ENHANCING PRESCRIBED BURN FIRE ACTIVITY PREDICTIVE ABILITIES WITH THE ADDITION OF A DEAD FIRE FUEL MOISTURE CONTENT ANALOG ON JOINT BASE LEWIS-MCCHORD PRAIRIES

by

Jason M. Keyes

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by

Jason M. Keyes

has been approved for

The Evergreen State College

by

Kathleen Saul, Ph.D.
Member of the Faculty

Date

ABSTRACT

Enhancing prescribed burn fire activity predictive abilities with the addition of a dead fire fuel moisture content analog on Joint Base Lewis-McChord prairies

Jason M. Keyes

This study addressed a gap in the Center for Natural Lands Management's (CNLM) Fire Effects Monitoring Operations (FEMO). Fire is a cost-effective restoration tool which yields positive ecological results almost immediately. However, prescribed burn managers lacked a simple and easily referenced dead fire fuel load index that could be used during the decision-making process on the morning of a potential prescribed burn event. Thus, my Thesis uses statistical analyses to answer the following question: "Do the benefits of adding a coarse fire fuel moisture load index to FEMO outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?" Using the 10-hour dead fuels moisture load analog "fuel moisture stick" data, I found moderately-strong positive correlations among shaded and unshaded relative humidity levels, and shaded and unshaded fuel moisture stick moisture loads. I then analyzed the monetary costs of implementing the new index and showed that fuel moisture sticks are worth the money to purchase, and the time to deploy and use for field work. Based on these correlative outcomes, I have concluded that CNLM should add and use this index as a regular component in their FEMO.

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-JMK

“You miss 100% of the shots you don’t take.”

-Wayne Gretzky

“Try not. Do, or do not. There is no try.”

-Yoda

Introduction

Fire ecology is a robust and forever evolving scientific endeavor used to restore and conserve the South Puget Sound Prairie-Oak ecosystem. As is often the case in science, seeking answers reveals more questions. These questions may address fundamental truths, while others are more subtle and nuanced. The question I answer in this Thesis is not whether or not the data exists, but whether the costs involved in gathering the data outweighs the benefits of having the data. The study protocol has four stated objectives (see Appendix A); My Thesis focused on the first objective: "Determine a relationship between 10-hour fuel moisture measured using fuel moisture sticks at the [Joint Base Lewis McChord] (JBLM) Fish and Wildlife Office and moisture measured in specific burn units of interest, to create a coarse and easily accessed reference point on the morning of a burn" (Kronland, Hill & Martin, p.1, 2017). I therefore re-framed the question as a testable hypothesis:

"Do the benefits of adding a coarse fire fuel moisture load index (fuel moisture sticks) to Fire Effects Monitoring Operations (FEMO) outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?"

H_0= The costs of adding fuel moisture sticks to FEMO outweigh the benefits of new data that could be used by fire managers before a prescribed burn event.

$H_{a=}$= The benefits of adding fuel moisture sticks outweigh the costs, and the new data should be used by fire managers before a prescribed burn event.

My Thesis' literature review comprises the first four chapters of this work. Chapter 1 explores the South Puget Sound prairies as they were maintained by the Native American tribes before European settlement. It also tracks the changes the prairies endured as European agricultural practices, and later, military operations, transformed the landscape into its current condition. Chapter 1 ends with an overview of current fire ecology, and introduces the Center for Natural Lands Management (CNLM) as the key player in the current prescribed burn regimes. The concept of “optimal” burns is clarified in this chapter as well.

Chapter 2 serves as a primer for the climate and weather in the South Puget Sound prairies. I explain how our climate is characterized on the Köppen Climate Classification system; I also explain key concepts such as relative humidity. Relative humidity plays a strong role in fuel moisture stick function as a dead fuel moisture index, and so warrants a detailed explanation within the context of my Thesis.

