ECOLOGICAL DRIVERS OF RIPARIAN MICROCLIMATE ON THE OLYMPIC PENINSULA OF WASHINGTON STATE

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

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by Katrina Keleher

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The Evergreen State College
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ABSTRACT

Ecological drivers of riparian microclimate on the Olympic Peninsula of Washington State

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Despite the regulatory emphasis on buffer zones in riparian areas, few studies have examined the effects of timber harvesting on near-stream microclimates—the suite of environmental variables that includes moisture, temperature, wind speed, and light. This study examines the spatial and temporal variability of microclimates over three years from ten different watersheds throughout State managed forests on the Olympic Experimental State Forest (OESF). Microclimates influence in-stream temperatures and near-stream habitat of riparian amphibians, small mammals, and invertebrates. Mixed multivariate models with both fixed and random effects were developed to examine the relationships between microclimate variables (vapor pressure deficit, air temperature, and cumulative degree days) and a number of discrete predictor variables including distance from stream, height above stream, percent shade, and solar radiation. Height above stream was found to have a statistically significant effect on microclimate variables in all three models, and solar exposure was found to be a significant predictor for air temperature and vapor pressure deficit. Additionally, height above stream was found to be a stronger predictor for microclimate than distance from stream in all three models. These results suggest the value of topographical variations when designating site-specific riparian management. This research also revealed the complexity between height above stream and riparian microclimate variables and directions for future research to improve ecological resiliency in riparian zones.

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Acknowledgements

I owe my gratitude to a number of people at WADNR have supported me throughout this project. Thank you to Richard Bigley, my technical advisor for this thesis work, who has provided me with guidance and expertise. By the time I came aboard this project, the hard work of creating the study design and deploying the microclimate stations had already been completed. With over 2 million lines of data, this project was no small feat. I could not have conducted the robust analysis without the mentorship I received from Warren Devine. Warren's expertise in data management served as a useful tool for me as I conducted this research. Thank you also to Teodora Minkova for initially welcoming me as a partner in this project.

The MES program at The Evergreen State College has given me so much. Kevin Francis, my MES thesis reader, patiently read my thesis drafts and sought to help me explain the technical aspects of this project in a way that was digestible to most anyone. Thank you also to my GIS Professor Mike Ruth for teaching me GIS and for helping me figure out how to map the microclimate transects. The solar radiation analysis could not have been conducted without this critical step. Thank you to MES faculty and staff, especially John Withey, Shawn Hazboun, and Andrea Martin, for supporting me in various capacities and acting as positive role models throughout my time in the MES program. The faculty and staff are what make the MES program and its students shine.

It was as an AmeriCorps member at Umpqua Watersheds in Southern Oregon where I discovered my deep interest in forest ecology and management. Thank you to my coworkers and mentors there who helped me realize this. I'm also grateful for my colleagues in WSDOT's Fish and Wildlife Program Kelly McAllister and Glen Kalisz who accommodated my full-time student schedule throughout this Master's program. It's a great thing to have great coworkers. Thank you also to Pablo Rosas-Anderson for directing me to the ASCE Standardized Reference Evapotranspiration Equation, which I used to calculate VPD for my multivariate models.

A special thanks to my MES colleagues and to my all of my friends. I am privileged to know so many intelligent and driven individuals who fill my life with laughter and friendship.

The adventurous curiosity that has driven me to study the ecological workings of forests can be attributed largely to my mom and dad. My parents have always fostered an environment supportive of academic and personal enrichment. The dozens of road trips they took me and my sisters on during our childhood instilled in me early on an appreciation for wildlife, ecosystems, and public lands—including the mossy forests of the Pacific Northwest. My sisters Madeline and Shannon also provide me with boundless support, with their sincere interest in my thesis research serving as proof. For example, Shannon, a licensed social worker, was so intrigued by my research that she asked me to show her the significance of riparian microclimate by drawing a meticulous diagram for her on a napkin. Madeline, an educator and a scientist, offered me ample support with R throughout this project while simultaneously conducting research of her own as a Postdoctoral researcher. Finally, thank you to my niece or nephew, who is currently an embryo and will be arriving into the world in January 2020. I am so excited to be your Aunt and take you on your first hike in a Pacific Northwest forest, where I'll teach you all about wildflowers, lichens, wildlife, bugs, soils, and big trees.

Acronyms

BLM – Bureau of Land Management

ESA – Endangered Species Act

FEMAT – Forest Ecosystem Management Assessment Team

GIS – Geographic Information System

HCP – Habitat Conservation Plan

NWFP – Northwest Forest Plan

OESF – Olympic Experimental State Forest

RMZ – Riparian Management Zone

TFW – Timber, Fish, and Wildlife

USDA – United States Department of Agriculture

USDI – United States Department of the Interior

USFS – United States Forest Service

VPD – Vapor Pressure Deficit

WADNR – Washington State Department of Natural Resources

CHAPTER 1: INTRODUCTION

Introduction

Riparian areas are multi-dimensional ecotones that include both aquatic and terrestrial ecosystems which range above the canopy, beneath the ground, across the floodplain, and upslope from streams (Ilhardt et al., 2000). In riparian zones, the surfaces of streams and rivers are directly influenced by the adjacent land, and likewise the land is influenced by those waters (Palik et al., 2004). Riparian systems support the highest biodiversity in forested areas due to their moist conditions, complex habitat structure, and high productivity (Olson et al., 2007). In riparian areas, stream energy is dissipated and soil is protected from erosion by stabilized stream banks (NRC, 2002; Anderson et al., 2007). Additionally, nutrients and pollutants distributed from uplands are filtered in riparian areas, and both water temperature and light regimes are regulated within these zones (Tiwari et al., 2016).

Extensive timber harvest can negatively influence the physical processes and biota within riparian areas. Harvesting can intensify solar radiation in riparian zones and increase exposure to wind, which often results in a decrease in relative humidity and an increase of air, stream, and soil temperatures (Moore et al., 2005). Moreover, protection of riparian streams and associated biota within these zones has become an important concern among land managers and scientists across the Pacific Northwest (Rykken et al., 2007).

An important component of riparian ecosystems is microclimate, which is the suite of environmental variables including moisture, temperature, wind speed, and light found within localized areas near the earth’s surface (Geiger, 1965). Microclimate and stream temperature are critical aspects of aquatic habitat conditions in and near streams, and are driven by the exchanges and interactions of water and energy within riparian zones (Moore et al., 2005). Riparian microclimate gradients for soil temperature, air temperature, stream temperature, and relative humidity are influenced by timber harvesting, largely due to shade reduction (Brosofske et al., 1997; Chen et al., 1993; Richardson et al., 2012). Additionally, changes in riparian microclimate as a result of logging has been linked with changes in nutrient cycling (Chen et al., 1999) and changes in forest vegetation structure (Davis-Colley et al., 2000). Research has shown that maintaining sections of vegetated area near streams can protect riparian areas from increased exposure to sun and soil erosion due to adjacent logging (Anderson et al., 2007; Rykken et al., 2007; Brosofske et al., 1997). While these studies provide insight into key interactions, few studies have examined ecological influences on riparian microclimate (Anderson et al., 2007; Moore et al., 2005).

Despite the significant role of microclimate in riparian systems, research in characterizing riparian microclimates as they relate to ecological processes, biodiversity, forest management, and habitat suitability is relatively uncommon (Olson et al., 2007). In order to accomplish ecologically-sound forest management practices, more research needs to examine riparian understory and overstory vegetation and microclimate (Eskelson et al., 2013). The results presented in this study will increase knowledge about the ecological drivers of microclimate and the relationship between timber harvest and microclimate, which may inform decisions about riparian buffer designations.

To provide a testing ground for questions such as the ecological role of riparian forests in maintaining habitat and alternatives in forest management the Washington State

Department of Natural Resources (WADNR) established the Olympic Experimental Forest (OESF), which contains over 270,000 acres (ac) (109,265 hectares (ha)) of state trust forestlands on the Olympic Peninsula. WADNR manages the OESF land under the guidance of the riparian conservation strategy in the State Trust Habitat Conservation Plan (WADNR, 1997), which is implemented with the OESF Forest Land Plan (WADNR 2016b). The goal of the riparian conservation strategy is to maintain biological and physical processes within riparian zones in order to preserve habitat for species who depend on these ecosystems. To evaluate the effectiveness of WADNR's success in achieving the conservation objectives presented in the Habitat Conservation Plan, WADNR is conducting a long-term monitoring study called *Status and Trends Monitoring of Riparian and Aquatic Habitat in the Olympic Experimental State Forest* to document status and changes in stream and riparian conditions within the OESF. A key habitat attribute included in this study is microclimate. WADNR's environmental impact analysis for the Forest Plan determined that increases in timber harvest operations could negatively impact riparian microclimate in managed stands. Currently, management effects on microclimate in the OESF are characterized as "medium impact" in almost half of the watersheds analyzed in the impact analysis (WADNR, 2016). These projected management effects are based on a number of assumptions about stream influence on microclimate and have not yet been validated.

To monitor microclimate variability across the OESF, WADNR staff installed dataloggers (HOBO Pro v2 Temp/RH dataloggers) at 10 of the 50 sample watersheds within the OESF. Within each sample reach, five microclimate monitoring stations were placed along randomly chosen 60m transects on either side of the stream. Microclimate monitoring stations were installed at 0, 10, 20, 40, and 60 m along each transect and they recorded air temperature and humidity every 2 hours for three years (2014-2016). The data were analyzed using mixed multivariate analyses to understand if and how predictor variables like distance from stream, height above stream, solar radiation, and canopy closure affected microclimate variables including mean summer maximum air temperature, mean summer vapor pressure deficit, and cumulative degree days. The questions examined in this thesis include:

1) What topographic and vegetation factors explain the variation of microclimate across the western Olympic Peninsula?
2) What are the ecological drivers of riparian microclimate?

For the OESF Environmental Impact Study, assumptions were made about the extent to which riparian streams and buffers ameliorate effects of timber harvest on microclimate processes. These assumptions were based on the limited literature available, and lacked robust empirical testing. Therefore, an aim of this thesis was to test these assumptions by quantifying how microclimate gradients are influenced by a number of ecological variables. These results will contribute to the validation of assumptions about stream influence on microclimate by the State Lands Habitat Conservation plan while providing a baseline for riparian microclimate in second-growth watersheds adjacent to timber harvest activities. Finally, these results will advance the greater scientific community's understanding of microclimate and its significance in riparian areas, which will be of particular interest to both scientists and land managers across the state and could contribute to the design of the riparian management areas in the future.

This thesis consists of four chapters. Chapter One contains this introduction, which set the scene for the thesis by providing an introduction to riparian systems and microclimate variables within them. This introduction will be followed by the literature review (Chapter Two), which provides the historical and ecological context for studying microclimate in riparian management zones. Chapter Three consists of the research manuscript, which describes the research questions, methods, experimental design, and statistical findings. This chapter concludes with a discussion of the broader consequences of the findings and recommendations for research direction. The thesis concludes with Chapter Four, which contains an assortment of information in numbered appendices intended to supplement this research.

CHAPTER 2: LITERATURE REVIEW

Literature Review

To understand the potential application of this research, one must understand the historical context that resulted in the relatively recent establishment of riparian protection zones and the intended ecological role of such protection in terms of microclimate. The story begins with an overview of historical logging in the Pacific Northwest and the evolution of current practices and riparian protections. This is followed by a discussion about riparian ecosystems and the objective of riparian protection practices. Next, this review will examine relevant literature on microclimates and studies related to microclimate gradients within riparian management zones (RMZs), with attention to both existing knowledge and gaps in knowledge. Finally, this review will explore current thinking of the success of riparian protections in meeting management objectives.

Logging in the Pacific Northwest

The Pacific Northwest region has served as a hub for timber harvest since the early 18th century, and the timber industry has long contributed to the region's economic growth and sustenance. In the early 1990's there was a rapid evolution in regulations in the State of Washington to protect streamside habitats primarily aimed a fish habitat. Federal and state regulations were revised and organizations began to take advantage of the section in the Federal Endangered Species Act (ESA) that allowed the development of long-term habitat conservation plans (HCPs) and forest managers to operate under a known set of environmental rules.

Today, how forests are harvested largely depends on which landowner or agency is managing that forest. Forests used to be harvested to the banks of streams (Figure 1.1), until it became evident that ecosystem health was being damaged due to nearby logging practices (Anderson et al., 2013). The evolution of State and private land riparian regulations under State Forest Practices was strongly influenced by the development of federal regulations.

Preserving vegetative strips alongside streams and rivers adjacent to timber harvesting was first applied on US forestlands in the 1960's (Calhoun, 1988), and it has since become common practice on federal, state, and private forestlands. In 1993, the U.S. government published *Forest Ecosystem Management: An Ecological, Economic, and Social Assessment* which presented new requirements for how riparian areas in federal forestlands (including U.S. Department of Agriculture (USDA), Forest Service (USFS), U.S. Department of the Interior (USDI), and Bureau of Land Management (BLM)) were managed in western Oregon and Washington (FEMAT, 1993). This report, which was brought on by a suite of ecological concerns including the listing of the Northern Spotted Owl (*Strix occidentalis caurina*) as Threatened under the ESA in 1990, led to the adoption of the Northwest Forest Plan (NWFP) in 1994 (Buchanan, 2016; Anderson & Ronnenberg, 2013). Two significant management objectives laid out in the NWFP were: 1) to manage late-successional habitat for vulnerable species including the Marbled Murrelet and the Northern Spotted Owl, and 2) to conserve and restore riparian and aquatic ecosystems that are vital towards sustaining biodiversity and salmon populations (USDA and USDI, 1994). Chen (1991) was a main source used to develop the FEMAT curves of riparian reserve ecological function (Figure 1.3).

A key component of the NWFP is the Aquatic Conservation Strategy (ACS), which guides management decisions in federally-managed riparian ecosystems aimed at restoring and maintaining ecological health of watersheds within forests (Young, 2000; Reeves et al., 2016). The ACS requires federal land managers in the Pacific Northwest to use the height of dominant overstory trees as a functional basis for designating riparian reserve boundaries, with varying requirements dependent on whether a stream is non-fish bearing or fish bearing (NRC, 2002). For example, for fish bearing streams, as described in the Oregon State Bureau of Land Management (BLM) and Region 6 USFS ACS Implementation Report, riparian buffers must consist of the “fixed” distance. This distance is equal to the height of two site-potential trees (which is the expected height of a tree upon maturity, or about 200 years), or 300 feet (ft) slope distance, whichever is greatest. Alternatively, for non-fish bearing streams, riparian buffers must consist of the distance equal to the height of one site-potential tree, or 150ft slope distance (BLM and USFS, 2005). In this case, the slope distance refers to the gradient, or the change in vertical distance over a specified horizontal distance. Although it was presumed the riparian buffer dimensions originally outlined in FEMAT and the ACS would be enhanced and updated, revisions have not been made and the original guidelines have been generally accepted throughout the BLM and USFS (Reeves et al., 2016). Likewise, considerations about buffer width have largely been absent on the landscape-level scale where considerations are made about ecological function of riparian processes (Richardson et al., 2012). Despite the general acceptance of the dated buffer requirements in the ACS, some prominent land managers across the Pacific Northwest are making efforts to apply site-based buffers while implementing experimental and novel harvest techniques to better protect riparian processes, as will be discussed in later sections of this literature review.

Figure 1.1. Unprotected streams next to logging operations in 1974, prior to the establishment of buffer requirements. Photographs courtesy of Hamish Kimmins from University of British Columbia. From: Richardson, J., Naiman, R., & Bisson, P. (2012). How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices? *Freshwater Science*, 31(1), 232-238.

Land Management on Washington State Trust lands

Washington State Department of Natural Resources (WADNR) currently manages nine *State Trust Lands Habitat Conservation Plan* (HCP) (WADNR 1996) planning units in the range of the northern spotted owl across Washington. In one of the nine HCP planning units, the Olympic Experimental State Forest (OESF), state trust lands are managed not only for timber harvest but also for ecological values through an "integrated management" approach. This experimental approach encourages natural processes to occur on lands where planting, thinning, and harvesting occurs (WADNR, 2016). The WADNR HCP is subject to Washington State Forest Practices regulations, but employs an independent stream typing system, and designation of RMZs that are sensationally different that Washington State Forest Practices regulations. Riparian and Wetland management zones encompass about a third of State managed lands.

Riparian Ecosystems

Riparian zones are environments on the shores of streams and lakes (Naiman and Décamps, 1997). Their ecological importance is well acknowledged in the scientific community (see Verry et al., 2000). Riparian systems possess spatial and temporal relationships between geomorphic processes, aquatic ecosystems, and terrestrial plant succession (Gregory et al., 1991) (Figure 1.2). The interactions between these processes allow for the important exchange of nutrients, such as leaf litter and insects, between terrestrial and aquatic systems (Nakano & Murakami, 2001). Additionally, the dense canopy cover in riparian areas reduces precipitation, wind speed, and solar radiation that is received at the ground surface (Moore et al., 2005).

Riparian forestlands in western Washington and Oregon consist of young and old-growth coniferous forests dominated by western hemlock (*Tsuga heterophylla*), western redcedar (*Thuja plicata*), and Douglas-fir (*Pseudotsuga menziesii*) (Anderson & Poague, 2014). This diversity of vegetative composition and structural characteristics is essential for the survival of many wildlife species (Kelsey & West, 1998). Riparian vegetation inputs course woody debris and nutrients into streams, which create habitat for a variety of aquatic invertebrates and amphibians (Gomi et al., 2002; Bilby & Bisson, 1998; Olson et al., 2014).

Amphibians and salmonids are widely considered to be indicators of overall riparian ecosystem health (Holthausen and Sieg, 2007; Welsh et al., 2005), and they occur in large numbers in riparian areas across the Pacific Northwest. In Oregon and Washington, 53% of the total wildlife (*n*=319 out of 593) require riparian habitats (Naiman et al., 2000), and 89% (*n*=42) of amphibian species live in forests (Olson et al., 2007). In addition to providing habitat for amphibians and invertebrates, riparian areas support a number of faunal groups with specific stream-riparian needs. Mollusks, for example, often occur in larger numbers in riparian areas than other ecosystems (Dunk et al., 2002). Riparian zones also serve as corridors for dispersal for terrestrial organisms (Naiman et al., 2005). The indispensable role these areas have in the survival and persistence of so many organisms substantiates their value in the broader ecological system.

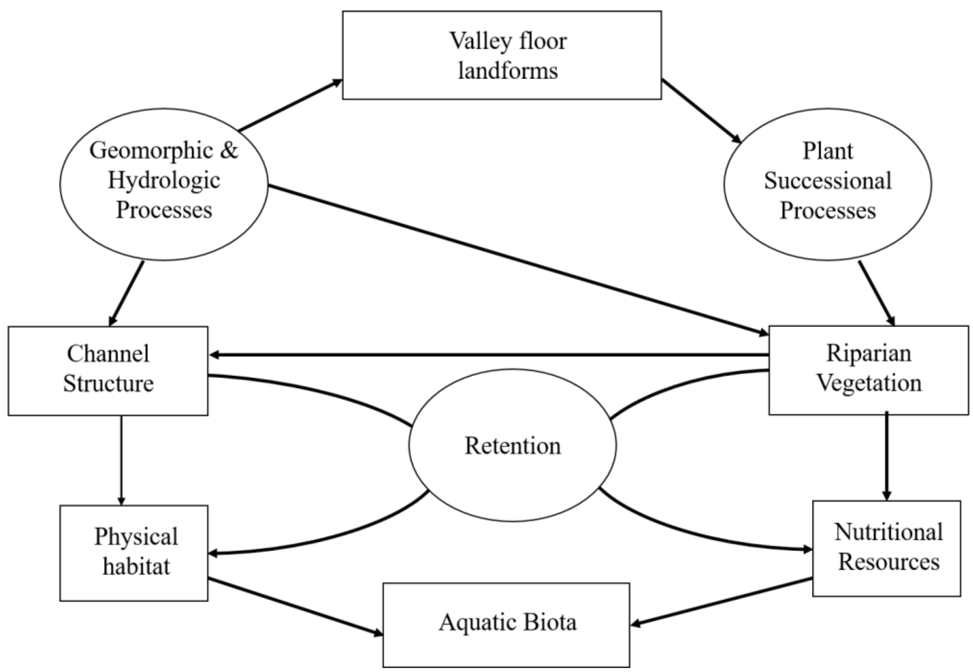


Figure 1.2. Representation of the relationship between geomorphological processes, aquatic ecosystems, and terrestrial plant succession in riparian areas. Biological components are displayed as rectangles, and physical and ecological processes are displayed as circles. Reproduced from: Gregory, S., Swanson, F., Mckee, W., & Cummins, K. (1991). An Ecosystem Perspective of Riparian Zones. *BioScience*, 41(8), 540-551.

Effects of Timber Harvest on Riparian Processes

Spence et al. (1996) showed that removing streamside vegetation can influence a variety of ecological processes that can impact the overall integrity of terrestrial and aquatic habitats within riparian systems. Because of the intricate role riparian zones play in linking aquatic and terrestrial ecosystems, including moving nutrient inputs from hillsides, adding organic matter into streams, and modifying microclimate variables, the protection of these areas is important.

The impacts of timber harvest on riparian processes like shade, water temperature, and detrital inputs, are well documented. Harvesting can intensify solar radiation in riparian zones and increase exposure to wind, which often results in a decrease in relative humidity and an increase of air, stream, and soil temperatures (Moore et al., 2005). These changes in microclimate conditions can significantly impact riparian organisms. For example, research has found that abundances of terrestrial mollusk populations, including a variety of slug and snail species, can be affected by harvest activities (Foster & Ziegltrum, 2013). Additionally, research has found that the terrestrial movements of tailed frogs (*Ascaphus truei Stejneger*) are impacted by forest condition, with fewer movements occurring in upland clearcuts compared to streams in older stands (Wahbe et al., 2004). Therefore, protection of riparian areas and associated biota has become an important concern among land managers across the Pacific Northwest (Rykken et al., 2007).

In many ways, older, unmanaged stands retain greater ecological resilience than managed stands. For example, research has shown that, compared to managed stands, unmanaged old-growth forests host greater diversity of epiphytic communities (Lesica et al., 1991). The greater structural diversity and volumes of course woody debris in these older forests offer a range of microhabitats for epiphytes and other organisms to inhabit, and these microhabitats can be fragmented by logging practices. That being said, sustainable forest management practices can help retain these structural characteristics to help maintain suitable habitat for riparian-associated taxa.

Riparian Microclimate

The Earth's surface consists of a patchwork of different surface slopes and resources, and each patch contains its own suite of radiative, moisture, thermal, and aerodynamic properties (Oke, 1987). How the energy balances exhibited on each unique patch of land are manifested determines what species can occupy that area. In riparian systems, the balance of energy and water dynamics both influences and is influenced by the localized climate. Given the dense vegetation and constrained hillslopes in riparian areas, streams are generally shaded and provide cool, moist habitats for a number of aquatic and terrestrial organisms (Moore et al., 2005). This cooling effect of streams can easily be felt upon walking through a forested landscape.

In riparian ecosystems, abundant vegetation, moist soils, and streams and rivers contribute to microclimate gradients spreading laterally from streams (Olson et al., 2007). A major driver of microclimate is the amount of light that penetrates an area (Matlack, 1993), which is largely dependent on overhead canopy cover (Davies-Colley et al., 2000). The amount of solar radiation that is absorbed and reflected through riparian canopies alters the quantity and quality of light available for terrestrial and aquatic primary producers in riparian zones (Gregory et al., 1991). The composition and size of riparian vegetation plays a key role in modifying solar inputs and influences stream temperatures

(Barton et al., 1985). Other significant contributors of microclimate are slope and aspect of physical environments.

