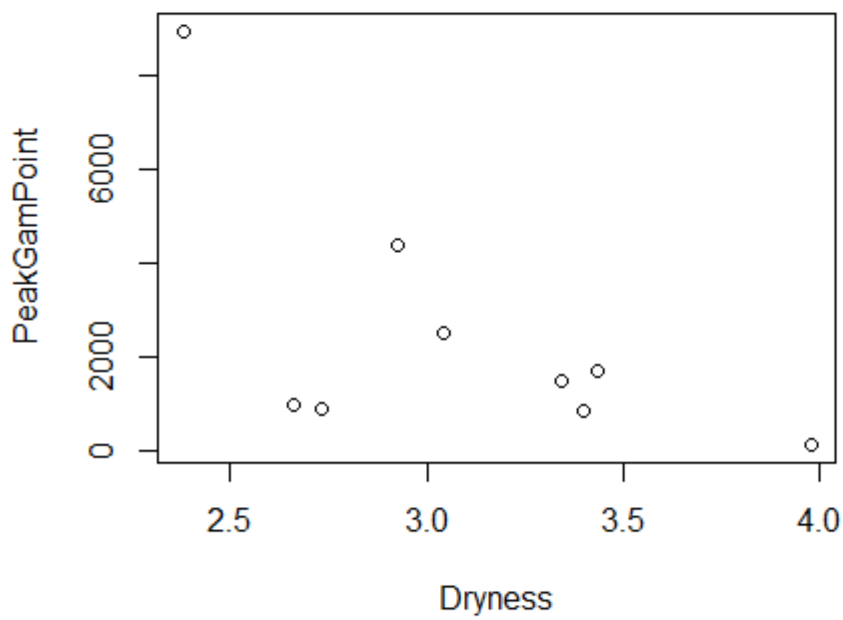
The correlation between the peak GAM abundance values and temperature was negative showing r=-0.15. There is not much correlation, so no linear model was needed for abundance values with respect to average winter temperature at this site.



Plot of peak GAM abundance values against the average winter temperature for site R50

Humidity

There was a negative correlation between the peak GAM points for abundance in this site and the humidity values measured in vapor pressure deficit. The correlation coefficient is r= -0.64, indicating a need for a linear model to be run. The linear model returned an adjusted R^2=0.32. The F-statistic (with 1 and 7 d.f.) was 4.8, with a p-value of 0.065. Higher winter humidity is somewhat associated with greater abundance of butterflies in R50 during the following spring.



Plot of winter average max vapor pressure deficit (Vpd) plotted against the peak GAM abundance values at site R50

Multivariate analysis at R50

A correlation analysis of all the weather variables for R50 showed the two variables, humidity and precipitation to be somewhat correlated, where r=.30. Additionally, humidity and temperature were also correlated at r= 0.40. Because of these correlations, humidity was not included in any of the models.

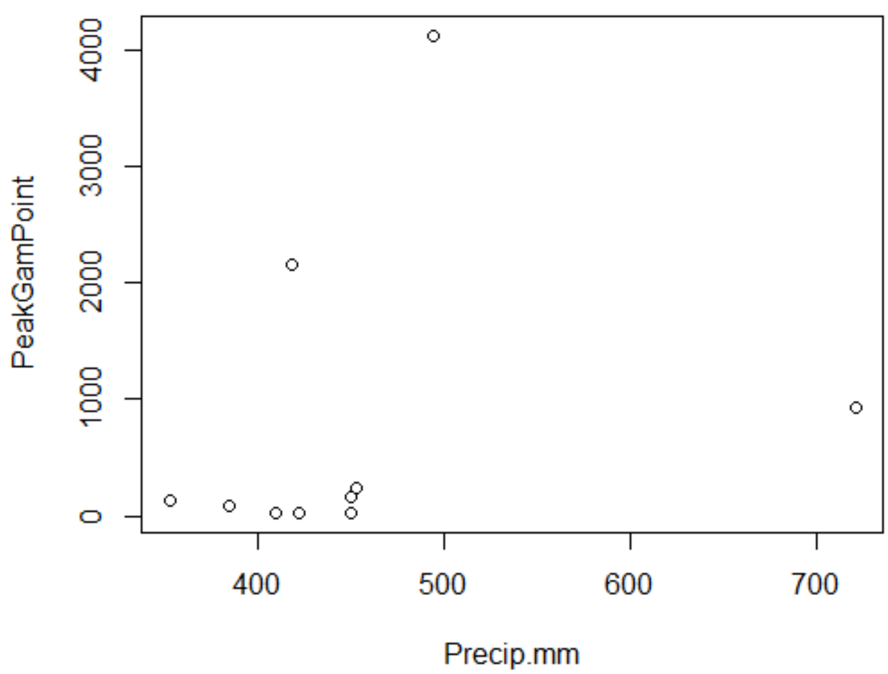
Upon looking at the multiple linear regression model of temperature and precipitation and how it affects the peak GAM points, an adjusted R^2 value was returned as -0.5. The F-statistic (with 2 and 6 d.f.) was 0.80 with a p-value of 0.493. This model is not a good fit.

Scatter Creek South analysis of raw data

Precipitation

There is not much effect that the sum of total winter precipitation is having on the abundance numbers of butterflies at Scatter Creek South. The correlation coefficient is r= 0.24. There seems to be some correlation, indicating a need for a linear regression model.