Fire managers strive for burn efficiency, as elucidated in Chapter 1, which means they must understand plant phenology. Chapter 3 examines plant phenology and its role in prescribed burns. The study tracked moisture loads of three specific plants found on the prairies: 1. Scotch broom (*Cytisus scoparius*), 2. Snowberry (*Symphoricarpos albus*) and, 3. Douglas fir (*Pseudotsuga menziesii*).

The fourth chapter focuses the scope considerably by providing a detailed look at the data collection processes. Fuel moisture stick data were collected over 18 days throughout the 2018 fire season, resulting in over 150 data points. Chapter 5 provides the results of my analyses and a cost-benefit analysis of deploying fuel moisture sticks for use in future FEMO protocols.

Chapter 1

The History of Fire Ecology on the South Puget Sound Prairies

1.1- Puget Sound Fire Ecology: Prehistoric to Modern Era

The deliberate use of fire to instigate change for anthropological benefit is a concept almost as old as the South Puget Sound prairies themselves. Washington state coastal tribes, such as the Upper Chehalis and Cowlitz, recognized the soils as ideal for what Westerners may term "sustainable" agricultural purposes (Boyd, 1987; 1999, pg. 256). These and other American and First Nation tribes realized the potential for catastrophe if trees and shrubs grew unchecked. Additionally, According to Hessburg, Agee & Franklin (2005), tribes burned the landscape for ecological reasons. For example, one high priority concern involved reducing and/or eliminating running crown fires. Running crown fires, in which fire jumps from treetop to treetop, are highly destructive and almost impossible to combat once a forest fire reaches this stage. Native Americans set relatively small and easy-to-manage fires that burned away excess detritus, destroyed saplings that contributed to multi-layered canopy structures, and restricted ladder fuel growth (Arno and Allison-Bunnell, 2002). Such fires created gaps along the forest floor so that fires could not achieve destructive sizes and temperatures (Chapter 2 of this work will discuss fire behavior and effects to greater detail). Thus, First Nations tribes used fires to promote food growth, feed their horses and lure game into more open spaces to be hunted for fresh meat (Leopold & Boyd, 1999). Figure 1.1a is an example of a prairie in relation to Puget Sound.