Ecological Significance of Microclimate

A variety of organisms and processes within riparian systems rely on microclimate to properly function. A number of species prefer particular microclimate conditions to persist in and disperse to (Sunday et al., 2014). Microclimate strongly influences the physiological and ecological processes displayed in riparian taxa as it maintains in-stream temperatures while providing cool, moist conditions alongside streams which amphibians, small mammals, and invertebrates require (Chen et al., 1999). Microclimate also serves as an important component of favorable conditions for many amphibians. Most amphibians move within 45ft (13.7 meters (m)) of stream channels, where the setting is shaded and humid (Olson & Kluber, 2014). Additionally, cool and moist conditions near downed wood provides habitat for terrestrial salamanders (Olson & Kluber, 2014; Rundio and Olson, 2007).

In addition to amphibians, mammals, and invertebrates, microclimate impacts plant and fungal species. Lichens, for example, grow within the canopy of forest stands and require ecological continuity to exist long enough for them to become established. In late successional forests, this can take over 200 years (Lesica et al., 1991). A range of environmental factors limit lichen distribution and growth, including microclimate variables like temperature, humidity, light, and moisture (Hawksworth & Hill, 1984). Since many fungi species have limited dispersal abilities, the spacing and diversity of stand types (especially old-growth) is important in order to maintain suitable fungi habitat (FEMAT, 1993).

Additionally, microclimate gradients impact various nutrient inputs and aquatic processes near riparian streams (Chen et al., 1995). In forested stands, summer maximum air temperatures generally increase, and minimum relative humidity generally decreases with distance from streams (Olson et al., 2007). Changes in microclimate gradients can impact many riparian organisms, including bryophytes (Steward and Mallik, 2006), beetles (Grimbacher et al., 2006), and amphibians (Bury & Corn, 1991). Research has also found that arthropods are associated with microclimate. For example, Allen (2016) found that the community structure of arthropods at three sites along the San Pedro River in Arizona were strongly associated with variations in microclimate variables.

How microclimate is exhibited in riparian systems is determined by a number of ecological variables. The magnitude and spatial microclimatic variability within a forest varies with solar radiation (Davies-Colley et al., 2000), precipitation (Harper et al., 2005), both seasonal and temporal variations (Wright et al., 2010), and wind (Chen et al., 1995). Strong winds can break stems or completely flatten trees and plants (Oke, 1987), which in turn creates critical habitat for a number of organisms in the form of downed logs and plant litter. The relationship between these physical processes and microclimatic variables demonstrates the complex interactions within riparian systems, each of which plays a unique, critical role in sustaining the intricacies of riparian ecosystems.

Microclimate Gradients in Riparian Management Zones

Compared to other riparian processes like woody debris recruitment, stream temperature, and sediment delivery, microclimate is widely understudied. When the ACS was developed in 1994, the only study examining the influence of timber harvest on microclimate conditions had been completed on level terrain in upland forests (Chen, 1991). Their research found that the effect of clearcuts on microclimate extended well into adjacent unharvested riparian areas. From these findings, FEMAT (1993) postulated that adding a second tree-height could ameliorate some of the negative effects of timber harvest on microclimate along fish-bearing streams. A number of studies have since examined the effect of timber harvest on riparian microclimate, and have found that, in general, the magnitude of changes in microclimate is inversely related to the width of the RMZ. The original FEMAT curves (Figure 1.3) have since been modified by a number of researchers (Spies et al., 2013; Reeves et al., 2016), (Figure 1.4). The modified curves were developed from a working hypothesis based on newer but limited literature, reassuring the notion that more research needs to be done on riparian microclimate.

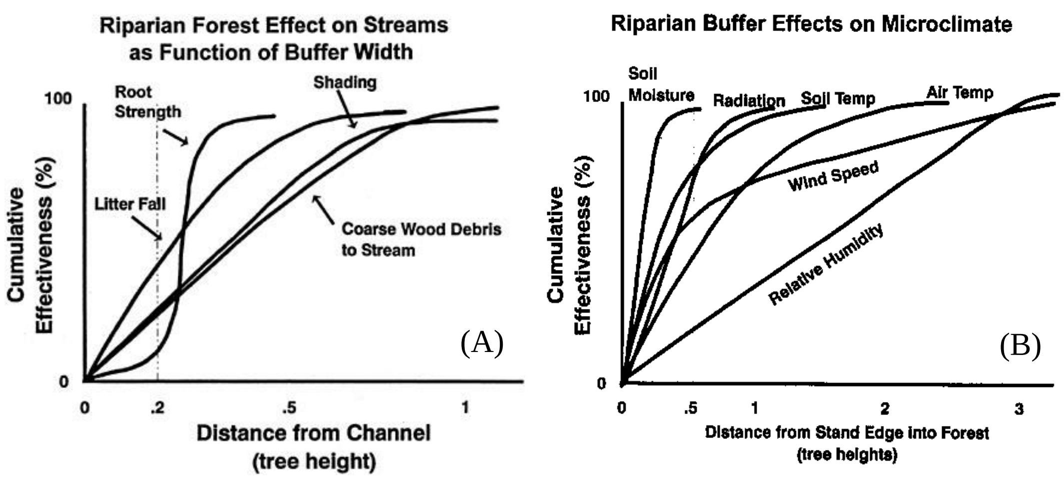


Figure 1.3. (A) Hypothesized effects of riparian processes on streams based on varying buffer widths, as explained with the percentage of ecological riparian processes occurring within identified distances from the stream channel. In this graph, a distance of "1" is equivalent to a buffer width equal to 1 site-potential tree; (B) Predicted microclimate changes from a clearcut edge to the interior of a forest, with percent of riparian function shown on the Y-axis, and site-potential tree heights (buffer width) on the X-axis. The graph indicates that when buffer widths are less than one site-potential tree height, relative humidity and the ability to maintain cool temperatures decrease intensely. From: Forest Ecosystem Management Assessment Team (FEMAT). (1993). Forest ecosystem management: an ecological, economic, and social assessment. Portland, OR: U.S. Department of Agriculture; U.S. Department of the Interior.

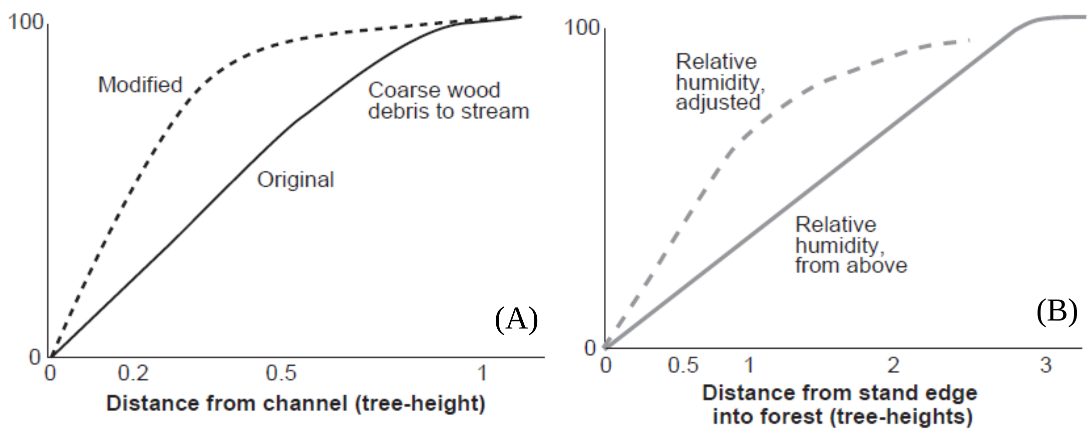


Figure 1.4. (A) Modified effectiveness curve for the relationship between distance from stream and riparian ecological functions. From: Spies, T., Pollock, M., Reeves, G., & Beechie, T. (2013). Effects of riparian thinning on wood recruitment: a scientific synthesis. Science Review Team Wood Recruitment Subgroup. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 46 p. On file with: Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331. (B) Modified effectiveness curve for the relationship between distance from stream and ecological factors influencing riparian microclimate. From: Reeves, G., Pickard, B., & Johnson, K. (2016). An initial evaluation of potential options for managing riparian reserves of the aquatic conservation strategy of the northwest forest plan. Gen. Tech. Rep. PNW-GTR-937. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 97 p.

Anderson et al., 2007 and Rykken et al., 2007 have shown that microclimate variables, including air and soil temperature, humidity, light, and wind speed vary depending on distance from stream within riparian areas adjacent to timber harvest. Chen and colleagues conducted some of the earliest studies looking at microclimate gradients within RMZs. Their work supported previous studies that found microclimate (both air temperature near the surface of the ground and solar radiation) to be sensitive to changes in vegetation and canopy cover (Chen et al., 1995, 1999).

Some studies have since examined microclimate gradients in RMZs adjacent to timber harvest. Brosofske et al. (1997) sampled five streams and adjacent riparian zones in western Washington before and after clearcutting, with the goal of characterizing the effects of RMZ width on associated stream microclimate. The researchers found that values of microclimate variables (air and soil temperature, relative humidity, wind speed, and short-wave solar radiation) were negatively affected by harvest to some degree. As a result of this research, the researchers suggested that buffers with a minimum with of 45m (147.6ft) on each side of a stream are necessary to maintain riparian microclimate processes (Brosofske et al., 1997). Therefore, many of the standard fixed buffer widths that are commonly used today may not be adequate for protecting microclimate processes near some streams, as their widths are often less than 45m (147.6ft) depending on site conditions.

In addition to considering RMZ width, research has indicated the need to consider the relationship between forest structure and microclimate. Frey et al. (2016) conducted the first study testing how structural characteristics in forests due to varying management practices influenced micro-scale temperature regimes. They modeled the spatial distribution of local-scale air temperatures beneath the forest canopy, and found vegetation structure to have an extensive influence on microclimate. Therefore, the researchers concluded that by conserving forest structural conditions, land managers may be able to ameliorate some negative ecosystem effects of regional warming on forested areas.

It is widely recognized that harvesting timber next to streams without riparian buffers usually results in major increases in stream temperature, but the RMZ width required to reduce these temperature increases remains uncertain (Leinenbach et al., 2013). A number of studies have examined RMZ width in relation to its effectiveness in preserving biota with specific microclimate needs. For example, Pearson and Manuwal

(2001) found buffers 30m (98.4ft) wide may not be wide enough to maintain Black-throated Gray Warbkerm Golden-crowned Kinglet, and Brown Creeper populations. Studies examining microclimate gradients within RMZs have generally found the influence of streams on air temperature to weaken at distances 30-60m (98.4-196.9ft) from the stream (Anderson et al., 2007; Brosofske et al., 1997; Rykken et al., 2007). Relative humidity gradients have shown to be expressed similarly to air temperature gradients, but with a further distance from the stream (Anderson et al., 2007; Brosofske et al., 1997; Rykken et al., 2007). Therefore, understanding this relationship between RMZ width and associated biotic and abiotic values is critical to consider while applying appropriate management prescriptions.

Protecting Microclimate through Management

As discussed earlier, vegetated buffers, which are defined as the distance of vegetative cover from a stream bank, were created to protect riparian streams from forest harvest (Rykken et al., 2007). Buffers provide shade protection, collect and input leaf litter and woody debris into streams, support root strength, and maintain streambank integrity and channel stability (NRC, 2002). Although designating a fixed-width of vegetation remains standard practice amongst most federal and many state land managers, researchers have not reached consensus on how wide a buffer must be to adequately protect ecological processes (Brosofske et al., 1997; Chen et al., 1999; Leinenbach et al., 2013),

While guidelines for stream-riparian protection vary greatly across land ownership and jurisdictions (Blinn & Kilgore, 2001), most federal forestry operations apply a fixed-width, vegetated buffer as determined by the NWFP, as was discussed earlier in this review (Ruzicka et al., 2013; NRC, 2002). In addition to federal land managers, many state and private jurisdictions across the Pacific Northwest require vegetative buffers to be retained next to large fish bearing streams (Young, 2000). Reaches of Smaller, non-fish bearing streams are often offered less, or no, protection with vegetative buffers.

The fixed-width approach to buffer designation is relatively straightforward to implement, and it is often the only option allowable by resource and time constraints (Hanowski et al., 2000; Reeves et al., 2017). This method requires federal land managers in the Pacific Northwest to define a predetermined distance from the stream, which assumes the subsurface flow is distributed uniformly across the riparian zone (Richardson et al., 2012). Overall, research has indicated the establishment of fixed-width buffers is more effective at protecting riparian processes than having no buffer at all (Anderson et al., 2007).

While the traditional fixed-width buffer method remains the most common practice for establishing buffers in the US, this approach has been criticized for overlooking complex variations in biodiversity and biogeochemical processes across different sites (Abood, 2016; Tiwari et al., 2016). When riparian buffers are of adequate width to provide shade protection and high levels of wood, litter inputs and bank stability are satisfied (NRC, 2002). Additionally, as mentioned earlier, it was predicted early on that buffers which are less than the width of one site-potential tree (which is the requirement for non-fish bearing streams under the NWFP) can negatively affect riparian microclimate variables like relative humidity (Figure 1.3) (FEMAT, 1993). This variation of buffer width effectiveness on preserving channel stability, streambank integrity, and microclimate suggests a generalized, fixed buffer-width may not be appropriate for every site.

An alternative approach to stream protection designates RMZ widths based on complex, site-specific ecosystem structure and functions. These approaches incorporate ecological sensitivity of stream reaches into RMZ designation decisions and have not been adopted by many land managers due in part to the uncertainty of their effectiveness (Richardson et al., 2012). Some research indicates that buffers defined through ecological factors, including topographic slope breaks, microclimate sensitivity, and vegetation types, can successfully mitigate the impacts of forest thinning on headwater stream microclimates (Anderson et al., 2007). Beyond ecological value, studies have shown riparian reserves determined by site-specific ecological factors can be cheaper per hectare than those determined by the fixed-width approach (Tiwari et al., 2016). Today, some researchers are experimenting with site-specific buffer designations with the goal of restoring and protecting functioning riparian processes and components like microclimate (Anderson et al., 2007; Olson et al., 2007; Minkova & Foster, 2017). Some of these studies will be discussed in more detail in the next sections of this literature review.

Effectiveness of Riparian Management Zones in Protecting Microclimate

The application of RMZs through fixed-widths has proven to support an array of riparian ecosystem processes, as is supported by a study from Bisson et al. (2013). The researchers applied and monitored three alternative buffer treatments to a collection of watersheds in the Black Hills and the Willapa Hills of southwest Washington (Bisson et al., 2013). The buffer designations included fixed-width buffer treatments, discontinuous patch-buffer treatments, and unbuffered streams next to unlogged catchments.

Monitoring took place between 2001 and 2006, with logging taking place within the watersheds between 2004 and 2005. Overall, the study observed considerable changes in ecological conditions where logging occurred, with the greatest changes being in the streams that had no buffers. In these unbuffered catchments, summer water temperatures were highest and the amount of organic matter inputs decreased post-logging, whereas few changes in organic matter inputs and invertebrate communities were exhibited in streams with fixed-width buffers.

Some researchers argue that the fixed-width RMZ designations have little functional relationship with the many ecological processes within riparian systems. It has been shown that standard RMZs are not adequate for protecting microclimate near streams adjacent to logging as they often do not consider individual site characteristics like topography or vegetation (Brosofske et al., 1997). Similarly, Palik et al. (2000) determined that the designation of riparian buffers through a fixed-width approach is insufficient as these RMZs don't effectively emulate natural riparian corridors. Additionally, the fixed-width approach embraces oversimplifications about riparian systems that may result in inaccuracies in estimations of land that is considered riparian (Aunan et al., 2005). Some researchers, however, have argued the relationship between ecological function and RMZ width needs to be better understood before economic consequences of riparian area delineation can be fully appreciated (Palik et al., 2004). This relationship between RMZ width and ecological processes is being examined by researchers today as alternatives to the fixed-width approach are being tested.

To assess the effects of fixed and varying RMZ widths on riparian and aquatic systems, the Bureau of Land Management, U.S. Geological Survey, Pacific Northwest

Research Station, and Oregon State University initiated the Density Management and Riparian Buffer Study (DMS) in 1994 (Anderson & Poage, 2014). The DMS is a long-term riparian management study across Pacific Northwest federal timberlands, and one of its key research objectives is to assess the effects of varying buffer widths on riparian microclimates within forests subjected to thinning (which is a common silvicultural practice on federal forestlands) (Cissel et al., 2006). To understand how thinning treatments and varying buffer widths affect microclimate variables, researchers from the BLM conducted a multi-year DMS study in young Douglas-fir stands across forestlands in western Oregon (Anderson & Poage, 2014). The researchers measured spatial variations in canopy cover, microclimate, and stand density up to 10 years after harvest across transects spanning from alternatively buffered streams to upslope thinned stands, unthinned stands, and patch openings (Anderson, 2007; Anderson & Poague, 2014). Measurements were taken from transects consisting of alternative buffer treatments: 1) Two site-potential tree heights (approximately 440ft or 134m), 2) one site-potential tree height (approximately 220ft or 67m), 3) variable width (which follows vegetative and topographic breaks, with a minimum slope distance (buffer width) of 50ft or 15.2m), and 4) streamside retention (one tree canopy width, or approximately 20-25ft or 6-7.6m), which is the narrowest buffer included in the study.

To investigate the relationship of variations in buffer widths on microclimate, the researchers monitored humidity, air, and soil temperatures, and water temperature in streams across the varying buffer widths (Cissel et al., 2006; Anderson et al., 2007; Chan et al., 2004). Two key findings related to riparian microclimate were discovered: 1) microclimate varied depending on distance from the stream, with soil and air temperatures increasing and humidity decreasing further from streams (also known as the "stream effect") (Anderson et al., 2007), and 2) buffer widths influenced microclimate gradients differently depending on the type of silviculture treatment applied (thinning, no thinning, or patch openings), with the general pattern being that canopy closure declined and microclimate variables were affected more with decreasing buffer widths (Anderson & Poague, 2014). Air temperatures 30 ft (9.1m) or closer to the stream were mostly maintained by upslope thinning, suggesting that thinning resulted in relatively small changes in microclimate within the variable buffers widths (Mazza, 2009). Despite this, air temperatures increased dramatically in reaches with narrow streamside-retention buffers (Anderson & Poague, 2014). However, compared to unthinned stands, air temperatures were considerably warmer in buffers next to patch openings (+3ºC) and within patch openings (+6-9º C) (Anderson et al., 2007). Therefore, the researchers concluded that the variable-width buffers used in their study, which were considerably narrower than the one and two-tree height "fixed-width" buffers required by the NWFP, were sufficient in protecting stream-microclimates from of upslope thinning, but that microclimates were better protected with larger RMZ widths. This study was one of the first integrated experiments to test the effectiveness of varying RMZ widths in preserving riparian function, and it has paved the way for further research in alternative buffer treatments across the Pacific Northwest.

Success of Riparian Protections in Meeting Management Objectives

Riparian protections have succeeded in meeting a variety of ecological management objectives. Since the implementation of the NWFP in the 1990's, the rate of clearcutting has slowed and the number of old growth trees being harvested has greatly reduced. This is important considering the limited amount of old growth remaining in the Pacific Northwest. As of 2006, approximately 3.5 million ha (8.6 million ac) of old growth forests remained throughout the coastal region of the PNW (Strittholt et al., 2006). The amount of old growth remaining across the region today remains disputed, but riparian protections are widely recognized as being crucial actors in their preservation.

An important objective of the initial increase of the riparian reserve boundary from one site-potential tree-height to two for fish-bearing streams was to protect microclimates within the first tree-height of the riparian area (Reeves et al., 2016; USDA and USDI 1994). Today, it is widely agreed upon by researchers that retaining vegetation alongside streams is important (see review by Moore et al., 2005). However, despite this recognition, many scientists and land managers recognize the need for more research in the effectiveness of riparian protections in preserving ecological processes. This need includes studies which examine riparian microclimate gradients and their ecological influences in areas adjacent to harvest activities (Hannah et al., 2008).

Conclusion

This literature review sought to provide context needed to prepare the reader for Chapter Three of this document, which consists of the Research Manuscript. This review of existing literature on riparian microclimate highlights a number of limitations with past studies. A primary limitation with past microclimate studies is the short sampling period duration. For example, Brosofske et al. (1997) sampled each study transect on different days throughout two different summers (1993 and 1994). The sampling periods were each approximately just one week long in June, July, or August. Chen et al. (1995) was another prominent study that examined microclimate gradients along riparian buffers.

Although data were collected for 134 total days in that study, sample stations only remained at each study site for 3-14 days until being moved to other locations. Although the findings from both of these studies were invaluable to the understanding of riparian microclimate as they both provided novel insights into the workings of microclimate, their narrow scope and short duration remain notable. Because riparian development regulations were based off of these limited studies, these regulations may be lacking a rigorous scientific foundation.

Because studies examining microclimate variables across different watersheds over a multiple-month time period are far and few between, current understanding of microclimate gradients is limited. Therefore, this thesis project hopes to build on previous riparian microclimate studies by providing results from a multiple-month long sampling period over three full calendar years. This research aims to supplement existing research and guide future research direction in the examination of microclimate gradients in RMZs.

CHAPTER 3: RESEARCH MANUSCRIPT

Abstract

Despite the regulatory emphasis on buffer zones in riparian areas, few studies have examined the effects of timber harvesting on near-stream microclimates—the suite of environmental variables that includes moisture, temperature, wind speed, and light. This study examines the spatial and temporal variability of microclimates over three years from ten different watersheds throughout State managed forests on the Olympic Experimental State Forest (OESF). Microclimates influence in-stream temperatures and near-stream habitat of riparian amphibians, small mammals, and invertebrates. Mixed multivariate models with both fixed and random effects were developed to examine the relationships between microclimate variables (vapor pressure deficit, air temperature, and cumulative degree days) and a number of discrete predictor variables including distance from stream, height above stream, percent shade, and solar radiation. Height above stream was found to have a statistically significant effect on microclimate variables in all three models, and solar exposure was found to be a significant predictor for air temperature and vapor pressure deficit. Additionally, height above stream was found to be a stronger predictor for microclimate than distance from stream in all three models. These results suggest the value of topographical variations when designating site-specific riparian management. This research also revealed the complexity between height above stream and riparian microclimate variables and directions for future research to improve ecological resiliency in riparian zones.

Keywords

Microclimate, riparian management areas, forest management, riparian ecosystems, Olympic Peninsula

Introduction

Since the early 1990's extensive riparian management zones (RMZs) accompanied timber harvest and other management on public lands in western Washington to protect and restore riparian ecosystems. On State managed lands in Western Washington about a third of lands are devoted to the protection of aquatic resources and habitat associated with streams and wetlands. Central to the management objective of the RMZs is the maintenance of riparian microclimate. Riparian areas are multi-dimensional ecotones that include both aquatic and terrestrial ecosystems which range above the canopy, beneath the ground, across the floodplain, and upslope from streams (Ilhardt et al., 2000). In riparian areas, the surfaces of streams and rivers are directly influenced by the adjacent land, and likewise the land is influenced by those waters (Palik et al., 2004). These areas support the highest biodiversity in forested areas due to their moist conditions, complex habitat structure, and high productivity (Olson et al., 2007). In riparian areas, stream energy is dissipated and soil is protected from erosion by stabilized stream banks (NRC, 2002; Anderson et al., 2007). Additionally, nutrients and pollutants distributed from uplands are filtered in riparian areas, and both water temperature and light regimes are regulated within these zones (Tiwari et al., 2016).