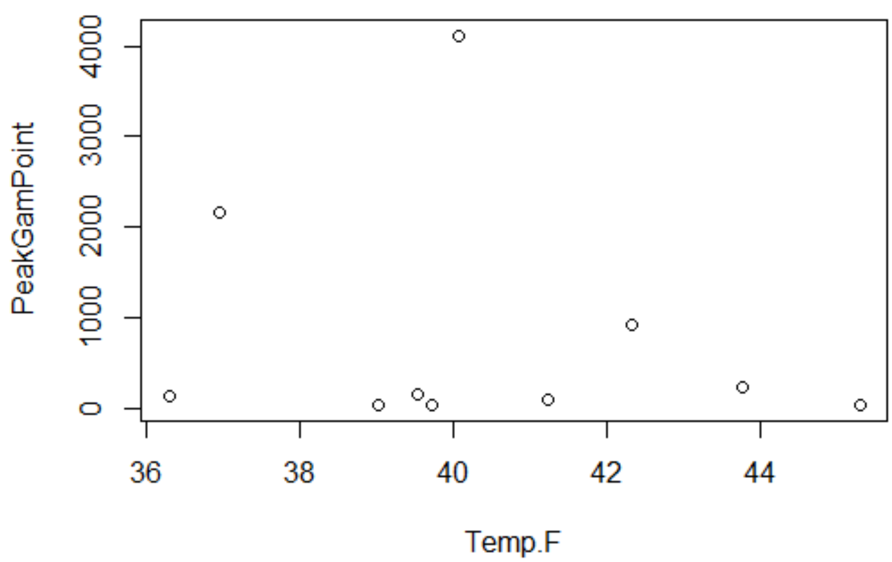
The adjusted R^2 is -.06. The F statistic (with 1 and 8 d.f.) in this regression is 0.51 and the p-value is 0.496. This indicates that winter precipitation does not affect the populations of butterflies. There may be an effect here, however the p-value is too large to reject the null hypothesis, further indicating that there may be other weather or confounding variables.



Plot of peak GAM abundance values against total winter precipitation values at Scatter Creek South

Temperature

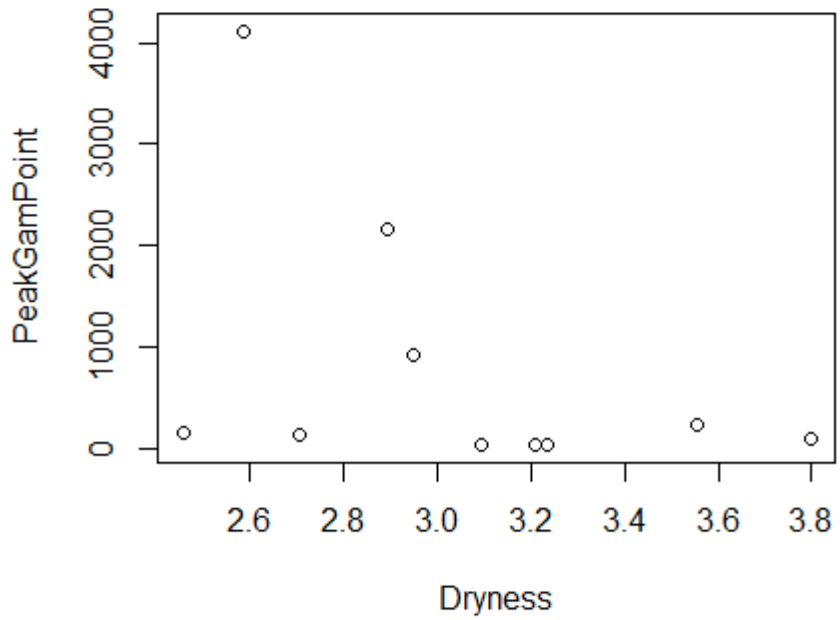
The return of a low correlation coefficient of r=-.20 indicates no need to run a linear regression model of temperature as it affects the values of peak GAM abundance values at Scatter Creek South.



Plot of average winter temperature against peak GAM values of abundance at the Scatter Creek South study site

Humidity

Though not as strong a correlation as site R50, there is still a negative correlation between the measure of vapor pressure deficit and the peak GAM values for butterfly abundance at this site. The correlation coefficient, r = -0.44, is a large enough correlation to run a linear regression model. The model returns an adjusted R^2 of 0.1. There is an F-statistic (with 1 and 8 d.f.) of 2.0 with a p-value of .198. This shows a pretty strong effect, but not enough to reject the null hypothesis.



Plot of the average max winter vapor pressure deficit (Vpd) against the peak GAM abundance values of butterflies at Scatter Creek South

Multivariate analysis at SCS

The correlation analysis of the independent variables (winter climatic variables) showed some correlation between humidity and temperature (r=0.49), as well as correlation between precipitation and temperature (r=0.35). For this reason, the only reasonable multiple linear regression model is that of precipitation and humidity that has a correlation value of r= (-0.18).

This multiple linear regression model returned an adjusted R^2 of -0.005. The F-statistic (with 2 and 7 d.f.) is 1.0 with a p-value of 0.408. This is not a good model fit.