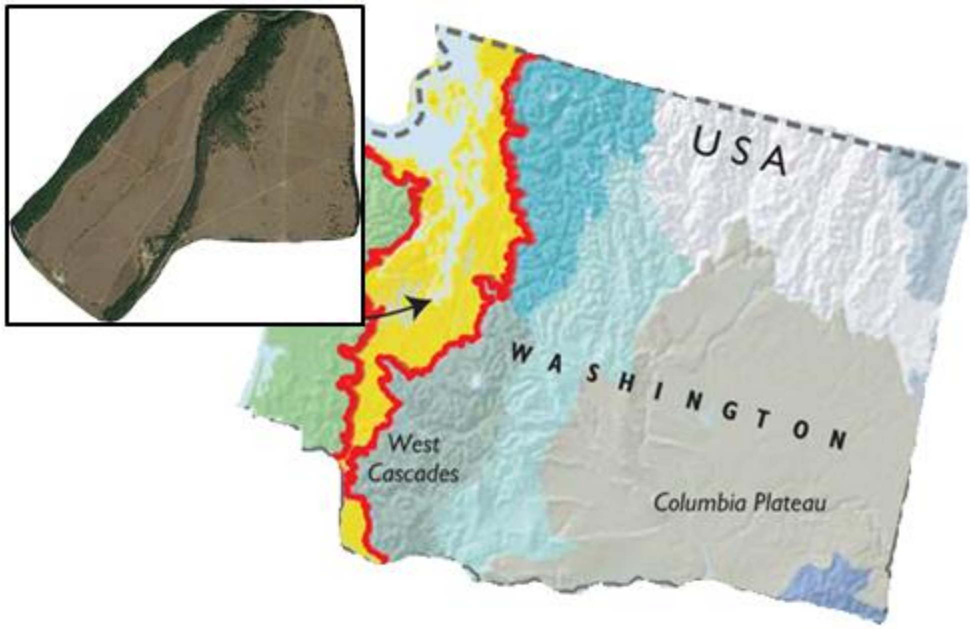

Figure 1.1a- The red line demarcates historical prairies from other distinctive landscapes. The yellow area highlights the Puget Trough, which is a portion of the larger Willamette Valley-Puget Trough- Georgia Basin biome. Upper and Lower Weir prairies are depicted in satellite imagery and serve as prime examples of historical and modern fire ecology regimes. *State map taken from Cascadia Prairie-Oak Partnership website (2019). Prairie image taken from Google Maps, (2019).*

European settlers, forever pursuing the "American dream" of wealth and prosperity, also recognized the prairies' rich farming potential. However, their methods stood in diametric opposition to that of their indigenous counterparts. European-style farms did not exist in symbiosis with the land or the people for whom they provided. Conquering the land for maximal European settler benefit was the prime motivator behind Manifest Destiny; as President John Quincy Adams said, quoting the Bible, "Be fruitful and multiply, and replenish the earth, and subdue it (Jones & Rakestraw, pg. 240, 1997).

Seemingly incompatible ideals introduced by Manifest Destiny and traditional ecological knowledge led to conflict that persists into the modern era. European settlers, backed by political machination and strengthened by military might, re-located Native Americans to reservations, or otherwise severely restricted how they could live according to their tribe's customs and practices. Beginning in the early 1800s, European settlers slowly but inexorably took complete control of the prairies which had already been cultivated by First Nations and Native Americans during the previous millennia.

Unlike the Native Americans and First Nations, Europeans did not view fire favorably. Many Christian-based religions equate with their concepts of hell, or eternal damnation. Following this logic, fire was destructive and ultimately evil; perhaps counterintuitively, witches were burned at the stake as a way of ridding an otherwise god-fearing populace of those who had "made a pact with hell" (Ellerbe, pg. 121, 1995). Religious overtones aside, European settlers often feared large-scale fires, and that fear is founded in their societal memory: London burned in 1666, just 46 years after settlers founded Plymouth Colony (later known as Plymouth Rock). Additionally, city-wide fires followed European settlers across the North America continent: Chicago (1871), Seattle (1889), San Francisco (1851 and 1906), and New York (1776, 1835 and 1845), wrought apocalyptic death and destruction. Given this historical perspective, it is of small wonder that European settlers in the Puget Sound prairies viewed fire as a power to be avoided except when used as a hearth fire or small camp fire. Therefore, the European cultural lens through which fire was viewed as dangerous became the dominant viewpoint in the prairies, and fire suppression tactics became the norm. Prescribed burns, in effect, eventually vanished from the landscape.

Turning this cultural lens to the Puget Sound prairies reveals that early settlers failed to take Western Washington's dynamic ecologic history into account. In addition to the urban fires listed here, tens of thousands of unpopulated acres had been consumed in wildland fires forest fires in Yellowstone and in other remote stretches of the West. The technology to combat extremely large wildfires did not exist, and so beginning in 1905, the newly-created United States Forest Service made suppression of early-stage fires on Federal lands its *raison d'état* (van Wagtendonk, 2007). The reason for suppressing fires in these areas was simple: The ruined post-fire wood was useless economically. City and ship construction depended almost entirely on virgin lumber taken from American forests; although the term "renewable resource" had yet to be coined, ecologists and economists in that era realized the lack of trees could spell doom to the young but booming American economy.