Extensive past timber harvest within and adjacent to riparian areas has negatively influenced riparian resources and physical processes. Timber harvesting in riparian areas can intensify solar radiation in and increase exposure to wind, which often results in a decrease in relative humidity and an increase in air, stream, and soil temperatures (Moore et al., 2005). Moreover, protection of stream and riparian- associated biota has become a central tenant in modern land management across the Pacific Northwest (Rykken et al., 2007).

Much of the character of riparian ecosystems is defined by its microclimate, which is the suite of riparian environmental variables including moisture, temperature, wind speed, and light found within localized areas near the earth's surface (Geiger, 1965). Microclimate and stream temperature are critical aspects of aquatic habitat conditions in and near streams (Moore et al., 2005). Riparian microclimate gradients for soil temperature, air temperature, stream temperature, and relative humidity are greatly influenced by timber harvesting, and are believed to be largely the result of reduction of shade (Brosofske et al., 1997; Chen et al., 1993; Richardson et al., 2012). The maintenance of shade along streams has been a consistent motivation to establishing riparian management areas. Changes in riparian microclimate, including increased air temperature and decreased relative humidity, as a result of logging has been linked with changes in nutrient cycling (Chen et al., 1999) and strong influence on riparian vegetation structure (Davis-Colley et al., 2000).

Despite the recognition of timber harvesting's effects on microclimate, only a few studies have examined the influences of established riparian protection on riparian microclimate (Anderson et al., 2007; Moore et al., 2005). It has been identified that by maintaining sections of vegetated area near streams, land managers can protect riparian processes like microclimate from increased exposure to sun and soil erosion due to adjacent logging (Anderson et al., 2007; Rykken et al., 2007; Brosofske et al., 1997). However, in order to accomplish ecologically-sound forest management practices, more research needs to examine riparian understory and overstory vegetation and microclimate

(Eskelson et al., 2013). Questions remain about the ecological drivers of microclimate and the effectiveness of RMZs in maintaining a variety of microclimate variables. This study seeks to address some of these questions through an examination of microclimate data across the Western Olympic Peninsula. From 2014-2016, air temperature and humidity data were collected along 20 microclimate transects across the Olympic Experimental State Forest. The data were analyzed using mixed multivariate analyses to understand if and how predictor variables like distance from stream, height above stream, solar radiation, and canopy closure affected microclimate variables.

Methods

Study Area

Since 2012, the Washington State Department of Natural Resources (WADNR) has been managing the Olympic Experimental Forest (OESF), which contains over 270,000 acres (109,265ha) of state trust forestlands on the Olympic Peninsula. The OESF is one of nine planning units of the State Lands Habitat Conservation Plan (HCP) and is managed as a sustainable harvest unit. The OESF has a flexible management approach designed to explore a variety of management strategies to meet the same conservation objectives. WADNR manages the OESF land under the guidance of the riparian conservation strategy in the HCP, which is applied under the OESF Forest Land Plan. The goal of the riparian conservation strategy is to maintain biological and physical processes within riparian zones in order to preserve habitat for species who depend on these ecosystems.

All sample watersheds on the OESF were selected for monitoring through a random design process stratified by gradient stratum of each basin (Minkova et al., 2012;

Minkova & Vorwerk, 2014) (Appendix A). OESF-specific riparian buffer practices were outlined in DNR’s HCP Riparian Conservation Strategy (WADNR, 1997). Currently, streams in the OESF have a 30.5m-45.7m (100- or 150ft) unharvested core buffer on each side (the width depends on stream size), plus an exterior buffer based on the local risk of windthrow to riparian trees. The ecological setting of the area is described further in the *Study Sites* section of this chapter.

In order to produce empirical data needed to assess the progress towards achieving conservation objectives outlined in the HCP, DNR implemented the *Status and Trends Monitoring of Riparian and Aquatic Habitat in the Olympic Experimental State Forest* in 2012 a long-term study documenting changes in riparian and aquatic habitat in the OESF (Minkova & Foster, 2017). The study is testing the hypothesis that current protections permit natural processes including succession and disturbance to improve habitat over time. Nine habitat attributes are being monitored as part of this larger study: channel morphology, stream temperature, channel substrate, stream discharge, in-stream large wood, habitat units, stream shade, riparian forest vegetation, and riparian microclimate.

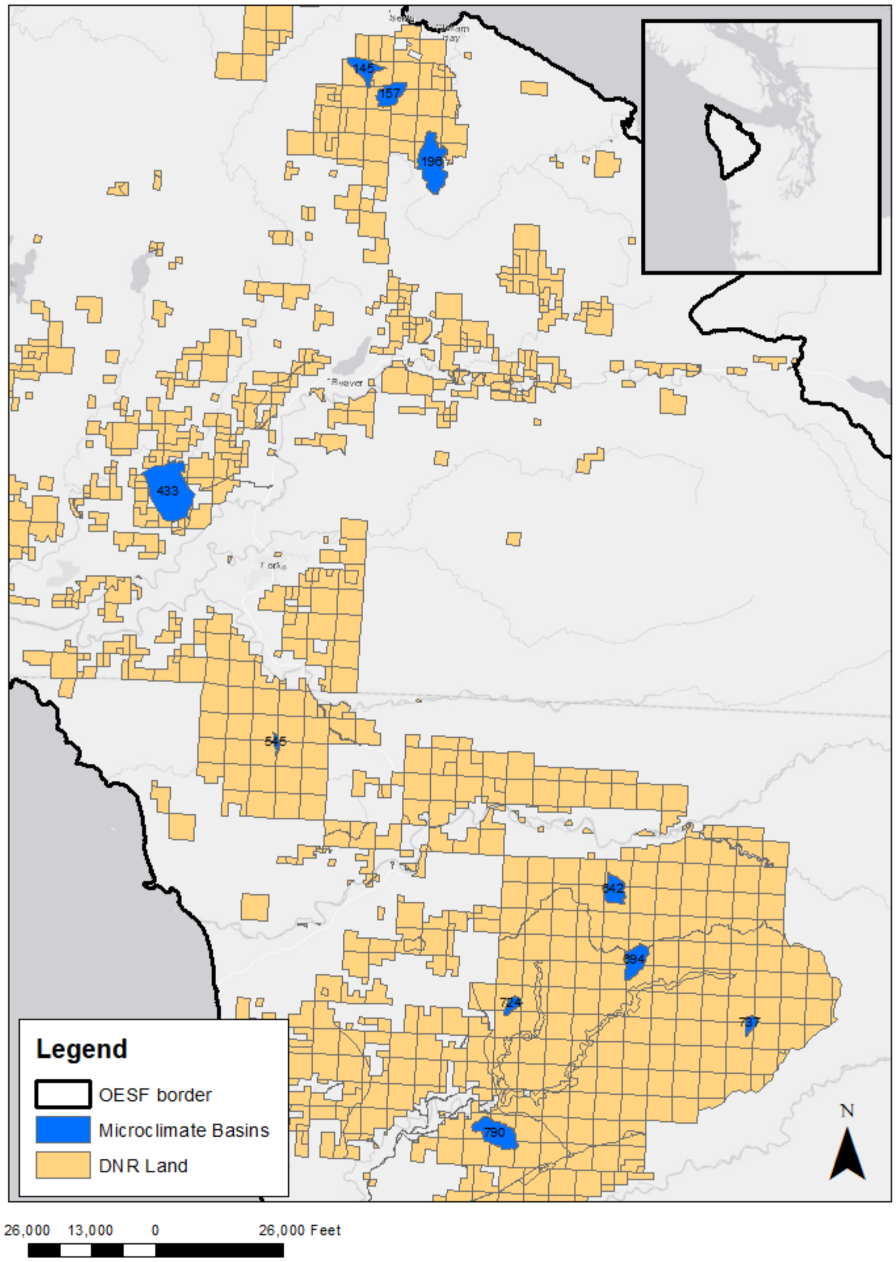


Figure 3.1. The ten microclimate basins included in this study within the boundary of the OESF. Grid lines are section lines, each section containing 259ha (640ac).

Monitoring Design

Spatial Monitoring Design

The spatial monitoring design for this study was adapted from Brosofske et al. (1997) and Anderson et al., (2007). As part of WADNR's *Status and Trends Monitoring* *of Riparian and Aquatic Habitat in the Olympic Experimental State Forest* study, 10 of the 50 type 3 (watersheds around the smallest fish-bearing streams) sample watersheds were randomly selected to be monitored for microclimate (Figure 3.1). Within each of these 10 sample watersheds, five microclimate monitoring stations were placed along two randomly selected 60m transects on opposite sides of the stream (Figure 3.2). Microclimate monitoring stations, which consisted of HOBO Pro v2 U23-001 Temperature/Relative Humidity dataloggers, were installed at approximately 0, 10, 20, 40, and 60m along each transect, and they recorded air temperature and humidity every 2 hours for three years.

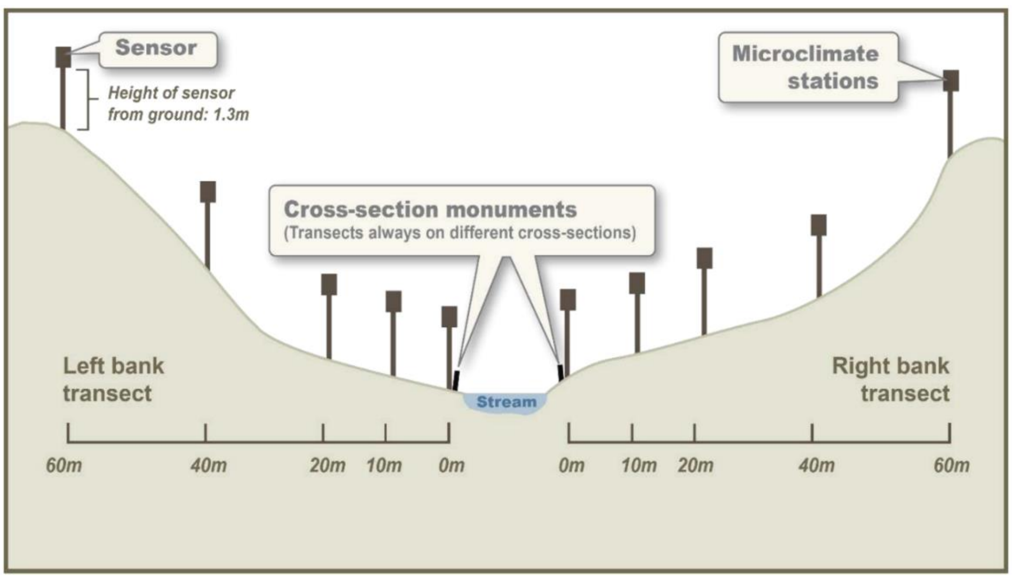


Figure 3.2. Idealized cross section of microclimate monitoring stations within a sample reach. Distances are horizontal distance. From WADNR (2017).

Transect Installation

Each microclimate station included a 1.5m (5ft) U-post, a bucket to serve as protective housing, and a HOBO® Pro v2 datalogger (Figure 3.3). Before field deployment, all dataloggers were tested and calibrated to assure accuracy and consistency. Microclimate transects began approximately 1-5m upslope of cross-section monuments (A-F) and perpendicular to the stream to avoid losing dataloggers to a flood event. In some instances, the first station of the transect (at 0m) began up to 5m upslope from the cross-section monument. The distances between each monitoring station were measured as horizontal distances using a laser range finder. Additionally, the azimuth and horizontal and vertical distances from the base of the cross-section monument to the base of the 0m station post were measured. The vertical distances, either positive or negative, were also measured for each subsequent station (at 10, 20, 40, and 60m) along each transect.

Figure 3.3. A section of a microclimate transect (left), and a microclimate station (right). From WADNR (2017).

Study Sites

Most of the forests in the OESF are currently in second-growth conditions and consist of a variety of tree species including Douglas Fir (*Pseudotsuga menziesii*), Western Hemlock (*Tsuga heterophylla*), Western Redcedar (*Thuja plicata*), Sitka spruce (*Picea sitchensis*) and Alder (*Alnus rubra*). The area receives between 203-355 cm of precipitation per year due to its proximity to the Pacific Ocean, most of which falls as rain throughout the winter. The 20 study sites across the 10 basins displayed a range of ecological and geographical diversity. Sites were either low-elevation forests (0 to 150m) within either the Sitka spruce zone or within the western hemlock zone (150 to 550m) as defined by Franklin and Dyrness (1988) (Table 3.1). Vegetation varied within and across each basin, including varying degrees of canopy height, stand age, species type and distribution, density, and basal area. The sites were all characterized by very high tree-growth rate and provide habitat for a range of fish including nine resident salmonid species: Chinook salmon, Coho salmon, chum salmon, sockeye salmon, pink salmon, steelhead trout, cutthroat trout, bull trout, and mountain whitefish. The sizes of the streams across the ten basins ranged from 2-9m, with nine confined and one moderately confined. Transect slope varied greatly across each 60m transect, as most transects did not follow a continuous slope up from the stream (Figures 3.4 and 3.5). Some transects were relatively flat, while others were quite steep. This variation was represented in the data within single transects and across the larger study area.

Table 3.1. Basin elevations and vegetation zones.
The elevation of and associated climax vegetation zone as defined by Franklin and Dyrness (1973).

Basin	Elevation of reach (m)	Vegetation zone
145	28.3	Sitka spruce
157	76.1	Sitka spruce
196	85.5	Sitka spruce
433	36.6	Sitka spruce
545	101	Sitka spruce
642	156.5	Western hemlock
694	262.8	Western hemlock
724	170.7	Western hemlock
737	362.2	Western hemlock
790	80.7	Sitka spruce

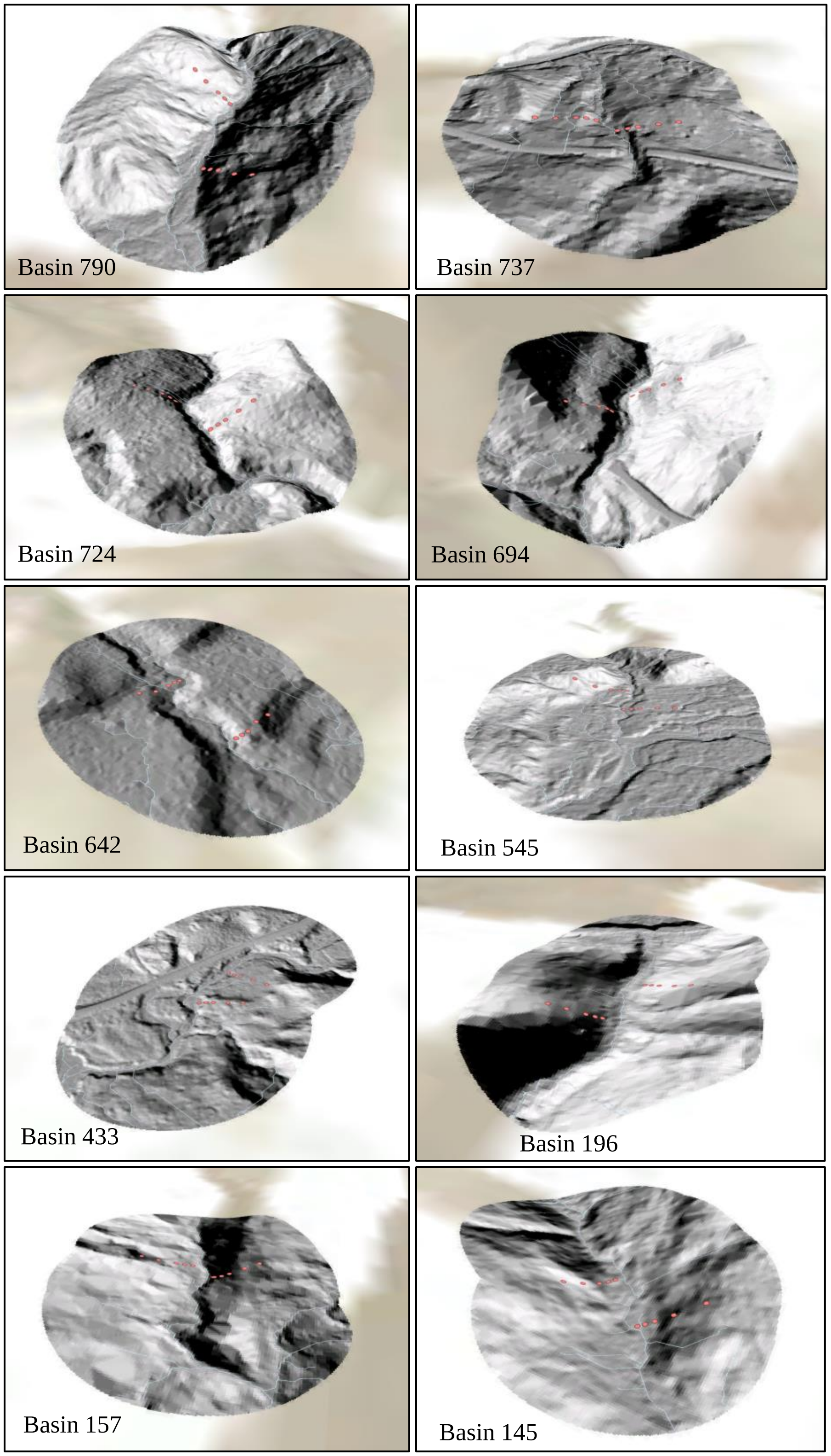


Figure 3.4. Three-dimensional renderings of each of the ten basins included in this study, generated in ArcGIS Pro. The ten sites demonstrated a wide range of topographical differences. For instance, transect 196C increased 32.4m, while transect 642D increased just 0.5m. The individual microclimate stations are represented as dark orange circles.

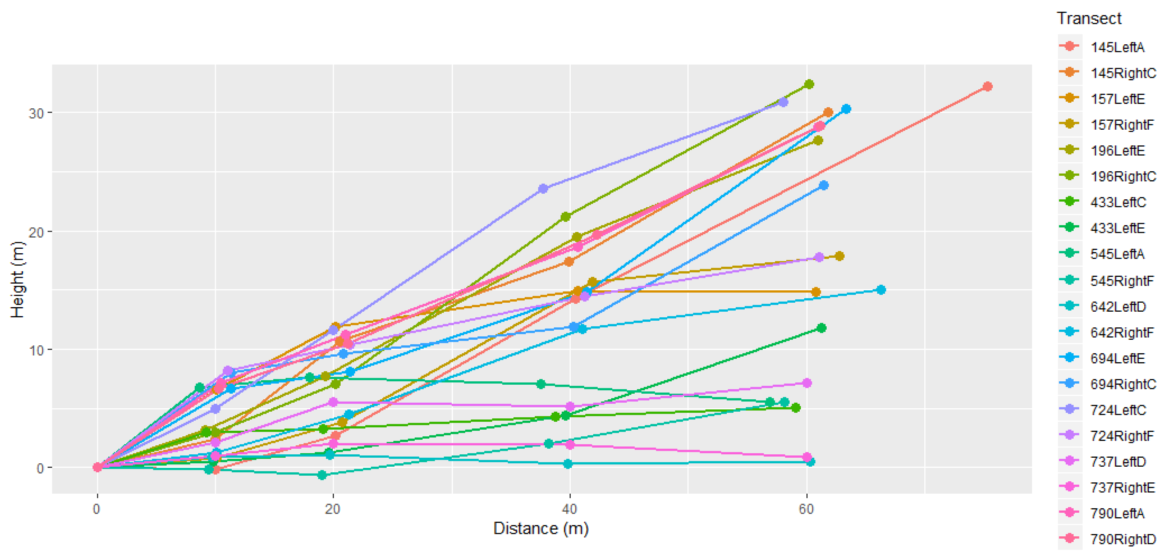


Figure 3.5. The topographical distribution of the study transects. Transect distances ranged from 58m to 75.3m and height from stream ranged from 0.5m to 32.4m.

Quality Control and Quality Assurance

All data were quality controlled by DNR staff and organized in a Microsoft Access database. Quality assurance included use of standardized protocols, field checks, and staff training. All microclimate data were evaluated graphically to detect outlier datapoints that might indicate instrument malfunction or other errors. Temperature and humidity data points from each datalogger (*n*=5) within each transect (*n*=20) were plotted together using the software R for one month. Graphs were reviewed by DNR scientists and staff, and data points were flagged as accepted, rejected, estimated, or missing based on the quality of the data. Once data went through the quality control process, they were ready for analysis.

Data Collection: Ground-truthing

At each site, dataloggers recorded air temperature and relative humidity every two hours for three years (2014-2016). Field data were collected in the summer of 2018 to verify precise microclimate datalogger station locations and measurements across each study transect. Horizontal and vertical distances between each microclimate station were re-measured using a laser rangefinder along all 20 transects. Additionally, GPS coordinates were recorded at each cross-section monument, along with horizontal distance and azimuth from each monument to the beginning of each transect (0m station) were measured and recorded. This field work allowed for the verification of station locations and transect arrangement.

Data Analysis

Three multivariate analyses were developed for three dependent variables: 1) average maximum summer air temperature (*n*=287 observations), 2) average maximum summer vapor pressure deficit (*n*=286 observations), and 3) cumulative degree days (*n*=268 observations). Data for each analysis were from the summer season (June 1 through August 31) for 2014, 2015, and 2016.

Data Preparation

Air Temperature Data

To prepare the air temperature data for analysis, the maximum air temperature was calculated for each microclimate station (*n*=100) for each day between June 1-August 31 for 2014, 2015, and 2016. Next, the means of the maximum daily temperature values were calculated for each station for each year (*n*=300). Because not all records had all 92 days of data due to falling trees or datalogger malfunction, they were not all treated equally in analysis. Therefore, 80% of summer days (*n*=73.6 days) was chosen as the minimum threshold for analysis. Temperature values flagged for rejection according to the data quality standards were nullified.

Degree Day Data

Degree days were added up for each calendar year (2014-2016). A complete dataset consisted of 12*365 (or 366 in 2016) records. The tolerance level for missing data was set at 2%. Missing data was limited to 2% to minimize the impact on the annual sum.

Zero was set as the base value for degree day analysis. Each record (representing 2 hours of data) was divided by 12 to indicate that it represented only 1/12 of a day, and then were summed up. The “ifelse” function in R was used to calculate degree hour for each record, or assign it “0” if the record fell below the base value. Next, degree days were summed by year and station. Finally, all degree day sums with missing data were reported as ‘NA’ and thus were not used in analysis.

Vapor Pressure Deficit Data

Vapor pressure deficit (VPD), which is the difference between the amount of moisture in the air and the holding potential of moisture the air has when it is saturated, was chosen for analysis instead of relative humidity (RH). Kalma (1968: 252) determined that, since RH averages are significantly different than the averages of daily maximum and minimum values, averaging VPD was a better metric to use. Compared to relative humidity, VPD is a much more biologically significant variable to track since it is directly correlated to the rate of evapotranspiration (Figure 3.6)

To prepare the microclimate data for analysis, variables for saturation vapor pressure and actual vapor pressure were created for reach record. VPD was calculated as the difference between actual and saturation vapor pressure variables:

$$VPD = e_s - e_a$$

Where e_s is the saturated vapor pressure and e_a is the actual vapor pressure. e_s was calculated from temperature with the following formula from ASCE-EWRI, 2005:

$$e_s = 0.6108 * \exp(17.27*T/T+237.3)$$

e_a was calculated using relative humidity:

$$e_a = e_s * RH/100$$

Once VPD data were calculated for the summer (June 1 through August 31) the maximum VPD was calculated for each day at each station (n=100) for 2014, 2015, and 2016. The mean of the daily maximum VPD was then calculated for each station at each site for 2014, 2015, and 2016 (n=300). VPD values flagged for rejection according to the data quality standards were nullified. 80% of days (73.6 days of the total 92 summer days) was set as the missing data threshold, which is consistent with the threshold set for the air temperature analysis.