Not only did prescribed fires go away, but all form of potentially large fires were also actively suppressed as settlers in the Puget Sound prairies sought to protect their homes, crops, livestock, and businesses (Leopold & Boyd, 1999). In the meantime, the priceless soils began dying because the fires to which they spent the previous several millennia adapting, no longer burned away the excess vegetation. Burnt dead plant matter releases valuable nutrients back into the soil, which promote healthy soil, but because burning was illegal, or at the very least strongly discouraged after 10:00 AM (van Wagtendonk, 2007), those nutrients remained secreted in living plant tissues. Soon the rich biodiversity First Nations and Native Americans tirelessly cultivated on the prairies disappeared as single-crop agriculture gulped down whatever nutrients the soil had sequestered until that time.

European settlers pushed into the Puget Sound prairies with their settlements, roads and railroads. Real estate became a prime commodity as people rushed to drop foundations into the deep, rocky soils. The American government encouraged this by enacting the Homestead Act of 1862. This Act made land acquisition easy for the American citizen, and the Puget Sound prairies were soon bought and developed as the new owners saw fit, provided they obeyed certain rules. One such rule was new land owners had to maintain residence for five years after the purchase date. Unfortunately, this also resulted in the almost complete removal of remaining tribal citizens from their ancestral lands; they were also rendered increasingly powerless as laws and treaties eroded their sovereignty. The "Indian Problem" (the euphemism for perceived Native American interference with European expansion policies during the 19th century) shrank from major threat to minor nuisance as treaties expelled the indigenous tribes from their ancestral homes onto to undesirable lands, by Capitalist-driven European standards (National Archives, 2018). Then, in 1918, the Great War erupted on the planet-wide stage.

President Woodrow Wilson proclaimed World War I WWI) to be "the war to end all wars" (Wilson, c. 1918). Its global scale required a strong military-industrial complex; Washington's prairies provided the perfect locations for long-term, wide spread military operations. Businessmen in the American Lake region near Tacoma, Washington invited top military leaders to the region to showcase the vast open spaces, characterized by the Commander of the Western Department of the U.S. Army Major General J. Franklin Bell, as "...the most magnificent field I have ever seen for military maneuvers"(Directorate of Plans, Training, Mobilization and Security website, 2018).

The Army, with President Wilson's blessing, built the installation which would eventually become Fort Lewis.

Major General Bell framed his glowing assessment of the prairies within the cultural lens of defense preparation: WWI needed well-trained, well-equipped troops and this site offered enough room to provide those for deployment to war fronts. Furthermore, large and devastating weapons still required calibration and trained soldiers for effective operations. The prairies quaked as explosions wracked the ancient lands. Large artillery firing reduced many Mima mounds, one of the few remaining geological mysteries, to craters. Incendiary rounds, which burn white-hot on impact, made short work of remnant prairies. Ironically, the fraction of native prairie known as the Artillery Impact Area (AIA) has persisted because of military live-fire training exercises held there (Tvenen, 1998). The military, at the time unaware of the profound ecological impacts their operations inflicted on the landscape, maintained artillery impact areas by prohibiting urban landscape encroachment, a restriction that persists through World War II and to this day.

1.2- Western Fire Ecology and Traditional Ecological Knowledge in the 21st Century

This section outlines the modern (20th – 21st century) history of JBLM fire ecology. The supportive evidence for my overview in this section is derived from the chapters in the Dunn & Ewing tome, but I cite the specific chapter's author(s). Other references gain full citation.

Fort Lewis, now a part of Joint Base Lewis-McChord (JBLM), remains the largest encapsulation of remnant prairies in South Puget Sound. Fire suppression tactics, developed and enforced since the early 20th century, remained largely unchanged, despite (or perhaps because of) growing human populations on base and in the surrounding civilian communities. Tveten (1998) concluded that JBLM has three fire regimes: 1. Fire suppression, 2. Prescribed fires during the spring months, and 3, Annual fires within the AIA. Of these three, Tventen realized fire suppression produced the most deleterious ecological results (1998). The absence of fire allowed for the encroachment of Douglas fir (*Pseudotsuga menziesii*), which had been specifically targeted by tribal citizens and subjected to burning.