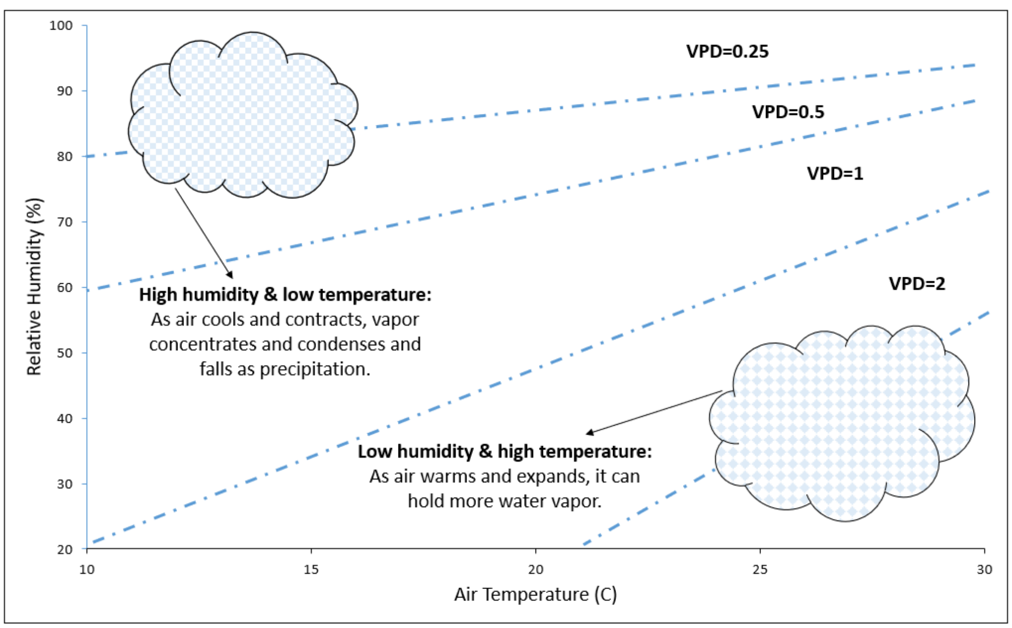


Figure 3.6. A hypothetical plot explaining the relationship between relative humidity, air temperature, and VPD. In this example, when air temperature is higher and relative humidity is low, VPD is greater than when air temperature is lower and relative humidity is high. Plot inspired from real data from Canty et al., 2016.

Solar Radiation Data

The ArcMap Area Solar Radiation tool was used to model incoming solar radiation received at each microclimate station using a USGS digital elevation model raster surface. The Area Solar Radiation tool's output rasters were in watt hours per square meter (WH/m2) and were then converted to watt hours per square kilometer (WH/km2). The analysis was run for the 15th day of every month (January-December) for the year of 2015. Then, solar radiation values were extracted to produce an attribute table at each of the datalogger points (Appendix B). The tool took into account slope and aspect information from the digital elevation model to yield an output raster with the total amount of incoming direct and diffuse solar insolation for each location.

Percent Canopy Closure Data

Hemispherical photos from vegetation surveys were captured at each microclimate station in 2014 for vegetation surveys for WADNR's *Status and Trends Monitoring of Riparian and Aquatic Habitat in the OESF* project. Sampling procedures for WADNR's multi-year trends of stream shade study were based on solar input protocols from Bonneville Power Administration's Columbia Habitat Monitoring Program (Bouwes et al., 2011). Hemispherical canopy photos were processed using Hemisfer software (Schleppi, 2016), which is designed to estimate the light regime and leaf area index (LAI) from hemispherical images. WADNR staff then used Hemisfer's output results to calculate the percent shade by calculating the count of black pixels in each image divided by the total number of pixels, multiplied by 100. Differences in site data due to tree type, tree height and age, and density are portrayed in hemispherical photos (Figure 3.7). Percent canopy closure ranged from 86.93% to 97.65% for the microclimate stations.

One of the transects (145C) was missing shade data due to shrub coverage of the camera lens, so shade data were interpolated for this site by averaging the shade values from the two nearest stations on that same transect. The site was originally calculated to have 98.26% shade, and after interpolation was determined to have 90.86% shade cover (Appendix C).

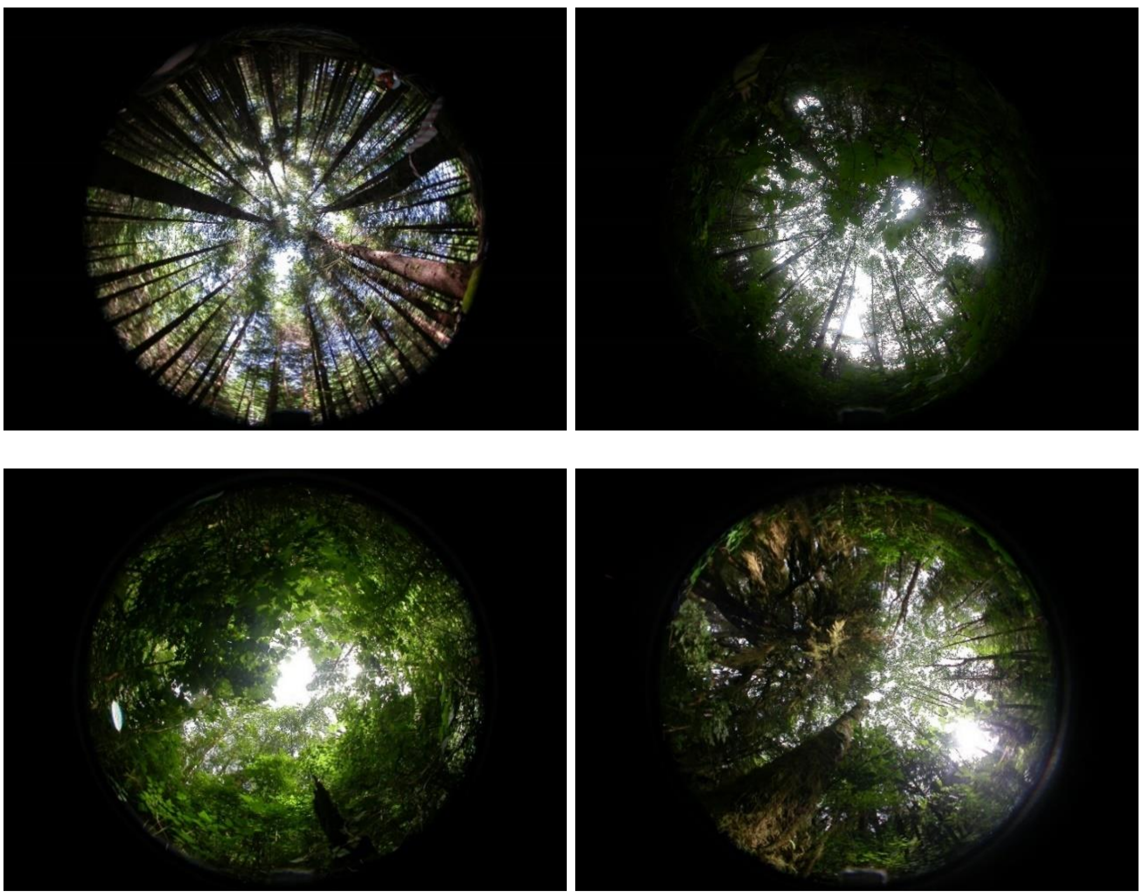


Figure 3.7. Hemispherical photos from four transects in different basins included in this study. Top left: 145A at 60m; top right: 157F 10m; bottom left: 433C at 20m; bottom right: 642D at 0m. Images from WADNR.

Multivariate Models

Using the lme4 package in R, three mixed multivariate models with both random and fixed effects explaining the variability of the microclimate data were developed to determine a rank of significance for the predictor variables. The three dependent variables used in the models were: 1) mean summer daily maximum temperature, 2) mean summer daily maximum VPD, and 3) cumulative degree days. The three discrete predictor variables included in the models were: 1) height above stream, 2) solar radiation, and 2) percent canopy closure (or percent shade). Year, a random variable since it could not be controlled or quantified in the experimental design, was also included in the models. Model assumptions were tested by checking for similar variance and normality of model residuals (Appendix D).

Multicollinearity

Initially, horizontal distance from stream was going to be included as a predictor variable in each of the mixed models, but it was found to be strongly correlated (r=0.74) with height above stream (Figure 3.8). Because of this strong correlation, it was determined that the variables were using much of the same information to explain the variations among the microclimate variables. To examine this correlation further, variance inflation factors (VIF) were calculated for each predictor variable (Table 3.2). Additionally, two separate models were developed for each of the three dependent variable inputs: one with height, solar, and shade, and the other with distance, solar, and shade. For all three dependent variables, height was shown to be a better predictor than distance (Table 3.3 and Appendix E). Therefore, the weaker of the two variables, distance from stream, was removed from the models. Correlation coefficients between all other predictors were 0.38 or lower, which were low enough to justify keeping them in the same model.

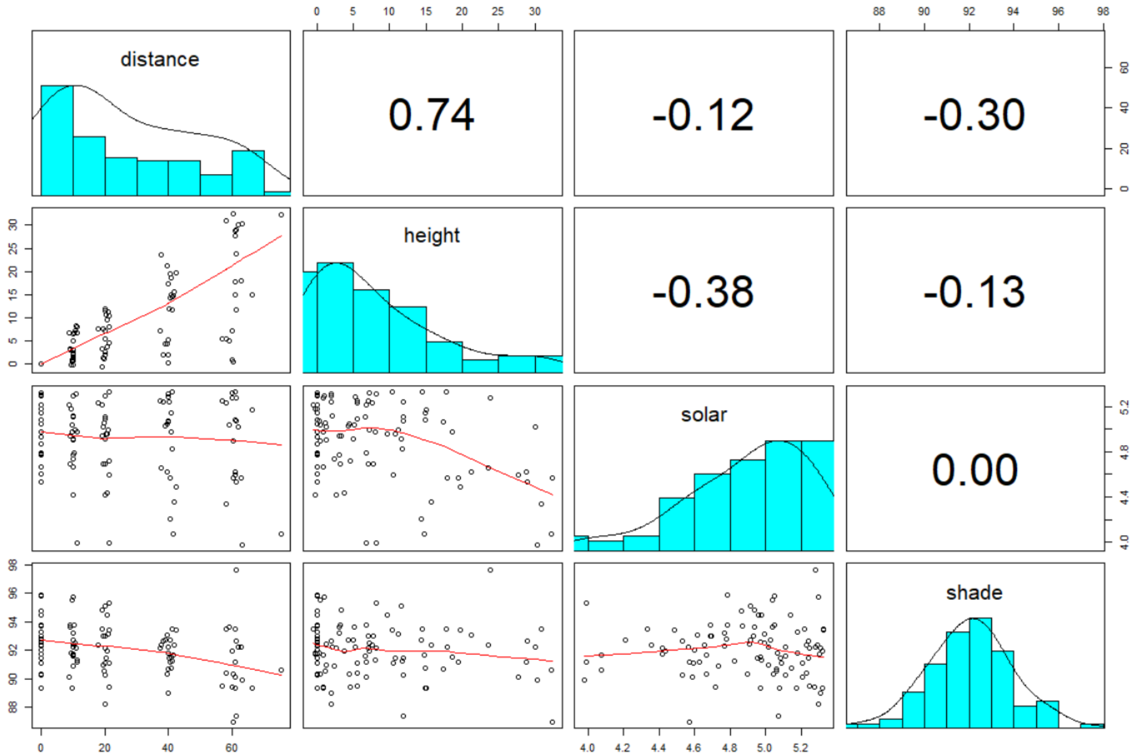


Figure 3.8. A simple correlation matrix for the four predictor variables. Matrix was created using the paris.panels function and "psych" package in R.

Table 3.2. Variance inflation factors (VIF's)
VIF's for each of the four predictor variables, calculated using the usdm package in R.

Predictors	VIF
Distance	2.582352
Height	2.746688
Solar	1.247970
Shade	1.124297

Results

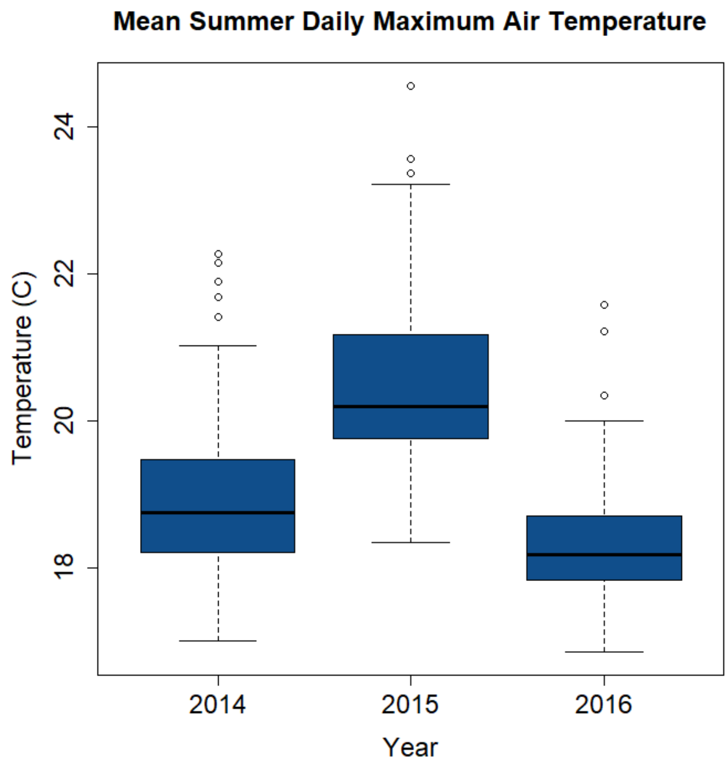
This study tested the hypotheses that distance from stream, height above stream, solar exposure, and percent canopy closure would each be strong predictors of microclimate in riparian management areas on the OESF. However, the complexity of the relationship, particularly with shade, was not anticipated.

Two of the three independent variables examined in this study, height above stream and solar exposure, were shown to be significant contributors to fit the models. Height above stream (β=0.027, P=0.000) and solar radiation (β=0.954, P=0.000) had significant effects on mean maximum air temperature. Likewise, height above stream (β=0.011, P=0.000) and solar exposure (β=0.181, P=0.000 also had significant effects on mean maximum vapor pressure deficit. For both the air temperature and vapor pressure deficit models, the significant predictor variables had a positive relationship with the dependent variables. This means that, as height above stream and solar radiation increased, air temperature and VPD also increased while accounting for all of the other variables in the model.

For the degree day analysis, height above stream (β=3.869, P=0.000) had a significant, positive effect on cumulative degree days. Unlike with air temperature and vapor pressure, however, solar exposure (P=0.47) was not shown to be a significant predictor of degree days. Percent shade was not shown to be a significant predictor in any of the models (temperature: P=0.564; cumulative degree days: P=0.432, VPD: P=0.680). For all analyses, height above stream was shown to be a better predictor of the dependent variables than distance from stream (Table 3.3; Appendix E).

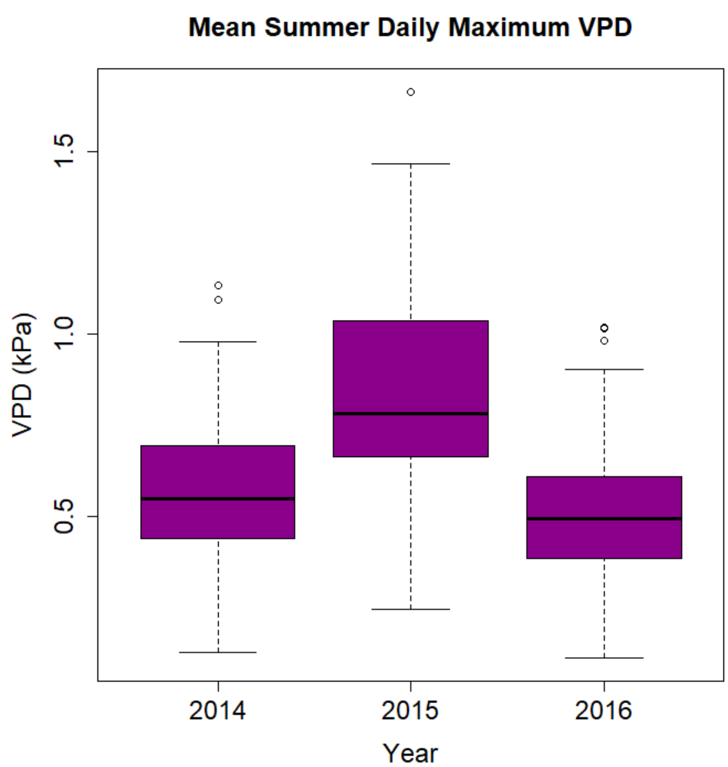
Overview of Statistical Trends

Temporal (Figure 3.9) and spatial variations (Figure 3.10) were examined for mean maximum air temperature, mean maximum vapor pressure deficit, and cumulative degree days data.



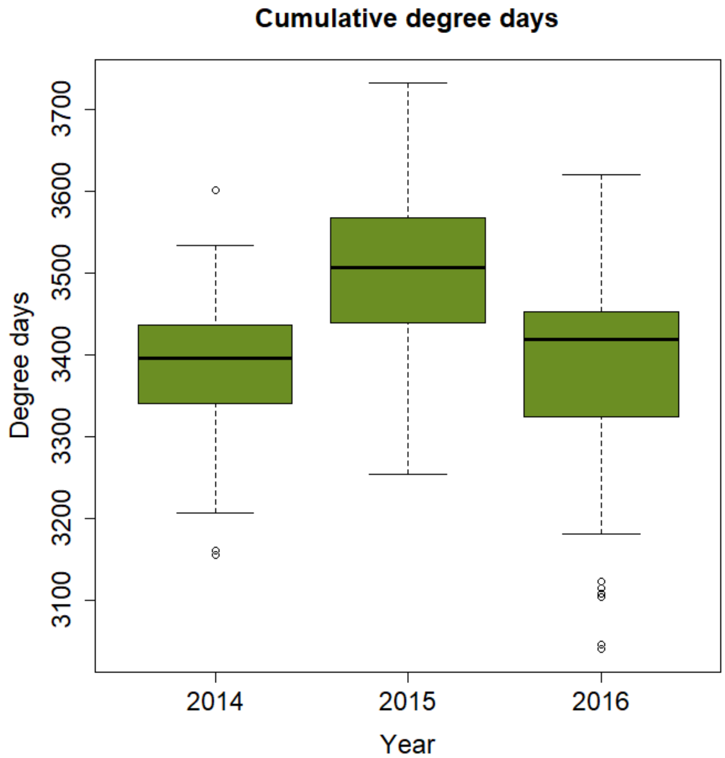
Mean Summer Daily Maximum Air Temperature
Temperature (C)
18
20
22
24
2014
2015
2016
Year

(A)



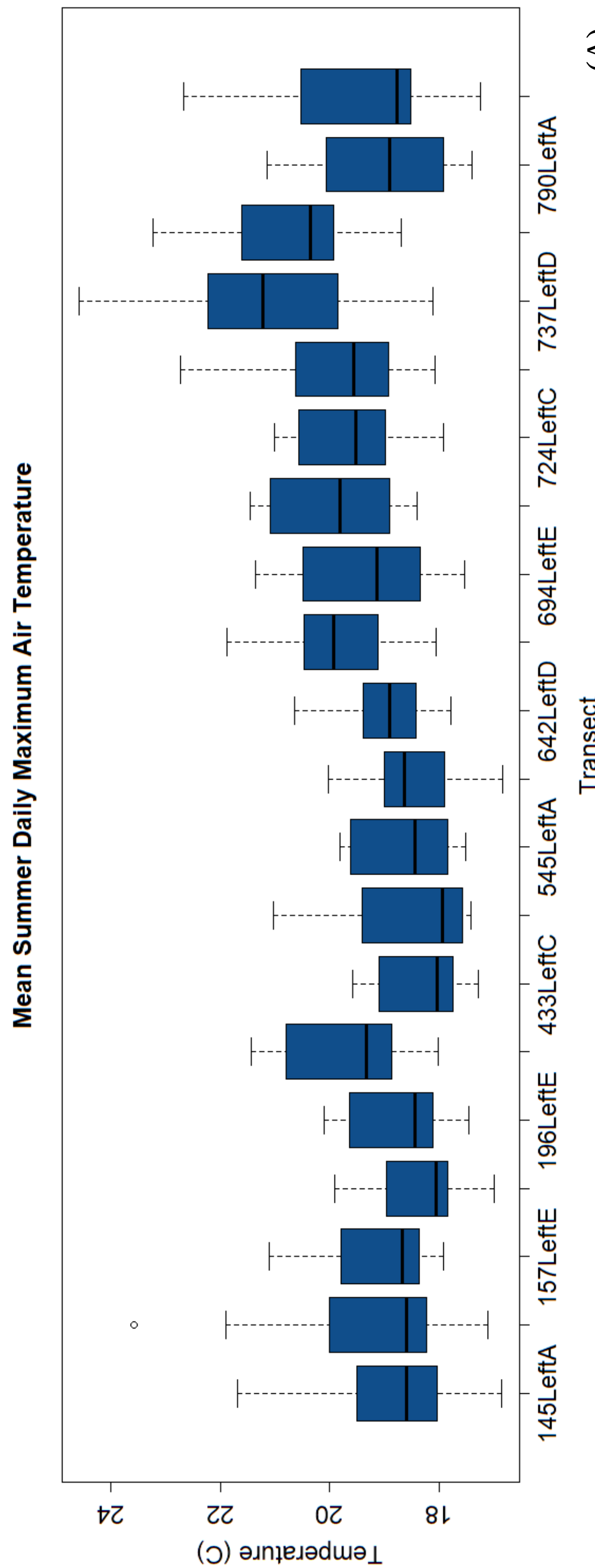
Mean Summer Daily Maximum VPD
VPD (kPa)
0.5
1.0
1.5
2014
2015
2016
Year

(B)



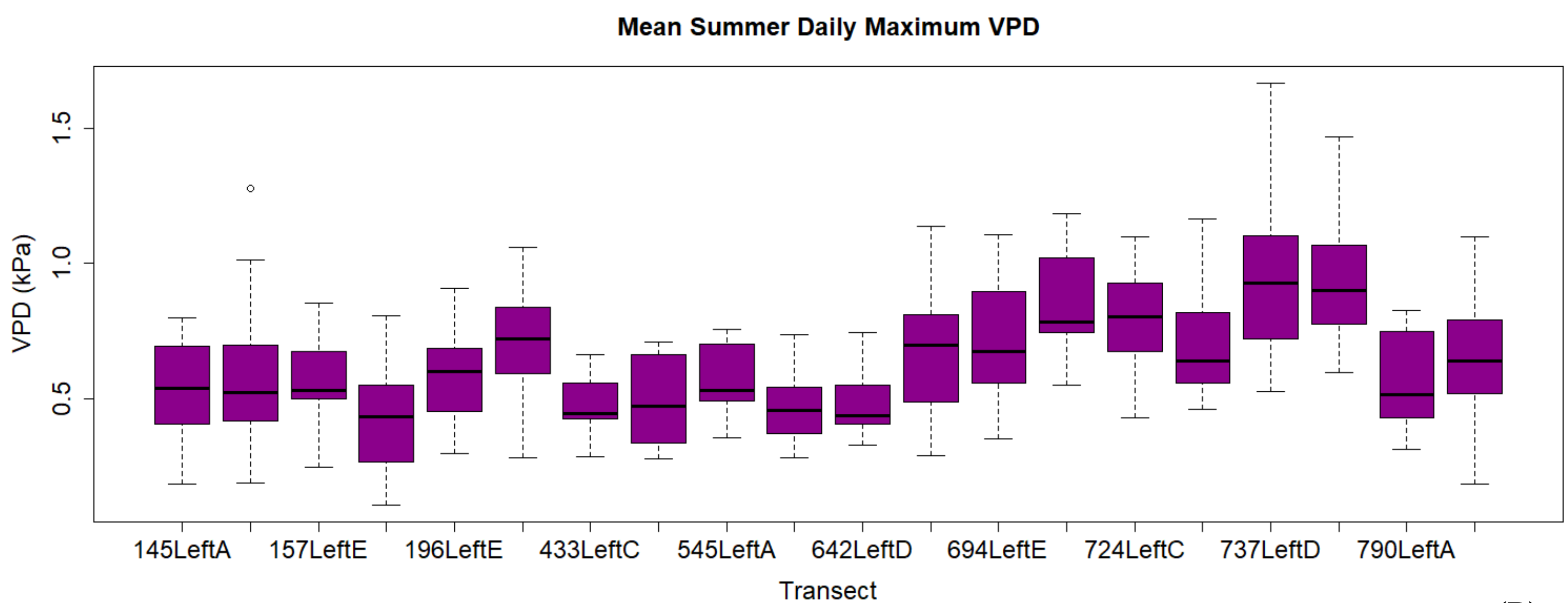
(C)

Figure 3.9. Mean summer daily maximum temperature (A), mean summer daily maximum vapor pressure deficit (B), and cumulative degree days (C) plotted against year. Years represented are full calendar years included in the study (2014, 2015, and 2016).