According to Pojar & McKinnon (2004), invasive Scotch broom (*Cytisus scoparius)* grows readily in degraded soils and easily overruns most other flora because of its generalist growing habits. Scotch broom is a large, woody shrub, and is considered detrimental to safe military training operations, such as parachuting. Parachuting from a moving aircraft requires large open spaces that are relatively free of obstructions that can either injure or entangle a parachutist during landing. Scotch broom foliage can rip lightweight parachute cloth (traditionally silk, but modern military parachutes are made from nylon);while trees, such as Douglas fir, simply impede large-scale movements. To combat these invasive species, the Army developed a prescribed burn program in the 1950s , not for ecological purposes, but to increase training efficiency (Forest Management Strategy, 2005).

Native Americans burned to keep Garry oak (*Quecus garryana*) and Douglas fir in check; the Army logged and sold the trees, regardless of their species, whenever necessary (Forest Management Strategy, 2005). As Perdue (1998) noted, this change in ecological approach marked a turning point in the life of the last, largest tracts of historical prairie landscape. Forest management began in the 1960s while strategic burning continued as the Army saw fit. No formal fire effects study was conducted in burned areas until Tveten's experiment in 1994 (Tveten, 1998). This landmark experiment is explained in the following section.

1.3- The first fire effects experiment on Fort Lewis

Tveten's experiment served as one of the first deliberate explorations of fire effects on remnant Puget Sound prairies. According to Teveten, the experiment tested three questions:

1. "What prairie plant communities have developed as a result the prescribed burning program and annual burning in the Artillery Impact Area on Fort Lewis?
2. "What fire regime best promotes native prairie vegetation?
3. "Do fall prescribed fires affect prairie vegetation differently from spring fires" (1998, p. 125)?

Tveten evaluated 180, 1-m^2 plots, selected at random, along 60m – 180m transects. Transects intercepted as many landscape features (forests and grasslands) as possible to capture how plant communities respond to fire regimes. The 180 plots were divided into three treatments: "30% to be burned in the spring, 30% to be burned in the fall, and 30% left unburned" (Tveten, 1998, pp. 126-127). Metal chips coated with paint that melted at specific temperatures were placed within each burn unit prior to ignition. The condition of the paints (melted or intact) depended on the temperature to which the paints were exposed; thus, Tveten gained priceless insight into ground temperatures during fire activity; this knowledge base remains foundational to fire effects monitoring operations (FEMO) to the present.

1.4- The Center for Natural Lands Management

Author's note: As the vast majority of prescribed fire operations on the prairies are conducted and monitored by the Center for Natural lands Management (CNLM), literature discussed and cited in this section originates from the Cascadia Prairie-Oak Partnership (CPOP) online document database, which is maintained by CNLM. Each paper is cited as usual, but unless noted, is found on the CPOP website.

The need for a more rigorous fire ecology program solidified as the prairies garnered increased attention. The terror attacks on 09 September 2001 prompted the Global War on Terror; JBLM's expansive and maintained lands were needed to support a new generation of troops engaging the new threat. Meanwhile, the military continued their prescribed burn regimes under the watchful gaze of the Washington State Department of Fish & Wildlife (WDFW). According to The Evergreen State College and Washington State Department of Corrections (2018), using a focused, science-based approach to prescribed fire could lead to safer and less-costly fire operations.

Furthermore, the military created Army Compatible Use Buffers (ACUBs) to act as a barrier against civilian infrastructure encroachment (Department of Military and Veterans Affairs, 2018). ACUB managers, to appease local communities, promise that the land not being used for equipment testing or major training operations, could be used for recreational and other non-essential purposes (Department of Military and Veterans Affairs, 2018).