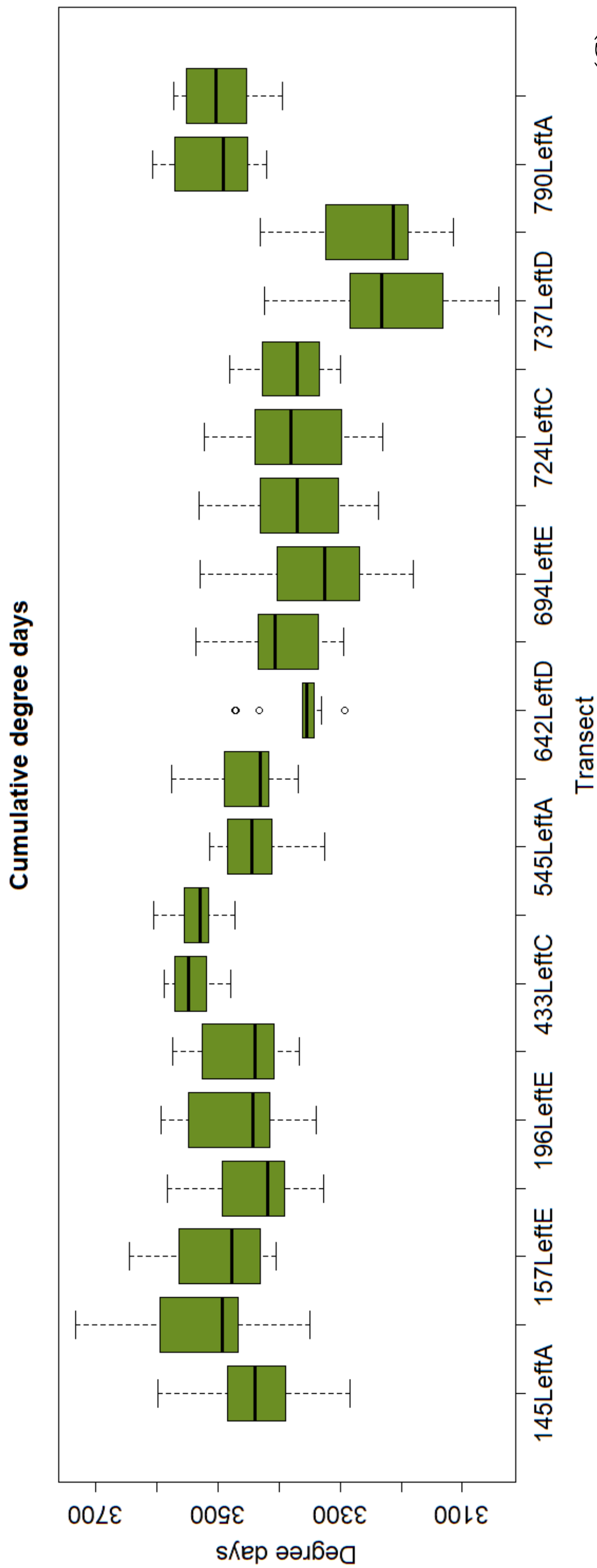


Mean Summer Daily Maximum Air Temperature
Temperature (C)
24
22
20
18
145LeftA
157LeftE
196LeftE
433LeftC
545LeftA
642LeftD
694LeftE
724LeftC
737LeftD
790LeftA
Transect

(A)


Mean Summer Daily Maximum VPD
VPD (kPa)
0.5
1.0
1.5
145LeftA
157LeftE
196LeftE
433LeftC
545LeftA
642LeftD
694LeftE
724LeftC
737LeftD
790LeftA
Transect

(B)



Cumulative degree days
Degree days
3700
3500
3300
3100
145LeftA
157LeftE
196LeftE
433LeftC
545LeftA
642LeftD
694LeftE
724LeftC
737LeftD
790LeftA
Transect

(C)

Figure 3.10. The raw mean maximum summer daily air temperature (A), mean maximum summer daily VPD (B), and cumulative degree day (C) data by transect. The 20 transects include 2 transects on either the left or right side of the stream in each of the 10 basins.

Table 3.3. Akaike information criterion values for each model.
For both the temperature and VPD models, values indicated the height model was of better quality than the distance model using Akaike information criterion (AIC).

	Model	**AIC**
Air temperature	Height + Solar + Shade	836.1
	Distance + Solar + Shade	842.1
Vapor Pressure Deficit	Height + Solar + Shade	-123.5
	Distance + Solar + Shade	-111.3
Degree Days	Height + Solar + Shade	3221.2
	Distance + Solar + Shade	3227.4

Air temperature analysis

The mixed model for mean maximum air temperature (Table 3.4, Figure 3.11) showed that both height above stream and solar exposure were significant predictors of air temperature.

Table 3.4. Linear mixed model fit by maximum likelihood of mean maximum air temperature.
The linear mixed model fit shows that height above stream and solar exposure are strong predictors for mean maximum air temperature. For the model with height + solar + shade, the height effect with one standard error would be 0.027 ± 0.007 and the solar effect would be 0.954 ± 0.186. This means that for every 1-meter increase in height, the air temperature increased by 0.027 degrees C, and for every 1 kWH/m2 of increase in solar exposure, air temperature increased by 0.954 degrees C. T-tests use Satterthwaite's method.

Model	**Predictor**	**Estimate**	**Standard Error**	**df**	**T**	***P***
Height + Solar + Shade	Height	0.027	0.007	284	5.095	0.000279***
	Solar	0.954	0.186	284	5.132	5.32e-07 ***
	Shade	-0.018	0.032	284	-0.578	0.563667
Distance + Solar + Shade	Distance	0.008	0.003	284	5.031	0.00691**
	Solar	0.764	0.176	284	2.721	2.00e-05***
	Shade	-0.011	0.033	284	-0.339	0.73514

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

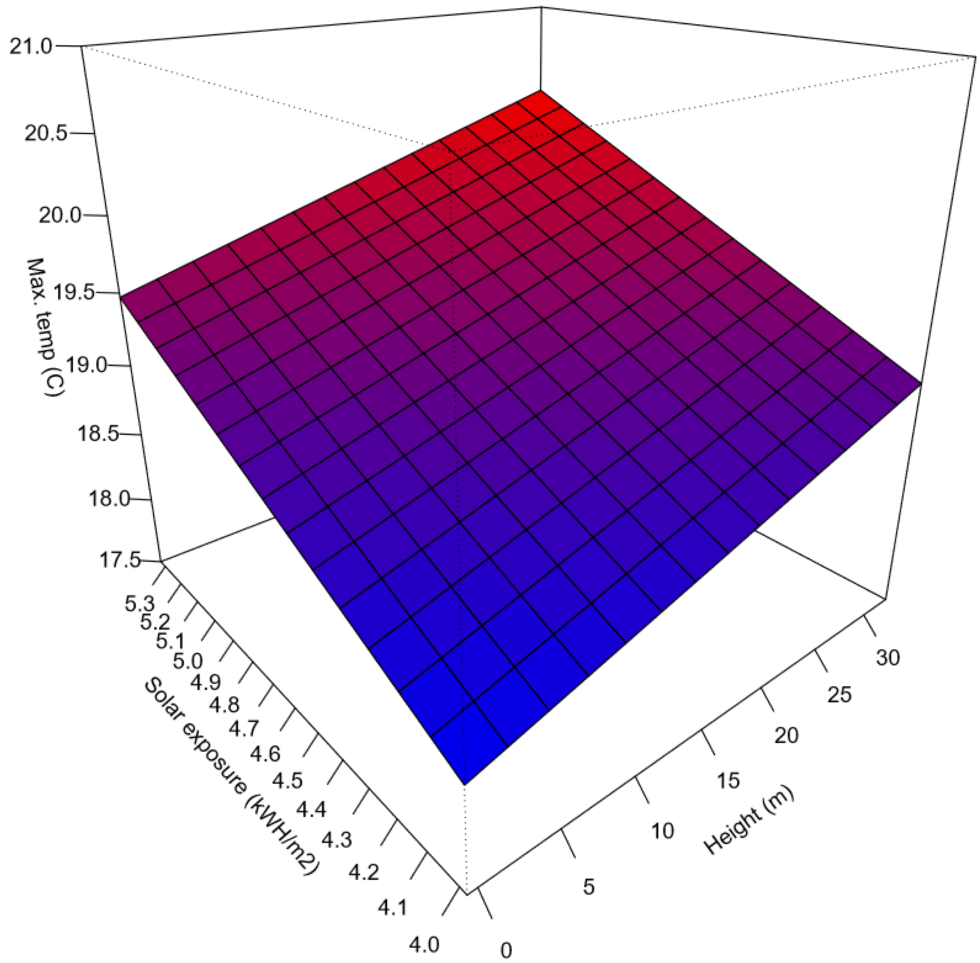


Figure 3.11. Three-dimensional plot for the mean maximum air temperature model with the two statistically significant predictor variables (height above stream and solar radiation) included. This plot shows that solar radiation is a stronger influence than height above stream. If solar stays low (i.e. 4.0 kWH/m2), increasing height above stream to 30+ meters only raises air temperature slightly (it is still mostly blue). However, if height above stream remains low (i.e. 0m), then increasing solar radiation to 5.3 kWH/m2 increases temperature greatly (red).

Vapor Pressure Deficit Analysis

Like the model for air temperature, the mixed model for mean maximum vapor pressure deficit (Table 3.5, Figure 3.12) showed that both height above stream and solar exposure were significant predictors of vapor pressure deficit.

Table 3.5. Linear mixed model fit by maximum likelihood of mean maximum vapor pressure deficit.
The linear mixed model fit shows that height above stream and solar exposure are both strong predictors for mean maximum vapor pressure deficit. T-tests use Satterthwaite's method.

Model	Predictor	Estimate	Standard Error	df	T	*P*
Height + Solar + Shade	Height	0.011	0.001	283	8.031	2.61e-14***
	Solar	0.181	0.035	283	5.176	4.30e-07***
	Shade	-0.002	0.006	283	-0.412	0.680
Distance + Solar + Shade	Distance	0.004	0.001	283	7.060	1.29e-11***
	Solar	0.109	0.034	283	3.240	0.00134**
	Shade	0.003	0.006	283	0.441	0.65933

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 '' 1

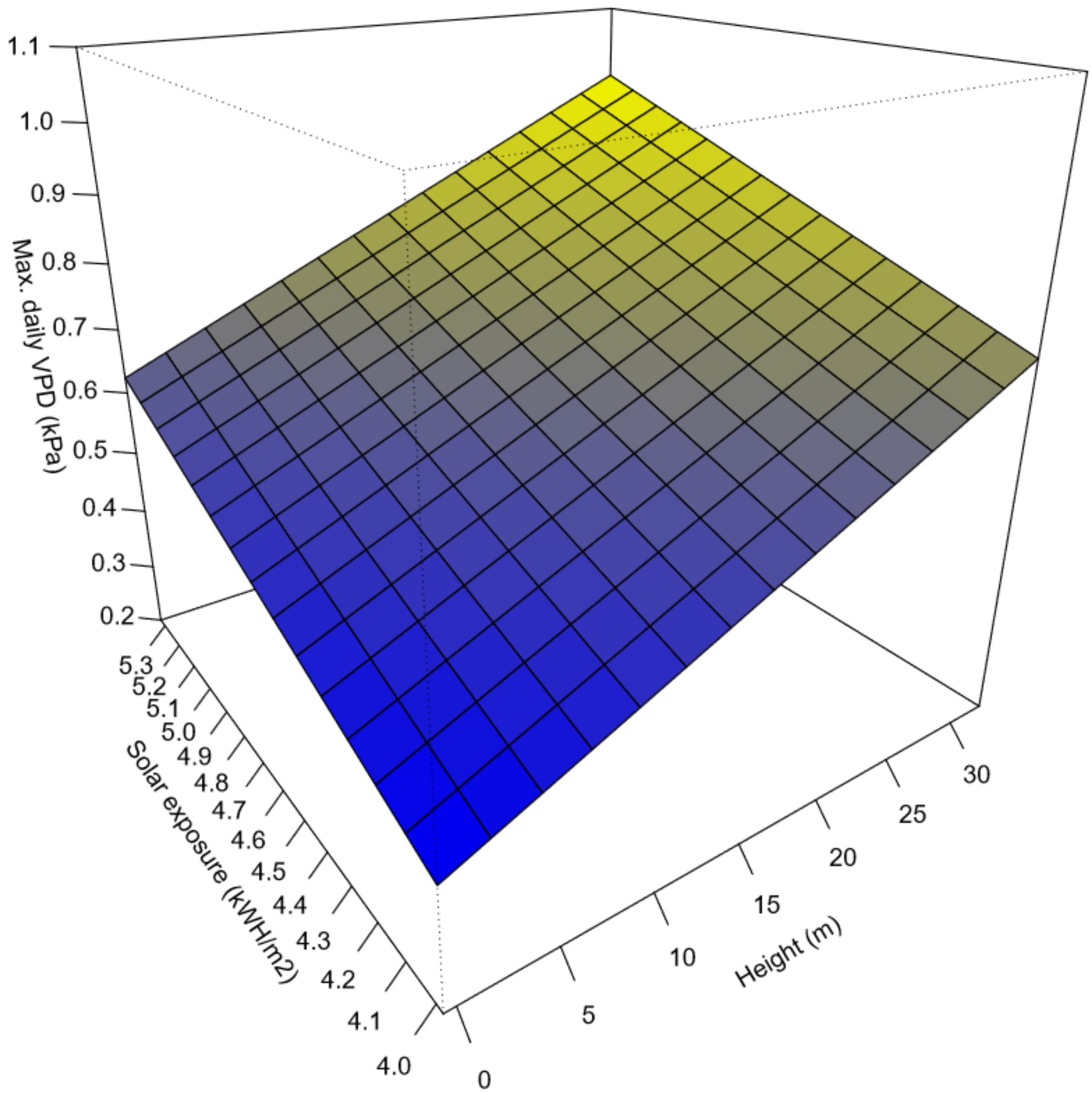


Figure 3.12. Three-dimensional plot for the mean maximum VPD model. This plot shows that, for maximum daily VPD, height above stream is a slightly better predictor than solar exposure, although both have strong effects on VPD.

Degree Day Analysis

Unlike the mixed models for air temperature and vapor pressure deficit, the model for cumulative degree days (Table 3.6, Figure 3.13) showed that there was only one strong predictor variable, being height above stream.

Table 3.6. Linear mixed model fit by maximum likelihood of cumulative degree days.
Height above stream proved to be the strongest predictor for cumulative degree days. Even though the distance model might look better than the height above stream model at first, its AIC is larger (3227.4 vs. 3221.2). T-tests use Satterthwaite's method.

Model	**Predictor**	**Estimate**	**Standard Error**	**df**	**T**	***P***
Height + Solar + Shade	Height	3.869	0.714	265	5.418	1.35e-07***
	Solar	-12.987	17.941	265	-0.724	0.470
	Shade	2.432	3.090	265	0.787	0.432
Distance + Solar + Shade	Distance	1.335	0.281	265	4.754	3.28e-06***
	Solar	-38.215	17.086	265	-2.237	0.0261*
	Shade	4.084	3.235	265	1.263	0.2079

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

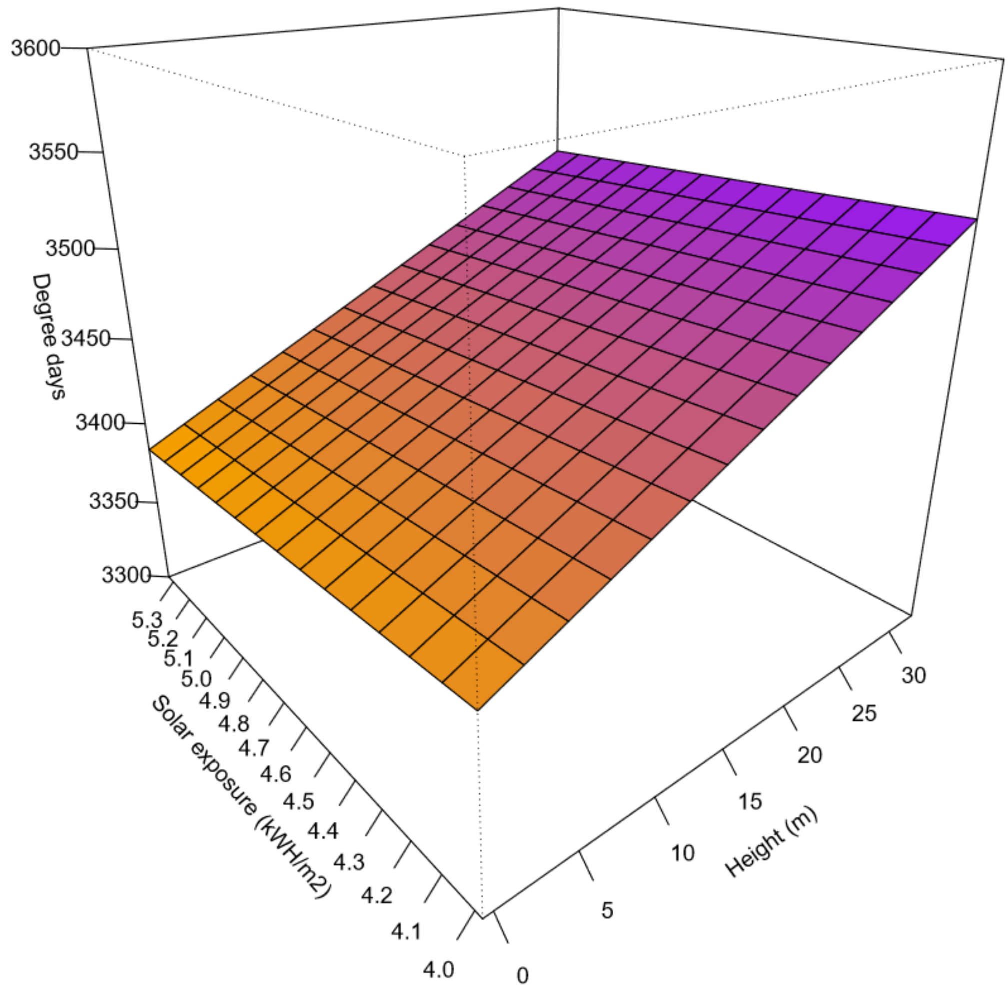


Figure 3.13. Three-dimensional plot for the cumulative degree days model. This plot shows that height above stream is a strong predictor for cumulative degree days in the study sites. Although solar exposure was not shown to be a significant predictor for degree days, it was included in this plot to highlight the strong effect of height above stream.

Discussion

This study examined the relationship between microclimate variables and a number of ecological factors in RMZs on the Olympic Peninsula. The results are broadly consistent with existing literature on riparian microclimate, while also raising some new questions about the drivers of microclimate. Overall, this research suggests that local microclimatic conditions may be more intricately related to topography and less related to shade cover than past studies have suggested.

As expected, height above stream was found to have a significant effect on all three mixed models: mean maximum summer air temperature, mean maximum summer vapor pressure deficit, and cumulative degree days. This was unsurprising, especially considering the strong correlation found between height above stream and distance from stream. Despite a number of studies having identified a relationship between microclimate and distance from stream (Anderson et al., 2007; Anderson and Poague, 2014; Brosofske et al., 1997), few have closely examined the relationship between microclimate and height above stream. Studies have found relationships between topographic constraints and microclimate characteristics (Richardson et al., 2005; Chen et al., 1995; Matlack, 1993), but most of these findings were product not of concentrating on height, but rather observing it as an artifact of distance. The focus on height in this study offers a unique investigation of this variable on its own, distinctly from distance.

In addition to topographical variations, this study found solar exposure to be a significant predictor of mean maximum summer air temperature and VPD, but not of cumulative degree days. This lack of effect on cumulative degree days is likely an artifact of that variable being a 24-hour sum. In contrast, the solar effect on temperature and VPD was likely associated with the fact that the maximum values occurred in the afternoon when the sun was striking the area. With this in mind, it is expected that solar exposure would be a good predictor of mean maximum air temperature and mean maximum VPD.

Conceiving why canopy closure was not found to be a good predictor of microclimate is not as straightforward as understanding the strong relationship between height above stream and solar exposure with microclimate. For each model, the effect canopy closure had on the dependent variables was not significant ($P=0.564$ for mean maximum air temperature; $P=0.680$ for mean maximum VPD; $P=0.432$ for cumulative degree days) when taking into account all of the other variables in the models. Therefore, these results suggest local riparian conditions may have to do more with air temperature, humidity, and VPD, than shade.

These results challenge much of the literature, which has broadly found shade cover to be intricately linked with microclimate (Brosofske et al., 1997; Chen et al., 1993; Moore et al., 2005). Common sense seems to also be challenged by these findings. It widely recognized and agreed upon that overhead canopy cover has a cooling effect air and soil temperatures. Why, then, was shade not a good predictor of air temperature and VPD in this study?

The answer may lay in the methods. Hemispherical photos are one of many ways obtain canopy shade data, and perhaps may not be the most comprehensive method of procuring these data. The hemispherical photos use a 180-degree field of view, which should theoretically include both vegetation and topographic shading. However, the outer part of the field of view was typically completely shaded by vegetation due to the low angle of the field. Therefore, the variation in shade among the different microclimate stations was usually more directly overhead. Because canopy closure was measured as the percentage of pixels not receiving direct sunlight according to the photos, the 180-degree field of view may not be indicative of the precise amount of sunlight received at each site. The narrow range of canopy closure values (86.93% to 97.65%) also suggests these metrics may not be particularly useful when examining localized changes in microclimate.

Some researchers have measured shade or light data using other methods that may be better indicators of direct sunlight. For example, Davies-Colley et al. (2000) measured light in a forest compared to a neighboring open pasture in New Zealand and measured sunlight exposure using photosynthetically available radiation (PAR). The researchers also examined the visible light exposure using Plant Canopy Analyzers. Diffuse-non-interceptance (DIFN), which is an index of the time-averaged sunlight exposure beneath a forest canopy, was calculated from the canopy analyzer data, and these indexes reflected the vast structural variability among the forest canopy. Even within the same study, the light exposure data collected by the PAR method were higher than indicated by the canopy analysis data. These differences in light measurements highlight the varying ways sunlight can be distributed beneath a forest canopy. Because of these complexities, determining which method is best to quantify light exposure (or, in the case of this study, shade), remains a challenge for researchers.

Considering Height and Distance When Designating RMZs

A key finding of this study is that height above stream was a better predictor for microclimate than distance from stream in all three multivariate models. This is significant since RMZs are almost always defined by distance from stream (FEMAT, 1993; USDA, 1994). A limitation of designating RMZs only by distance is that it overlooks the breadth of physical and ecological complexities that exist within riparian systems, including an array of topographical, biogeochemical, and microclimatic distinctions. Therefore, when possible, variables other than just distance from stream should be considered when designating RMZs to maintain the naturally occurring microclimate.

Research and monitoring efforts have shown that designating a RMZ effective in maintaining ecological values remains a challenge for scientists and land managers. In a recent review, Gordon Reeves et al. (2018) reviewed literature on riparian microclimate and concluded that considerable uncertainties remain about the size of RMZs. These uncertainties have substantial implications when considering changes in RMZ width in Northwest Forest Plan reserves. Designating too wide of a RMZ can result in loss of economic value, and designating too narrow of a RMZ can result in ecological degradation. Therefore, it is important to consider the breadth of existing literature before considering a RMZ width reduction or modification.

The magnitude of change in riparian microclimate due to adjacent timber harvesting has been found to be largely dependent on RMZ width (Brosofske et al., 1997; Chen et al., 1993, 1995; Davis-Colley et al., 2000; Spittlehouse et al., 2004). Because of the distinction distance has in RMZ guidelines and designation, its importance has widely been recognized by researchers and land managers. Despite distance from stream not being found to be a as strong of a predictor for microclimate as height above stream in this study, it is important that it not be unappreciated for its role in protecting a number of riparian values, including habitat preservation. RMZs defined by distance from stream have been found to effectively support instream vertebrate communities and amphibians residing on stream banks (Olson et al., 2014), as well as a number of other riparian processes. Therefore, it is not my recommendation that height above stream replace distance from stream in buffer designation guidelines, but rather it be considered in conjunction with distance. Approaching RMZ designation and management with a well-rounded understanding and consideration of the complexities of riparian and aquatic systems could yield more ecologically resilient forestlands.

Limitations

There are several limitations to this study that should be considered before these findings be integrated as management decisions. This study examined microclimate variables across 20 transects adjacent to timber harvest before harvest activities occurred. Without post-harvest data, the full effects of management on microclimate cannot be quantified. Additionally, this study did not examine dependent microclimate variables other than humidity (or VPD) and air temperature. Wind speed, soil temperature, and moisture are other important microclimate variables that should be considered when considering a comprehensive look at riparian microclimate. These limitations do not devalue this study, but rather serve as points of caution and reminders as to what research yet needs to be done.

Conclusion and Research Direction

This study found support for the hypotheses that solar radiation and height above stream influence riparian microclimate, while also challenging the notion that shade is consistently a strong predictor of microclimate. These findings are significant, since research in microclimate has lagged behind other aspects of riparian science. For example, stream temperatures have been the focal point of numerous studies, but few studies have examined temperatures spanning adjacent terrestrial area. Therefore, these findings add to the limited research on the ecological drivers of microclimate in riparian systems. Future research on the influence of harvesting on microclimate will be imperative to continuing to understand the complexities of riparian areas that are important to consider when designing RMZs.

Although height above stream was consistently found to be a better predictor of riparian microclimate than distance from stream in this study, distance can and should be used if height data is not acquirable. It is important to consider, however, that with today's exceptional LiDAR (light detection and ranging) coverage, it is now possible to identify height data for almost every square foot of riparian land. As LiDAR technology continues to become accessible to land managers, height data will become available and can be considered when designating RMZs.

Future studies should further examine this relationship between height and microclimate in RMZs. Perhaps instead of collecting canopy closure data, future research could examine tree height as it relates to microclimate. Additionally, future studies should explore spatial variations using metrics other than just maximum values to understand the full extent of the variability persisting across localized areas. Research examining the influence of adjacent timber harvesting on microclimate is also imperative. Examining changes in riparian microclimate and other riparian values pre- and post-harvest is rare, with Brosofske et al. (1997) and Bisson et al. (2013) providing some of the most robust, yet limited, studies investigating these changes.

With all of this in mind, it is important to reiterate that it not my recommendation that height above stream be used in lieu of distance, but instead in conjunction with distance when designating RMZs. It is important, however, to consider the scope of this study, which does not include the influence of timber harvest on microclimate gradients. Therefore, applying this research into management prescriptions should be done so with caution. Overall understanding of riparian microclimate remains limited, and further research should seek to offer support for existing research while answering new questions about the ecological drivers of microclimate and the extent to which these variables influence microclimate gradients.

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CHAPTER 4: APPENDICES

This final chapter provides supplemental material that was not presented in previous chapters of this thesis. The first section, Appendix A, contains various information related to WADNR's OESF *Status and Trends Monitoring of Riparian and Aquatic Habitat in the OESF* project. This includes the microclimate field installation form and information consequential to the microclimate gradients modeled in WADNR's OESF Final Environmental Impact Statement. Appendix B provides data and raster outputs resulting from the solar radiation analysis. Appendix C contains information related to the percent canopy closure analysis. Appendix D presents the statistical tests completed to check assumptions of the multivariate models. These tests include checking for similar variance and checking the normality of model residuals. Finally, Appendix E presents the full mixed multivariate model output tables. The tables include information for all three dependent variables (mean maximum air temperature, mean maximum vapor pressure deficit, and cumulative degree days) with height included and with distance included, for a total of six output tables. Together, these appendices offer information needed to understand the full richness and broader implications of this thesis research.

Appendix A: OESF Methods & Models

Date:		Watershed:	Crew:	
Transect #1		Transect azimuth (bet. 0- and 60-m stations) (deg.):		
Crossection:		Bank:	Recording Interval: 2hr	
Azimuth from x-sec. monument to 0-m station:				
Dist. from x-sec. monument to 0-m station:				
Distance(m):	Serial #:	Logger Name:	Elevation difference (+ or -) measured at base of each post:	
0				(monument to 0-m station)
10				(from 0-m to 10-m station)
20				(from 10-m to 20-m station)
40				(from 20-m to 40-m station)
60				(from 40-m to 60-m station)
Transect #2		Transect azimuth (bet. 0- and 60-m stations) (deg.):		
Crossection:		Bank:	Recording Interval: 2hr	
Azimuth from x-sec. monument to 0-m station:				
Dist. from x-sec. monument to 0-m station:				
Distance(m):	Serial #:	Logger Name:	Elevation difference (+ or -) measured at base of each post:	
0				(monument to 0-m station)
10				(from 0-m to 10-m station)
20				(from 10-m to 20-m station)
40				(from 20-m to 40-m station)
60				(from 40-m to 60-m station)
Camera #:	Photos #:			
General Notes:				

Figure A.1. Riparian microclimate installation field form. From: Minkova, T. and A. Foster (Eds.). (2017). Status and Trends Monitoring of Riparian and Aquatic Habitat in the Olympic Experimental State Forest: Monitoring Protocols. Washington State Department of Natural Resources, Forest Resources Division, Olympia, WA.

Table A.1. **Equations for microclimate gradients for select variables.**
From: Washington State Department of Natural Resources. (2016a). Olympic Experimental State Forest HCP Planning Unit Forest Land Plan Final Environmental Impact Statement. Washington State Department of Natural Resources, Olympia, WA. *http://file.dnr.wa.gov/publications/amp_sepa_nonpro_oesf_feis.pdf*

Parameter	Maximum extent of gradient (feet)	Equation (x measured from the edge of the floodplain for Type 1-4 streams, or the edge of the stream channel for Type 5 and 9 streams)	Units		Source
			X	Y	
Daytime air temperature	Floodplain + 164 feet	$y = 0.000000553141472013225x^3 - 0.000254873390545266x^2 + 0.0452130262626149x - 2.99999999999999$	Feet	°C	Brosofske and others (1997)
Daytime soil temperature	Floodplain + 164 feet	$y = 0.00000911158085003185x^2 + 0.00616189357086708x - 1.2447561460419$	Feet	°C	Brosofske and others (1997)
Daytime relative humidity	Floodplain + 122 feet	$y = 0.000521626779968096x^2 - 0.145659074960127x + 9.99999999999998$	Feet	Percent (partial pressure / saturated vapor pressure)	Brosofske and others (1997)
Harvest-edge daytime air temperature (0 to 10 years from harvest)	418 feet	$y = 0.00000000000000052294204195x^6 - 0.00000000000059188283954701x^5 + 0.000000000214176225131555x^4 - 0.0000000221164868660292x^3 + 0.0000214816397332562x^2 - 0.0243238241318835x + 4.8808147928371$	Feet	°C	Interpreted from FEMAT (1993), Chen (1991), and Chen and others (1995)
Harvest edge daytime air temperature (attenuated, 10 – 20 years from harvest)	296 feet	$y = 0.000000000000000295820691517x^6 - 0.00000000000236753136084030x^5 + 0.000000000605781845527758x^4 - 0.000000442329738763875x^3 + 0.000030379626376198x^2 - 0.0243238241395183x + 3.45125723816118$	Feet	°C	Interpreted and modified from FEMAT (1993), Chen (1991), and Chen and others (1995)
Harvest edge daytime soil temperature (0 to 10 years of harvest)	261 feet	$y = -0.0000000000000005901845885713x^6 + 0.00000000000498821033543454x^5 - 0.000000158757294155167x^4 + 0.0000223854299110648x^3 - 0.000942809923592858x^2 - 0.0949935454213033x + 10.3956074986478$	Feet	°C	Interpreted from FEMAT (1993), Chen (1991), and Chen and others (1995)

Parameter	Maximum extent of gradient (feet)	Equation (x measured from the edge of the floodplain for Type 1-4 streams, or the edge of the stream channel for Type 5 and 9 streams)	Units		Source
			X	Y	
Harvest edge daytime soil temperature (attenuated, 10 to 20 years from harvest)	185 feet	$y = -0.0000000000033385882201958x^6 + 0.00000000199528414670482x^5 - 0.000000449033439681168x^4 + 0.0000447708600790908x^3 - 0.00133333459194951x^2 - 0.0949935452435966x + 7.35080455647197$	Feet	°C	Interpreted and modified from FEMAT (1993), Chen (1991), and Chen and others (1995)
Harvest edge daytime relative humidity (0 to 10 years from harvest)	545 feet	$y = -0.00000000000000033142546817x^6 + 0.00000000000044037764960245x^5 - 0.000000000221815355319621x^4 + 0.0000000524934395233073x^3 - 0.0000576257233988464x^2 + 0.0483763379590982x - 23.4487968414528$	Feet	Percent (partial pressure / saturated vapor pressure)	Interpreted from FEMAT (1993), Chen (1991), and Chen and others (1995)
Harvest edge daytime relative humidity (attenuated, 10 to 20 years from harvest)	385 feet	$y = -0.0000000000000187482557116x^6 + 0.0000000000176151060221084x^5 - 0.00000000627388569373298x^4 + 0.00000104986879369273x^3 - 0.0000814950796197422x^2 + 0.0483763379109234x - 16.5808032547911$	Feet	Percent (partial pressure / saturated vapor pressure)	Interpreted and modified from FEMAT (1993), Chen (1991), and Chen and others (1995)

Table A.2: The initial list of Type 3 watersheds selected for sampling in the OESF. *From: Minkova T., J. Ricklefs, S. Horton, and R. Bigley. (2012). Riparian Status and Trends Monitoring for the Olympic Experimental State Forest. Draft Study Plan. WADNR Forest Resources Division, Olympia, WA. 61 p.*

#	Basin ID	Percent DNR ownership	DNR acres	Total acres	Median gradient	Gradient stratum
1	698	77%	201	261	0	0 – 9%
2	627	67%	480	718	4	0 – 9%
3	846	100%	1,791	1,791	4	0 – 9%
4	642	100%	263	263	5	0 – 9%
5	550	53%	246	464	6	0 – 9%
6	630	89%	1,228	1,379	8	0 – 9%
7	658	72%	550	764	9	0 – 9%
8	568	100%	463	463	11	10 – 19%
9	796	88%	1,552	1,764	11	10 – 19%
10	721	66%	807	1,215	15	10 – 19%
11	192	64%	473	738	16	10 – 19%
12	463	53%	61	115	17	10 – 19%
13	583	62%	934	1,509	18	10 – 19%
14	523	100%	2,037	2,037	18	10 – 19%
15	582	100%	181	181	19	10 – 19%
16	498	93%	1,473	1,585	19	10 – 19%
17	467	60%	43	71	20	20 – 29%
18	460	100%	128	128	21	20 – 29%
19	370	54%	276	511	21	20 – 29%
20	544	100%	126	126	21	20 – 29%
21	834	74%	36	49	23	20 – 29%
22	597	67%	565	837	24	20 – 29%
23	608	82%	339	415	24	20 – 29%
24	65	54%	285	524	26	20 – 29%
25	158	100%	519	519	26	20 – 29%
26	763	78%	342	439	31	30 – 39%
27	497	87%	433	499	33	30 – 39%
28	488	54%	171	318	33	30 – 39%
29	798	100%	327	327	34	30 – 39%
30	136	75%	257	341	36	30 – 39%
31	712	100%	475	475	38	30 – 39%
32	790	100%	849	849	39	30 – 39%
33	717	100%	150	150	42	40 – 49%
34	577	83%	821	992	44	40 – 49%
35	724	100%	177	177	46	40 – 49%
36	776	100%	176	176	48	40 – 49%
37	625	100%	537	537	49	40 – 49%
38	576	71%	646	908	50	50 – 59%
39	773	100%	414	414	53	50 – 59%
40	654	100%	1,503	1,503	53	50 – 59%
41	697	100%	1,434	1,434	55	50 – 59%
42	750	100%	298	298	56	50 – 59%
43	687	100%	736	736	57	50 – 59%
44	635	100%	318	318	60	60 – 69%
45	639	100%	327	327	61	60 – 69%
46	653	100%	149	149	64	60 – 69%
47	844	99%	700	709	4	0 – 9%
48	542	100%	382	382	17	10 – 19%
49	443	51%	183	359	20	20 – 29%
50	730	87%	775	895	39	30 –39%

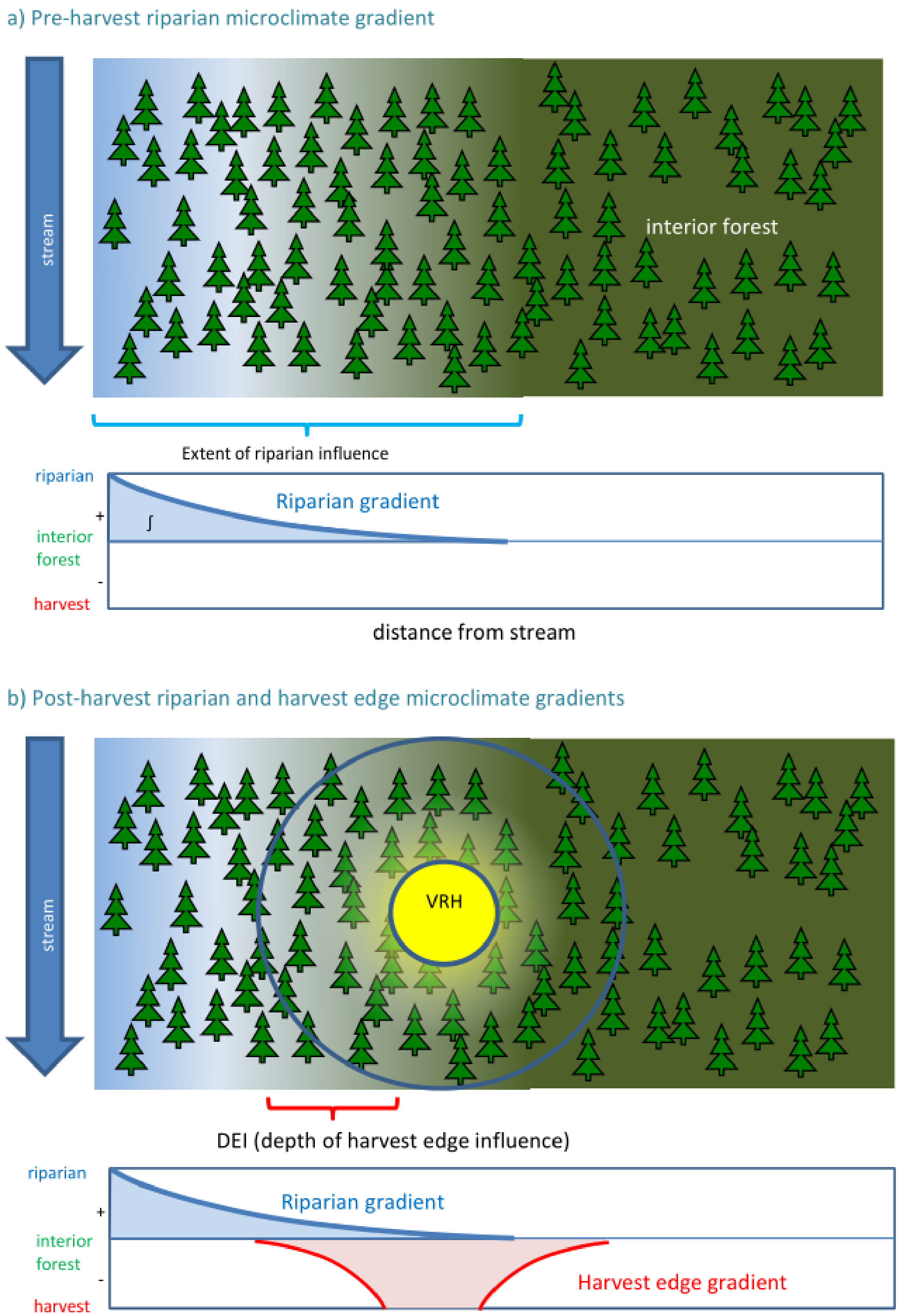


Figure A.2. Microclimate gradients as modeled in the OESF Final Environmental Impact Statement. *From: Washington State Department of Natural Resources. (2016a). Olympic Experimental State Forest HCP Planning Unit Forest Land Plan Final Environmental Impact Statement. Washington State Department of Natural Resources, Olympia, WA.* *http://file.dnr.wa.gov/publications/amp_sepa_nonpro_oesf_feis.pdf*

Appendix B: Solar Radiation Analysis

Table B.1: Solar exposure data (in WH/m2) for each datalogger location (Jan-Jun). *Data are from the 15th day of each month for January-June, 2015.*

BasinID	Distance	solar0115	solar0215	solar0315	solar0415	solar0515	solar0615
145LA	0	246.632	745.077	1743.15	3226.89	4492.74	5121.66
145LA	10	204.565	648.046	1583.56	3035.77	4305.05	4945.97
145LA	20	204.565	648.046	1583.56	3035.77	4305.05	4945.97
145LA	40	160.823	559.395	1413.14	2824.02	4091.8	4742.51
145LA	60	159.476	486.064	1289.92	2676.26	3955.83	4616.75
145RC	0	201.068	682.793	1676.56	3160.24	4419.04	5049.51
145RC	10	266.854	804.059	1854.99	3380.82	4637.04	5239.34
145RC	20	335.606	971.486	2113.7	3658.2	4861.12	5425.32
145RC	40	423.434	1144.64	2340.53	3857.36	4981.27	5489.35
145RC	60	518.884	1280.63	2488.02	3937.7	4954.81	5398.85
157LE	0	381.519	984.483	2088.77	3631.76	4876.4	5473.87
157LE	10	449.556	1112.36	2270.97	3819.34	5019.79	5585.36
157LE	20	449.556	1112.36	2270.97	3819.34	5019.79	5585.36
157LE	40	506.592	1214.12	2399.7	3922.3	5067.21	5590.34
157LE	60	481.031	1163.87	2327.33	3844.22	4996.95	5529.61
157RF	0	267.609	766.154	1765.31	3270.65	4560.01	5197.39
157RF	10	267.609	766.154	1765.31	3270.65	4560.01	5197.39
157RF	20	163.724	628.817	1556.32	3022.56	4321.74	4977.97
157RF	40	184.794	586.873	1486.42	2939.39	4242.09	4904.59
157RF	60	235.089	697.639	1664.55	3153.88	4452.15	5102.29
196LE	0	343.145	889.317	2052.78	3565.79	4766.51	5350.38
196LE	10	345.745	877.149	2008.08	3451.9	4600.73	5149.88
196LE	20	345.745	877.149	2008.08	3451.9	4600.73	5149.88
196LE	40	324.27	840.221	1888.91	3319.11	4476.56	5036.4
196LE	60	317.807	834.552	1870.28	3316.11	4494.08	5067.53
196RC	0	303.238	870.904	1926.79	3431.86	4665.88	5271.75
196RC	10	303.238	870.904	1926.79	3431.86	4665.88	5271.75
196RC	20	302.869	864.015	1899.71	3380.03	4592.65	5179.95
196RC	40	298.096	844.535	1863.94	3317.76	4517.83	5097.94
196RC	60	321.809	887.626	1901.94	3321.07	4478.44	5030.26
433LC	0	335.141	893.655	1954.52	3489.85	4764.57	5385.51
433LC	10	359.97	941.805	2026.23	3570.32	4836.21	5448.11
433LC	20	359.97	941.805	2026.23	3570.32	4836.21	5448.11
433LC	40	395.191	1009.81	2126.16	3679.52	4929.58	5526.96
433LC	60	400.599	1020.25	2141.54	3695.85	4943.13	5538.13
433LE	0	405.555	1029.25	2154.34	3708.73	4952.19	5544.39
433LE	10	400.461	1019.57	2140.53	3694.4	4941.07	5535.9
433LE	20	392.294	1004.1	2117.88	3669.85	4920.33	5518.61