Today, JBLM partners with the Center for Natural Lands Management (CNLM) in prescribed fire operations. As a non-profit organization, the CNLM is funded in part by the JBLM ACUB program. This partnership ensures prescribed burns continue not only for the Army's benefit, but also for the advancement of scientific knowledge. The scientists at the CNLM build on Tveter's experiment: Using best practices, they determine fire effects on South Puget Sound prairies' resident native and invasive flora and fauna. They carefully manage and monitor each fire, and collect and analyze data. The results of the analyses determine if fire operations function at optimal efficiency. The terms "optimal", "efficient", "effective" and their like are used throughout these reports and this work. In short, the terms describe how well a prescribed fire burns according to specific goals for a given fire. For example, a fire ignited in patchy fuels interspersed within an oak tree stand is considered effective if the patchy fuels are destroyed, but the oak trees remain intact and healthy. According to the South Puget Sound Ecological Fire Program, 2009 Program Summary, full-scale prescribed burn operations began during the summer of 2008. Forty separate prescribed burn events took place throughout various ACBs as at the Glacial Heritage Preserve (McKinley, 2010).

Author's note: Reports are filed in January of the following year; the 2009 summary displays a published date of 2010 on its cover page. This is the standard practice for this program.

The 2010 program summary bears the first mention of fuel moisture as a hindrance for effective fire operations in a patch of Reed canarygrass (*Phalaris arundinacea*). According to the Washington State Noxious Weed Control Board website (2018), RCG threatens endemic ecosystems, particularly those with high soil saturation levels throughout the year. This grass, which was introduced as grazing material for cattle, spreads via shoots and seeds, and rapidly outcompetes all other flora in the infestation area (Adams & Galatowitsch, 2006). Mature stands contain individual grass stalks up to 6 feet tall. Dead RCG builds a thick, virtually 100% sunlight-excluding thatch that also further prohibits floral competition. The very thick thatch also restricts animal food sources and shelter, reducing a riparian zone's viability as habitat. As a result, reed canarygrass is targeted for prescribed burns, such as the event described in the 2010 program summary. Fire crews experienced extreme difficulty when attempting ignition of a reed canarygrass patch, ultimately poured 10 gallons of propane directly onto the target, thus finally achieving ignition. Restoration and Ecological Fire Program Manager Mason McKinley noted that the process was "slow, but effective… and was approved by DNR [Department of Natural Resources]…" (2010, p. 12).

A review of later reports indicates a steady annual increase in the number of prescribed burns; these burns also grew in physical size with the addition of more firefighters and better equipment. The 2012 summary mentions unusually wet early-year conditions, followed by drought-like conditions beginning in the mid-Summer and persisting into late Fall of that year. McKinley's concern regarding fuel moisture levels is evident: "At this time, the dryness of the fine fuels created conditions where only the most secure units were attempted – even when burning with higher humidities [*sic*] and lower temperatures" (p.7, 2012).

McKinley's 2014 report was the first to show a statistical analysis of the impact on fire behavior of relative humidity (RH), air temperature, season, and soil temperatures. The 2015 fire operations were significant in fire size, frequency, and burn intensity because of exceptionally dry conditions that began in early spring and persisted until late fall. This allowed for ample opportunity for more scientific analyses of prescribed fires- including those conducted by CNLM Prairie Restoration Specialist Kathryn Hill. In her Master's thesis, Hill examined fire effects on potential butterfly habitat by correlating atmospheric conditions and fire fuel characteristics. Critically, she measured "cured" live fire fuels. According to Hill, "cured" is the term to describe latent moisture content in live fire fuels. Low moisture levels in live fire fuels characterize that fire fuel as "cured" (2017 p. 28). Prior to Hill's work, fuel moisture levels were determined by observing and using known visual cues of how plants express desiccation and senescence. The need for better, more quantifiable plant phenology data, and to establish its relation to fire ecology and weather, is plain in the 2016 summary (2017, pp. 16-17).