433LE	40	403.139	1024.95	2148.25	3702.38	4947.51	5541.05
433LE	60	416.126	1050.1	2184.58	3740.63	4978.43	5565.76
545LA	0	479.049	1167.73	2353.25	3918.64	5123.23	5682.96
545LA	10	479.049	1167.73	2353.25	3918.64	5123.23	5682.96
545LA	20	491.908	1191.77	2387	3952.28	5147.85	5700.6
545LA	40	499.508	1205.88	2406.55	3971.26	5161.03	5709.42
545LA	60	501.93	1210.31	2412.55	3976.78	5164.4	5711.23
545RF	0	470.296	1149.59	2324.92	3884.21	5089.81	5651.54
545RF	10	470.296	1149.59	2324.92	3884.21	5089.81	5651.54
545RF	20	480.305	1169.71	2356.71	3923.27	5129.75	5689.58
545RF	40	495.809	1198.7	2397.19	3963.52	5159.3	5710.13
545RF	60	503.186	1210.85	2408.27	3966.74	5146.21	5689.88
642LD	0	448.287	1097.61	2220.54	3716.9	4887.2	5432.18
642LD	10	448.287	1097.61	2220.54	3716.9	4887.2	5432.18
642LD	20	447.431	1104.59	2248.4	3772.68	4970.91	5532.77
642LD	40	412.348	1042.06	2169.18	3724.25	4973.39	5565.49
642LD	60	340.449	903.662	1968.57	3510.94	4794.84	5419.54
642RF	0	416.609	1102	2315.02	3841.22	4993.43	5538.15
642RF	10	459.541	1151.71	2292.5	3742.75	4835.56	5329
642RF	20	450.937	1098.83	2181.79	3588.43	4646.69	5126.9
642RF	40	445.64	1082.69	2179.41	3626.77	4743.72	5264.73
642RF	60	441.895	1097.65	2258.01	3834.15	5078.49	5666.79
694LE	0	151.319	711.99	1851.56	3413.23	4680.13	5275.31
694LE	10	145.718	522.083	1384.12	2674.23	3876.68	4494.58
694LE	20	145.718	522.083	1384.12	2674.23	3876.68	4494.58
694LE	40	147.168	519.622	1450.42	2772.21	3960.58	4567.91
694LE	60	148.958	503.698	1380.91	2667.41	3864.08	4483.73
694RC	0	184.261	844.822	2178.19	3867.56	5053.47	5579.42
694RC	10	300.503	1120.12	2447.83	3910.93	4942.79	5326.62
694RC	20	438.546	1298.52	2580.33	4002.37	4931.39	5262.06
694RC	40	598.031	1423.23	2692.66	4216.14	5198.54	5578.05
694RC	60	629.96	1458.15	2714.73	4244.78	5236.11	5623.77
724LC	0	416.344	1031.65	2129.17	3711.7	4961.55	5537.41
724LC	10	375.769	953.25	2018.29	3573.79	4823.14	5411.92
724LC	20	375.769	953.25	2018.29	3573.79	4823.14	5411.92
724LC	40	324.01	847.174	1846.32	3332.91	4554.77	5146.43
724LC	60	270.706	732.873	1657.55	3043.21	4235.05	4822.56
724RF	0	528.579	1277.92	2539.53	4110.01	5220.63	5706.48
724RF	10	552.125	1305.2	2568.46	4129.12	5242.09	5730.21
724RF	20	559.344	1323.19	2591.56	4148.48	5259.11	5745.67
724RF	40	563.945	1319.7	2573.43	4131.92	5255.6	5754.03
724RF	60	568.272	1333.04	2587	4139.58	5256.49	5751.4
737LD	0	427.163	1212.07	2512.13	4068.14	5219.35	5743.13
737LD	10	461.062	1256	2552.85	4001.13	5045.19	5503.32

737LD	20	487.147	1275.47	2571.04	4018.04	5020.38	5461.64
737LD	40	474.708	1264.88	2577.69	4101.88	5207.9	5699.89
737LD	60	435.21	1204.8	2492.95	4062.9	5237.13	5774.74
737RE	0	430.115	1210.91	2500.19	4068.35	5241.64	5774.85
737RE	10	423.08	1186.88	2463.5	4030.13	5211.61	5755.69
737RE	20	423.08	1186.88	2463.5	4030.13	5211.61	5755.69
737RE	40	424.06	1164.21	2443.81	4027.19	5221.65	5775.81
737RE	60	413.104	1123.36	2387.34	3973.38	5184.19	5749.67
790LA	0	324.423	886.921	1989.17	3556.27	4834.65	5439.98
790LA	10	342.497	923.508	2065.03	3639.38	4901.29	5490.6
790LA	20	342.497	923.508	2065.03	3639.38	4901.29	5490.6
790LA	40	343.696	937.412	2065.12	3635.35	4873.52	5468.38
790LA	60	315.731	855.136	1878.4	3343.12	4530.7	5105.78
790RD	0	317.159	844.519	1910.39	3453.3	4685.95	5277.94
790RD	10	317.159	844.519	1910.39	3453.3	4685.95	5277.94
790RD	20	295.512	790.968	1791.55	3267.46	4494.75	5085.84
790RD	40	289.925	773.335	1743.2	3195.12	4387.34	4969.06
790RD	60	302.549	797.846	1780.36	3237.81	4432.71	5009.6

Table B.2: Solar exposure data (in WH/m2) for each datalogger location (Jul-Dec). *Data are from the 15th day of each month for July-December, 2015.*

BasinID	Distance	solar0715	solar0815	solar0915	solar1015	solar1115	solar1215
145LA	0	4872.98	3808.19	2319.48	1059.68	349.329	153.758
145LA	10	4694.77	3615.15	2143.54	937.279	297.113	122.456
145LA	20	4694.77	3615.15	2143.54	937.279	297.113	122.456
145LA	40	4486.65	3398.77	1949.74	814.956	247.341	119.652
145LA	60	4351.45	3254.67	1811.9	722.789	207.091	119.914
145RC	0	4801.44	3735.99	2250.81	994.383	304.238	118.611
145RC	10	5004.84	3961.43	2457.24	1140.46	377.192	171.488
145RC	20	5208.49	4225.66	2734.46	1350.04	482.995	223.182
145RC	40	5297.04	4393.88	2962.39	1543.68	592.414	289.787
145RC	60	5232.57	4425.18	3092.9	1698.43	705.313	366.032
157LE	0	5238.76	4212.09	2702.81	1341.4	516.243	265.613
157LE	10	5363.1	4380.19	2895.66	1492.9	599.526	317.84
157LE	20	5363.1	4380.19	2895.66	1492.9	599.526	317.84
157LE	40	5384.18	4462.32	3017.81	1607.47	668.521	363.155
157LE	60	5319.48	4386.11	2943.69	1547.77	637.746	344.625
157RF	0	4943.96	3862.42	2351.22	1080.17	376.136	181.858
157RF	10	4943.96	3862.42	2351.22	1080.17	376.136	181.858
157RF	20	4715.11	3614.48	2119.21	911.647	274.627	123.216
157RF	40	4638.84	3531.45	2041.5	861.087	265.905	125.319
157RF	60	4842.18	3747.62	2240.32	996.016	332.003	158.071
196LE	0	5127.62	4116.55	2658.71	1284.25	460.63	238.177
196LE	10	4941.15	3982.04	2581.4	1274.85	457.59	240.197
196LE	20	4941.15	3982.04	2581.4	1274.85	457.59	240.197
196LE	40	4815	3856.51	2458.54	1192.41	433.252	228.794
196LE	60	4841.44	3861.77	2445.48	1171.02	432.727	221.778
196RC	0	5039.7	3998.35	2515.39	1208.25	416.586	210.305
196RC	10	5039.7	3998.35	2515.39	1208.25	416.586	210.305
196RC	20	4951.13	3947.55	2488.25	1199.36	418.553	215.06
196RC	40	4876.79	3880.58	2437.34	1176.24	417.459	210.718
196RC	60	4818.37	3864.28	2464.35	1215.77	448.077	225.607
433LC	0	5138.57	4078.86	2559.14	1231.26	458.088	234.1
433LC	10	5205.12	4156.93	2637.18	1289.1	489.158	253.094
433LC	20	5205.12	4156.93	2637.18	1289.1	489.158	253.094
433LC	40	5290.28	4261.23	2744.98	1370.43	533.315	280.206
433LC	60	5302.48	4276.64	2761.32	1382.91	540.128	284.408
433LE	0	5309.95	4287.93	2774.61	1393.58	546.052	288.056
433LE	10	5300.32	4274.78	2760.09	1382.09	539.699	284.156
433LE	20	5281.54	4251.44	2735.74	1363.61	529.646	277.979
433LE	40	5306.02	4282.28	2768.29	1388.46	543.248	286.364
433LE	60	5333.41	4318.11	2807.03	1418.36	559.702	296.511

545LA	0	5462.45	4484.58	2986.8	1557.86	637.274	344.751
545LA	10	5462.45	4484.58	2986.8	1557.86	637.274	344.751
545LA	20	5483.07	4514.97	3022.11	1586.2	653.215	354.684
545LA	40	5493.75	4531.82	3042.39	1602.77	662.621	360.562
545LA	60	5496.21	4536.52	3048.52	1607.95	665.609	362.439
545RF	0	5430.03	4450.04	2955.17	1535.72	625.84	337.854
545RF	10	5430.03	4450.04	2955.17	1535.72	625.84	337.854
545RF	20	5469.21	4490.37	2990.6	1560.35	638.509	345.541
545RF	40	5494.03	4526.94	3033.04	1594.49	657.738	357.561
545RF	60	5477.08	4523.63	3043.03	1607.37	666.656	363.514
642LD	0	5218.43	4266.12	2821.14	1465.97	596.505	321.442
642LD	10	5218.43	4266.12	2821.14	1465.97	596.505	321.442
642LD	20	5311.05	4332.22	2864.21	1479.43	599.099	321.478
642LD	40	5331.97	4306.78	2789.59	1407.66	553.595	291.327
642LD	60	5171.19	4103.02	2575.25	1243.87	464.61	236.326
642RF	0	5329.49	4386.89	2929.73	1511.85	572.534	289.96
642RF	10	5132.89	4260.24	2884.07	1544.35	618.644	332.185
642RF	20	4939.21	4088.86	2751.67	1460.31	599.088	327.706
642RF	40	5059.39	4149.03	2765.35	1443	591.422	320.166
642RF	60	5434.21	4415.27	2890.3	1475.83	590.7	316.005
694LE	0	5047.89	4006.8	2471.36	1061.56	250.353	114.264
694LE	10	4250.7	3223.62	1861.09	795.723	204.534	109.401
694LE	20	4250.7	3223.62	1861.09	795.723	204.534	109.401
694LE	40	4337.57	3311.15	1962.27	818.318	195.323	111.311
694LE	60	4248.42	3200.88	1865.61	769.191	202.734	112.679
694RC	0	5389.5	4448.85	2906.53	1285.56	282.154	121.435
694RC	10	5189.18	4420.35	3074.04	1604.23	460.889	188.061
694RC	20	5140.99	4472.47	3168.08	1766.39	647.95	296.656
694RC	40	5437.3	4702.18	3323.57	1881.62	799.592	424.751
694RC	60	5477.79	4737.64	3365.59	1920.54	826.998	455.327
724LC	0	5313.21	4297.33	2778.16	1394.32	556.851	298.771
724LC	10	5183.13	4156.23	2643.72	1299.96	503.309	264.252
724LC	20	5183.13	4156.23	2643.72	1299.96	503.309	264.252
724LC	40	4916.99	3895.52	2437.12	1169.39	438.89	226.469
724LC	60	4588.14	3592.88	2200.91	1027.81	370.352	187.688
724RF	0	5519.84	4643.23	3186.78	1716.99	702.719	377.555
724RF	10	5542.63	4663.48	3221.32	1736.07	722.117	392.986
724RF	20	5559.43	4682.32	3238.46	1753.67	735.106	400.379
724RF	40	5562.13	4669.03	3216.16	1742.36	736.422	407.159
724RF	60	5560.92	4673.59	3227.31	1756.19	743.459	411.962
737LD	0	5545.08	4621.31	3153.09	1666.48	608.544	246.855
737LD	10	5329.99	4507.41	3152.21	1721.49	654.412	269.624
737LD	20	5296.22	4505.42	3178.65	1753.16	679.318	286.04
737LD	40	5510.1	4631.14	3208.45	1742.61	649.555	295.887

737LD	60	5568.28	4619.82	3134.71	1663.28	598.12	280.142
737RE	0	5570.99	4624.77	3142.75	1651.19	600.869	236.903
737RE	10	5548.19	4588.62	3104.71	1624.11	585.156	234.194
737RE	20	5548.19	4588.62	3104.71	1624.11	585.156	234.194
737RE	40	5563.57	4591.3	3088.07	1599.12	592.042	279.291
737RE	60	5533.08	4544.29	3030.91	1547.7	571.844	256.419
790LA	0	5196.6	4156.62	2619.44	1261.72	446.956	223.681
790LA	10	5261.51	4230.91	2690.85	1305.15	471.348	239.099
790LA	20	5261.51	4230.91	2690.85	1305.15	471.348	239.099
790LA	40	5235.12	4208.66	2687.39	1297.42	476.62	241.843
790LA	60	4876.62	3892.09	2469.15	1173.3	439.681	223.739
790RD	0	5054.42	4025.38	2520.8	1176.28	437.505	223.579
790RD	10	5054.42	4025.38	2520.8	1176.28	437.505	223.579
790RD	20	4846.71	3840.74	2387.02	1096.92	401.285	202.993
790RD	40	4746.32	3744.26	2324.43	1073.04	395.653	203.462
790RD	60	4789.05	3785.89	2359.6	1112.18	412.113	216.019

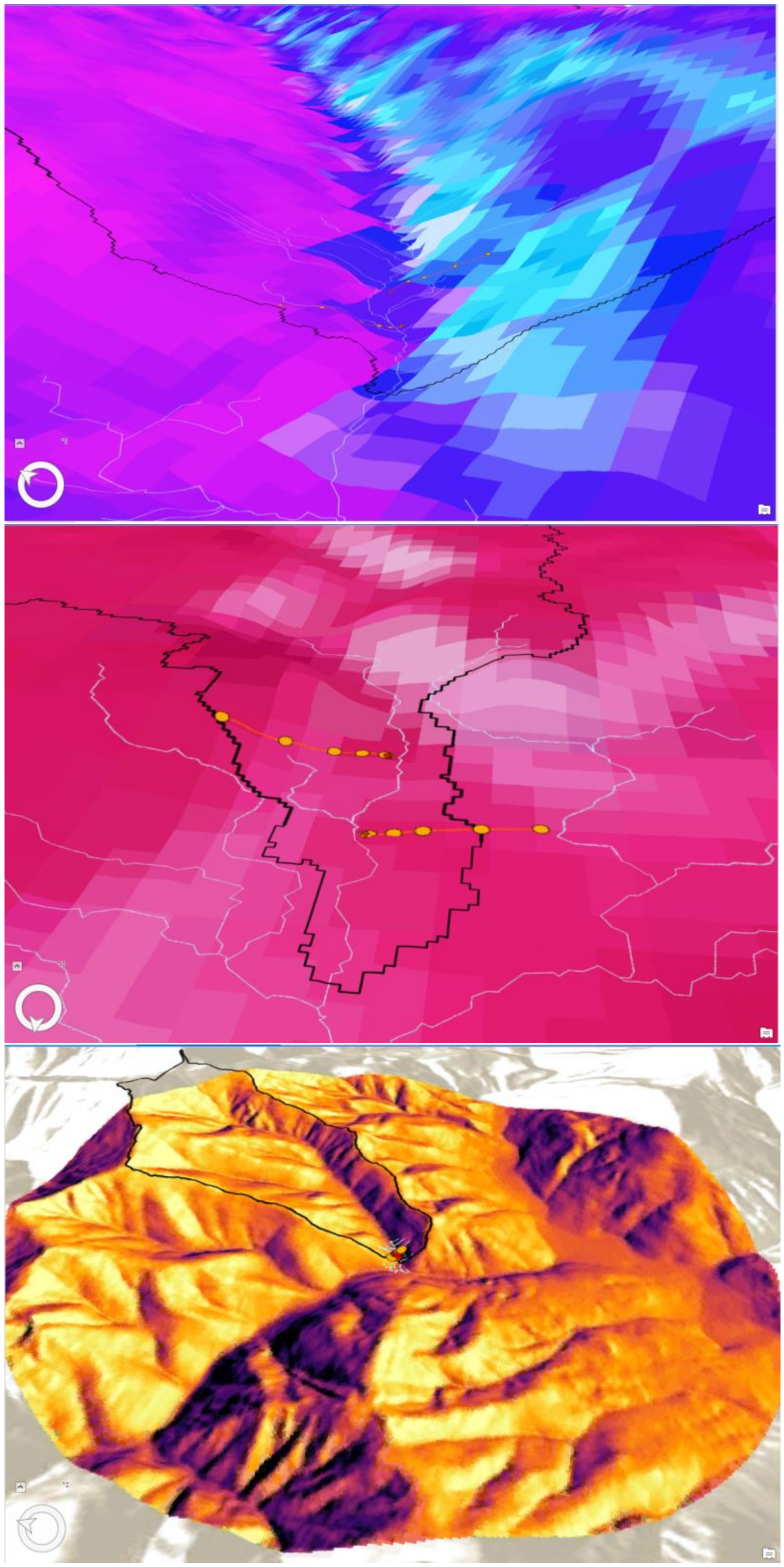


Figure B.1. Examples of the solar radiation analysis output rasters. Solar radiation analysis was conducted in ArcGIS using the Area Solar Radiation tool. For all three examples, the darker the color, the more solar radiation was received at that raster pixel.

Appendix C: Percent Canopy Closure Analysis

Table C.1: Hemisfer software settings chosen for hemispherical canopy photo analysis.

From WADNR's shade monitoring protocol. From: Minkova, T. and A. Foster (Eds.). (2017). Status and Trends Monitoring of Riparian and Aquatic Habitat in the Olympic Experimental State Forest: Monitoring Protocols. Washington State Department of Natural Resources, Forest Resources Division, Olympia, WA.

Parameter class	Parameter	Setting	Reason for setting
Image registration	Center x	1142	Determined by carefully examining images and fitting a circle to the perimeter of the hemispherical photograph.
	Center y	870	
	Radius	800	
	North, Declination, Slope, Aspect	0	We do not need to adjust these settings for the current analysis.
	Rings	1	For this analysis, we are not using multiple rings.
	Width	90	90 degrees represents the full hemisphere.
	Sectors	1	We are not using separate sectors in this analysis.
Site	All parameters	Leave either blank or zero.	We do not use these settings for our analysis.
Lens	Lens	Nikon FC-E8	This is the lens used for our photographs.
Colours	Red, Green, Blue	Red=0; Green=0; Blue=100	In the literature, the blue band is widely regarded as the best choice for image analysis.
Threshold	Minimum, maximum	Minimum=64; Maximum=255	Default setting.
	Gamma	1.0	This setting was used in previous DNR analyses (2007) and it seems to produce the most reasonable threshold values in the current set of photos.
	Threshold	Automatic detection	Permits batch processing by calculating a specific threshold value for each photo in the batch.
	Threshold method	Nobis & Hunziker (2005)	Regarded in the literature as the best method currently available.
Results	Level of detail	Full results	This gives detailed output, including the total count of pixels and the total count of white and black pixels.

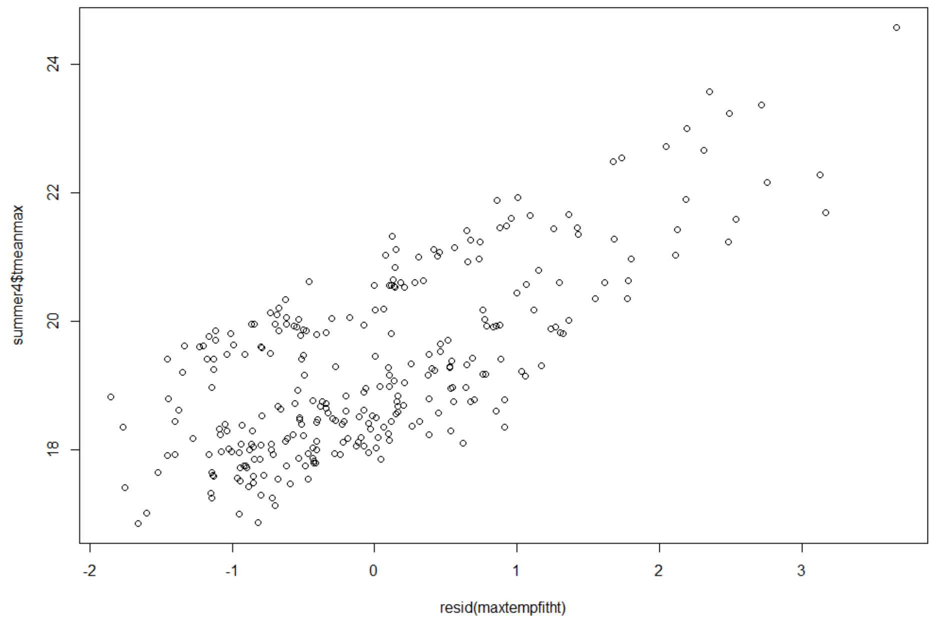
Table C.2: Canopy closure data for each of the microclimate sites.
Basin 145 Right C at 10m, was rejected due to shrubs covering the camera, resulting in no view of canopy. Percent shade was 98.26% for this site, and was interpolated to be 90.86%.

Basin	Bank	Cross Section	Sample Plot	Black Pixels (Percent)
145	Left	A	0	92.02
145	Left	A	10	91.73
145	Left	A	20	92.17
145	Left	A	40	92.7
145	Left	A	60	90.59
145	Right	C	0	90.28
145	Right	C	10	90.86
145	Right	C	20	91.43
145	Right	C	40	90.67
145	Right	C	60	92.25
157	Left	E	0	94.48
157	Left	E	10	91.62
157	Left	E	20	90.22
157	Left	E	40	90.77
157	Left	E	60	89.35
157	Right	F	0	90.32
157	Right	F	10	91.68
157	Right	F	20	91.91
157	Right	F	40	92.37
157	Right	F	60	92.23
196	Left	E	0	94.76
196	Left	E	10	93.79
196	Left	E	20	92.99
196	Left	E	40	91.2
196	Left	E	60	90.14
196	Right	C	0	92.29
196	Right	C	10	93.19
196	Right	C	20	93.02
196	Right	C	40	93.05
196	Right	C	60	86.93
433	Left	C	0	93.7
433	Left	C	10	93.62
433	Left	C	20	94.81
433	Left	C	40	92.74
433	Left	C	60	93.61
433	Left	E	0	93.77
433	Left	E	10	95.54

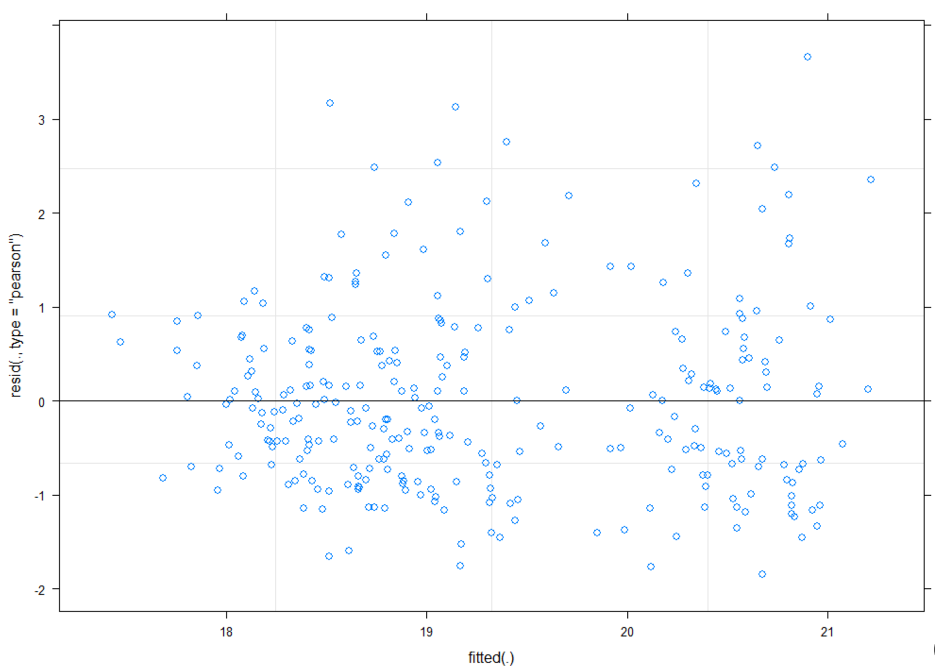
433	Left	E	20	90.95
433	Left	E	40	90.35
433	Left	E	60	87.4
545	Left	A	0	91.1
545	Left	A	10	90.09
545	Left	A	20	92.39
545	Left	A	40	92.16
545	Left	A	60	89.46
545	Right	F	0	93.24
545	Right	F	10	91.8
545	Right	F	20	93.49
545	Right	F	40	92.66
545	Right	F	60	90.36
642	Left	D	0	92.54
642	Left	D	10	89.35
642	Left	D	20	90.51
642	Left	D	40	91.8
642	Left	D	60	90.33
642	Right	F	0	91.44
642	Right	F	10	92.4
642	Right	F	20	89.38
642	Right	F	40	91.26
642	Right	F	60	89.34
694	Left	E	0	92.8
694	Left	E	10	91.2
694	Left	E	20	95.34
694	Left	E	40	91.68
694	Left	E	60	89.91
694	Right	C	0	94.49
694	Right	C	10	91.29
694	Right	C	20	94.43
694	Right	C	40	91.48
694	Right	C	60	97.65
724	Left	C	0	95.79
724	Left	C	10	92.69
724	Left	C	20	95.11
724	Left	C	40	92.37
724	Left	C	60	93.5
724	Right	F	0	92.34
724	Right	F	10	92.16
724	Right	F	20	93.41
724	Right	F	40	93.48
724	Right	F	60	93.49

737	Left	D	0	91.75
737	Left	D	10	92.25
737	Left	D	20	91.12
737	Left	D	40	92.21
737	Left	D	60	91.93
737	Right	E	0	89.35
737	Right	E	10	95.75
737	Right	E	20	88.21
737	Right	E	40	88.97
737	Right	E	60	89.44
790	Left	A	0	92.97
790	Left	A	10	92.5
790	Left	A	20	93.15
790	Left	A	40	91.5
790	Left	A	60	91.14
790	Right	D	0	95.85
790	Right	D	10	93.76
790	Right	D	20	91.07
790	Right	D	40	93.4
790	Right	D	60	92.66

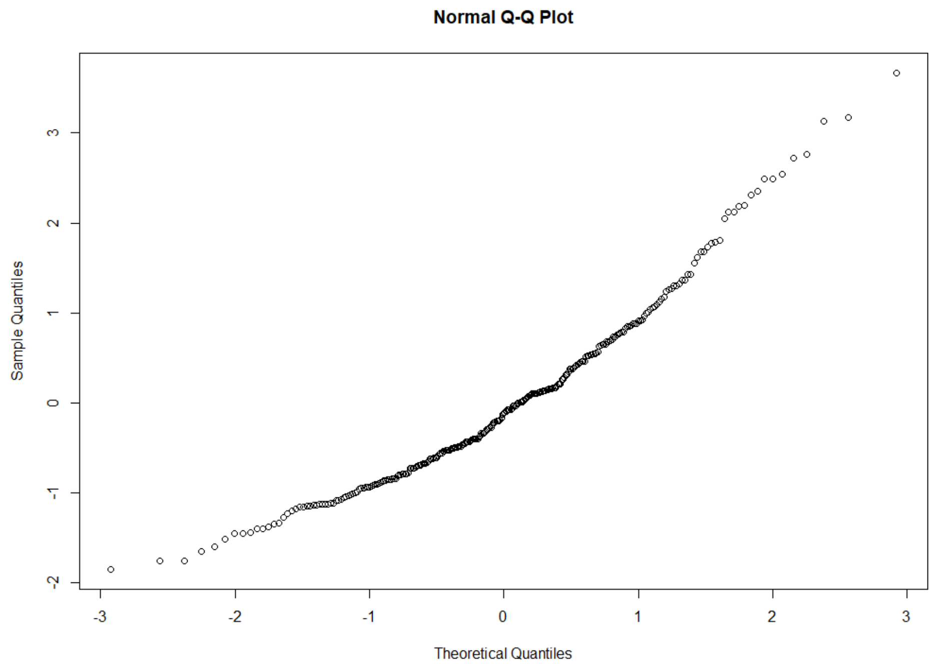
Appendix D: Checking Model Assumptions



(A)

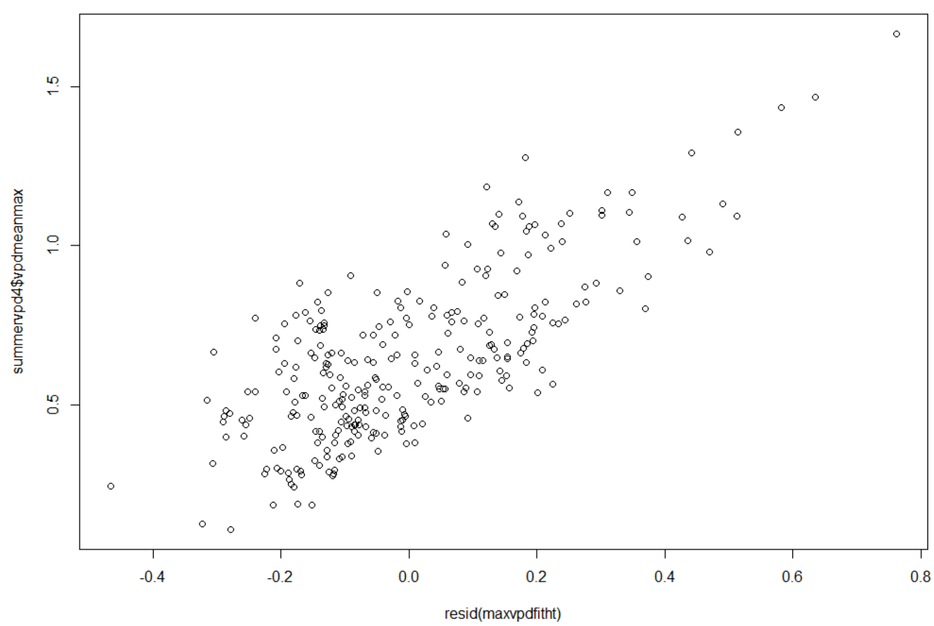


(B)

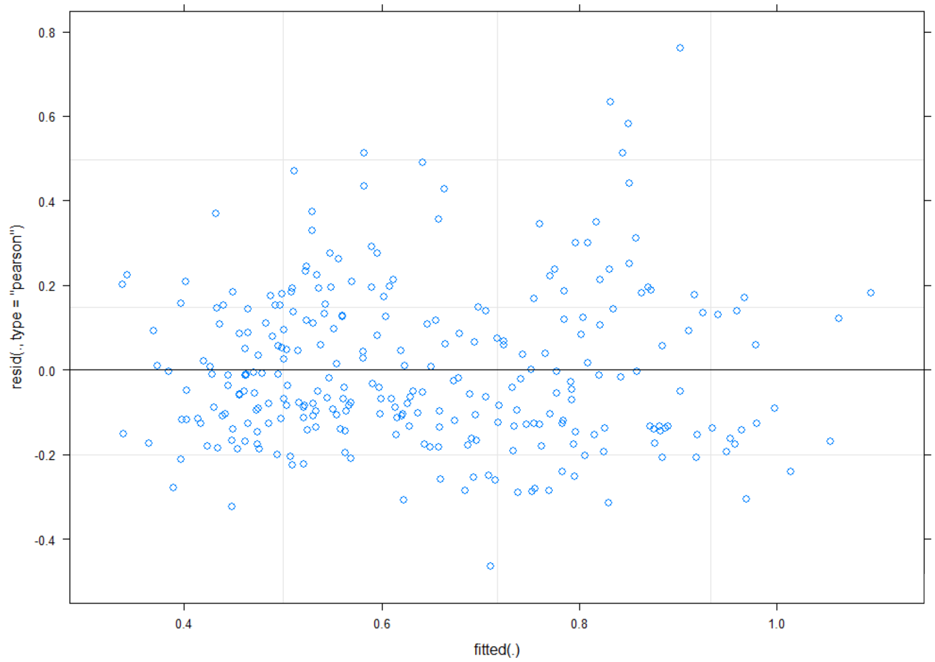


(C)

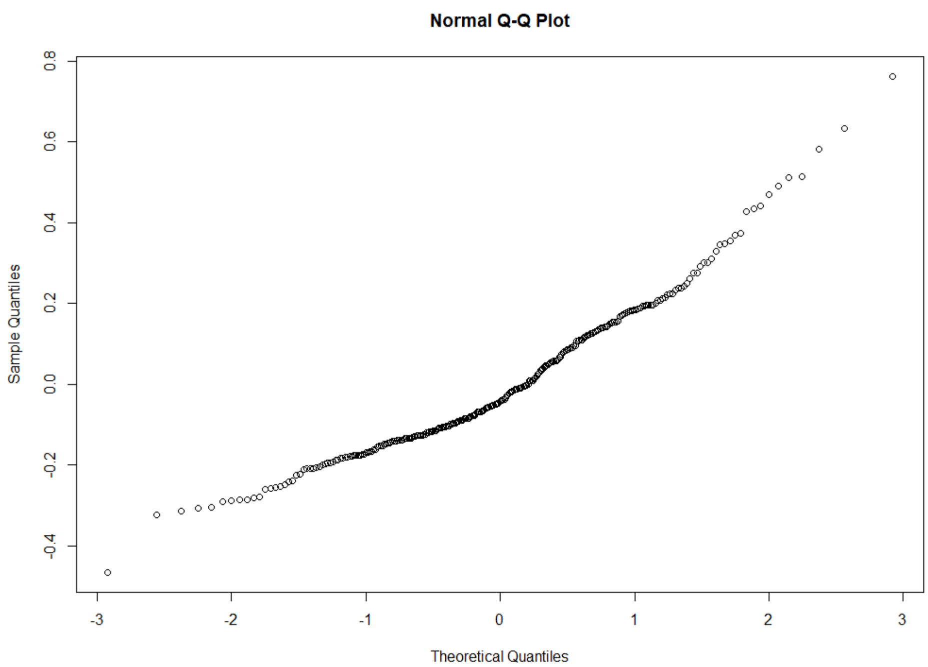
Figure D.1. Mean Maximum Air Temperature model assumption check. Checking model assumptions using the mixed model with height + solar + shade and the prepared air temperature data. Checking for similar variance (A) and checking normality of model residuals (B and C).



(A)

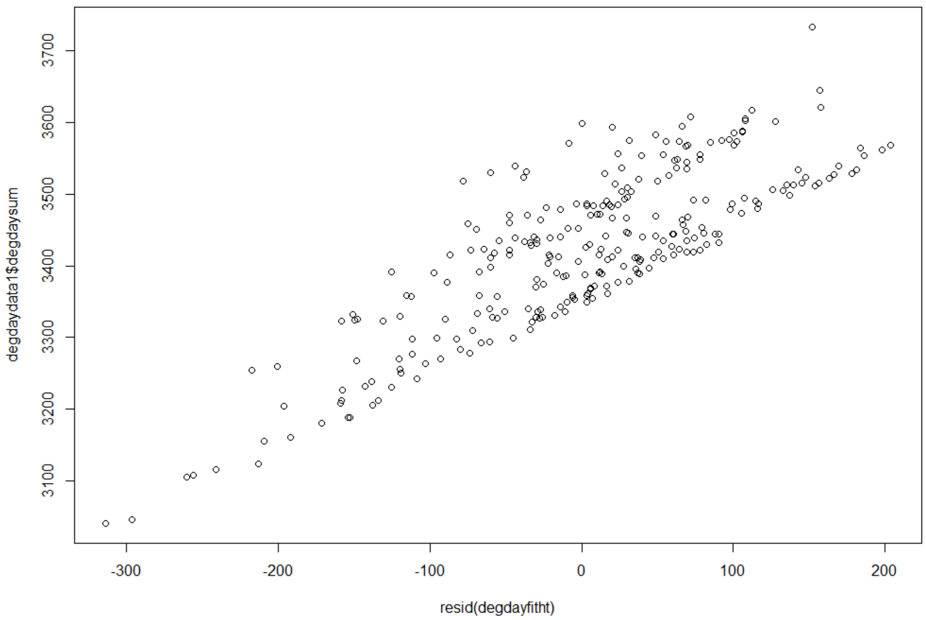


(B)

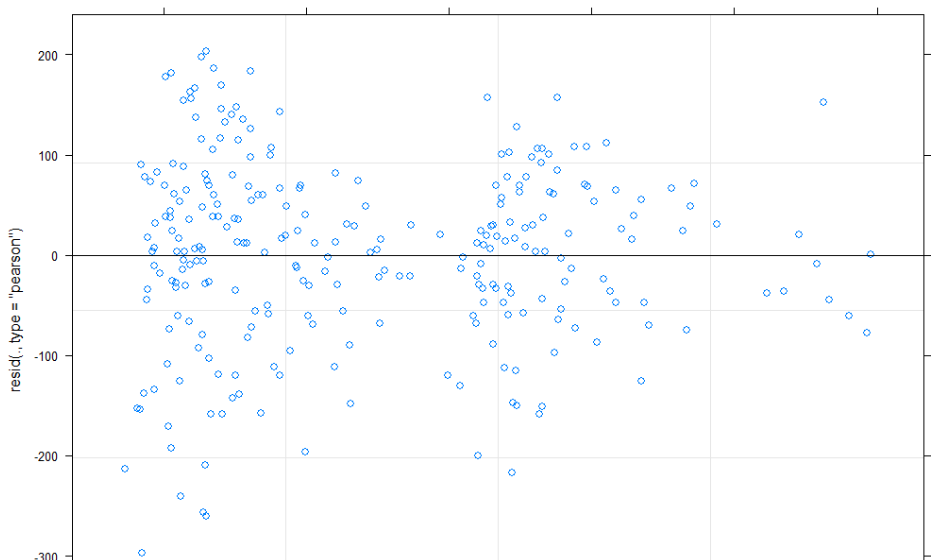


(C)

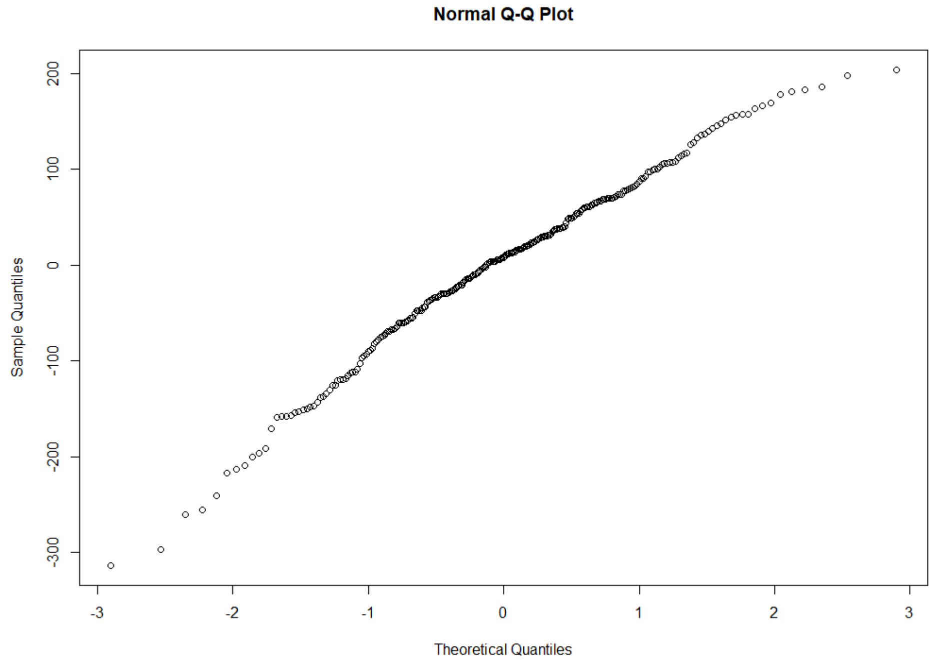
Figure D.2: Mean Maximum VPD model assumption check. Checking model assumptions using the mixed model with height + solar + shade and the prepared air vapor pressure deficit data. Checking for similar variance (A) and checking normality of model residuals (B and C).


degdaydata1$degdaysum
3100
3200
3300
3400
3500
3600
3700
-300
-200
-100
0
100
200
resid(degdayfitht)

(A)


resid(., type = "pearson")
200
100
0
-100
-200
-300
3350
3400
3450
3500
3550
3600
fitted(.)

(B)



(C)

Figure D.3: Cumulative degree days model assumption check. Checking model assumptions using the mixed model with height + solar + shade and the prepared degree days data. A) Checking for similar variance (A) normality of model residuals (B and C).

Appendix E: Mixed Multivariate Model Output Tables

Table E.1: Mean Maximum Air Temperature: Linear mixed model fit by maximum likelihood, with height above stream included.

AIC	BIC	LogLik	Deviance	Df residuals
836.1	858.1	-412.1	824.1	281

Scaled residuals:

Min	1Q	Median	3Q	Max
-1.8616	-0.7298	-0.1191	0.5470	3.6878

Random effects:

Groups	Variance	Standard Deviation
Year (Intercept)	0.8285	0.9102
Residual	0.9878	0.9939

Number of observations: 287
Groups: year, 3

Fixed effects:

	Estimate	Std. Error	df	t-value	*P*
Intercept	16.099692	3.159979	278.710163	5.095	5.095 6.44e-07***
Height	0.026578	0.007223	284.000434	3.680	0.000279***
Solar	0.953566	0.185796	284.001075	5.132	5.32e-07***
Shade	-0.018335	0.031718	284.000923	-0.578	0.563667

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

	Intercept	Height	Solar
Height	-0.286		
Solar	-0.337	0.365	
Shade	-0.941	0.176	0.046

Table E.2: Mean Maximum Air Temperature: Linear mixed model fit by maximum likelihood, with distance from stream included.

AIC	BIC	LogLik	Deviance	Df residuals
842.1	864.0	-415.0	830.1	281

Scaled residuals:

Min	1Q	Median	3Q	Max
-2.0417	-0.6942	-0.1390	0.6332	3.4388

Random effects:

Groups	Variance	Standard Deviation
Year (Intercept)	0.8349	0.9137
Residual	1.0085	1.0043

Number of observations: 287
Groups: year, 3

Fixed effects:

	Estimate	Std. Error	df	t-value	*P*
Intercept	16.385297	3.256610	279.964537	5.031	8.72e-07***
Distance	0.007784	0.002861	284.000817	2.721	0.00691**
Solar	0.764367	0.176190	284.004182	4.338	2.00e-05***
Shade	-0.011224	0.033145	284.001726	-0.339	0.73514

Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

	Intercept	Distance	Solar
Distance	-0.343		
Solar	-0.287	0.126	
Shade	-0.949	0.307	0.020

Table E.3: Mean Maximum Vapor Pressure Deficit: Linear mixed model fit by maximum likelihood, with height above stream included.

AIC	BIC	LogLik	Deviance	Df residuals
-123.5	-101.6	67.8	-135.5	280

Scaled residuals

Min	1Q	Median	3Q	Max
-2.4901	-0.7125	-0.2259	0.6671	4.0750

Random effects:

Groups	Variance	Standard Deviation
Year (Intercept)	0.01981	0.1408
Residual	0.03495	0.1870

Number of observations: 286
Groups: Year, 3

Fixed effects:

	Estimate	Std. Error	df	t-value	***P***
Intercept	-0.107394	0.592351	283.936882	-0.181	0.856
Height	0.010912	0.001359	283.001816	8.031	2.61e-14 ***
Solar	0.181165	0.035000	283.004858	5.176	4.30e-07 ***
Shade	-0.002462	0.005969	283.002098	-0.412	0.680

Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

	Intercept	Height	Solar
Height	-0.287		
Solar	-0.341	0.365	
Shade	-0.945	0.176	0.048

Table E.4: Mean Maximum Vapor Pressure Deficit: Linear mixed model fit by maximum likelihood, with distance above stream included.

AIC	BIC	LogLik	Deviance	Df residuals
-111.3	-89.4	61.7	-123.3	280

Scaled residuals

Min	1Q	Median	3Q	Max
-2.4279	-0.7398	-0.1574	0.7146	3.4053

Random effects:

Groups	Variance	Standard Deviation
Year (Intercept)	0.02023	0.1422
Residual	0.03648	0.1910

Number of observations: 286
Groups: Year, 3

Fixed effects:

	Estimate	Std. Error	df	t-value	*P*
Intercept	-2.469e-01	6.176e-01	2.844e+02	-0.400	0.68963
Distance	3.843e-03	5.443e-04	2.830e+02	7.060	1.29e-11 ***
Solar	1.088e-01	3.357e-02	2.830e+02	3.240	0.00134 **
Shade	2.784e-03	6.309e-03	2.830e+02	0.441	0.65933

Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

	Intercept	Distance	Solar
Distance	-0.346		
Solar	-0.290	0.127	
Shade	-0.953	0.307	0.022

Table E.5: Cumulative Degree Days: Linear mixed model fit by maximum likelihood, with height above stream included.

AIC	BIC	LogLik	Deviance	Df residuals
3221.2	3242.8	-1604.6	3209.2	262

Scaled residuals:

Min	1Q	Median	3Q	Max
-3.3149	-0.5790	0.0853	0.6816	2.1530

Random effects:

Groups	Variance	Standard Deviation
Year (Intercept)	2926	54.09
Residual	8943	94.57

Number of observations: 268
Groups: Year, 3

Fixed effects:

	Estimate	Std. Error	df	t-value	***P***
Intercept	3230.9765	304.9814	267.9974	10.594	< 2e-16 ***
Height	3.8691	0.7141	265.0096	5.418	1.35e-07 ***
Solar	-12.9872	17.9410	265.0047	-0.724	0.470
Shade	2.4317	3.0900	265.0109	0.787	0.432

Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:

	Intercept	Height	Solar
Height	-0.300		
Solar	-0.339	0.354	
Shade	-0.950	0.193	0.047

Table E.6: Cumulative Degree Days: Linear mixed model fit by maximum likelihood, with distance from stream included.

AIC	BIC	LogLik	Deviance	Df residuals
3227.4	3248.9	-1607.7	3215.4	262

Scaled residuals:

Min	1Q	Median	3Q	Max
-3.2401	-0.4974	0.0982	0.6846	2.0813

Random effects:

Groups	Variance	Standard Deviation
Year (Intercept)	2966	54.46
Residual	9152	95.67

Number of observations: 268
Groups: Year, 3

Fixed effects:

	Estimate	Std. Error	df	t-value	*P*
Intercept	3198.7574	314.5647	267.9831	267.9831	< 2e-16***
Distance	1.3352	0.2809	265.0207	4.754	3.28e-06***
Solar	-38.2153	17.0856	265.0023	-2.237	0.0261*
Shade	4.0837	3.2346	265.0134	1.263	0.2079

Significant codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Correlation of Fixed Effects:

	Intercept	Distance	Solar
Distance	-0.353		
Solar	-0.282	0.113	
Shade	-0.957	0.318	0.014