Quantifying fuel load moisture levels is not a brand-new concept. The Utah Bureau of Land Management had already conducted a very similar study sometime around 2004. Hill and CNLM Prairie Restoration Project Manager Bill Kronland looked to their Utah BLM scientific counterparts and found their live/ dead fuel collection procedures useful for their own study. Hill and Kronland collected preliminary and comparative data in 2017 and 2018, in accordance with the procedures outlined by Pollet & Brown (2007). This process is discussed in Chapter 4: "Data Collection Procedures".

1.5- Summary

Chapter one provided a brief history of fire ecology on the South Puget Sound prairies. First Nations tribes such as the Upper Chehalis and Cowlitz maintained the postglacial landscape with fire for sustainable agricultural and game hunting purposes. The 19th century witnessed an influx of European settlers as they fulfilled Manifest Destiny; with them came their latent fear of fire. Fire suppression tactics were employed by settlers to protect livestock, homes, and crops. The Army's need for space for personnel training and artillery practice was found in the vast, relatively flat expanses of open land found on the South Puget Sound prairies. Fire suppression became a greater concern for the Army base as the prairies floral biomass increased because of the lack of fire until the 1950s, when the Army recognized fire as a quick and cost-effective method for clearing the once open land of encroaching Douglas fir trees and Scotch broom. Tvetner's landmark experiment in the mid-nineties was the first attempt at studying fire effects. Fire ecology on the South Puget Sound prairies continues to this day under the CNLM's robust prescribed burn program.

The next chapter discusses weather, its importance in predicting fire behavior, and its ultimate role in answering this Thesis' question: "Do the benefits of adding a coarse fire fuel moisture load index to Fire Effects Monitoring Operations (FEMO) outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?"

Chapter 2

The Climate and Weather on the South Puget Sound Prairies

2.1- Introduction

Chapter one examined the history of fire ecology during the preceding millennia. Native Americans used fire as a tool for maintaining wide open spaces that attracted game. European settlers, and later American soldiers, viewed those same spaces as excellent farming and training grounds. Fire, whether set intentionally or not, maintained those spaces- the Western Washington state prairies (albeit in heavily degraded and fragmented conditions). However, fire only tells part of the story. Native Americans, European settlers, soldiers and civilians alike enjoyed the cool, moist winter months and warm, dry summer months that are typical to this region.

This chapter explains the driving force behind South Puget Sound's weather. Section 2.2 is an introduction of weather- and climate-related terms and concepts. Section 2.3 acknowledges climate change as an increasingly relevant factor in future prescribed burns. Section 2.4 gives data: fire ecology thrives or fails according to the weather, which is why prescribed burn crews pay close attention to local conditions. Weather data from 2017 and 2018 bear greater scrutiny here because I collected this Thesis' data during those two years.

2.2- Terms and Concepts

Climate

"Climate" and "weather" are sometimes used interchangeably, but this is incorrect. Climate refers to average weather conditions in a given region over time. In the case of Puget Sound's prairies, the climate is determined by moist offshore winds interacting with the Olympic Mountains on the Olympic Peninsula, and the Cascade

Mountains further inland to the East. Puget Sound itself also contributes to the overall climate. Thus, the Puget Sound climate is characterized by mild, very precipitous winters when temperatures rarely fall below freezing, and very warm-to-hot summers with few precipitation events. The following section provides a more detailed look at the Puget Sound climate.

The Köppen Climate Classification System

The Köppen Climate Classification system, a widely-used global climate model, bins general climate conditions into five Groups: A) tropical, B) dry, C) temperate, D) continental and E) polar.

Further refinement within each bin occurs as the classification system narrows in scope. South Puget Sound temperatures range from 27 °F in the winter to 71.6 °F in the summer. The majority of precipitation occurs between October and March while summers remain very warm (*s*) and with little precipitation (*a*). Therefore, the Köppen Climate Classification rates South Puget Sound “Csa”, or hot-and-dry-summer Mediterranean climate (Beck, et al., 2018).

Weather

Weather describes local atmospheric conditions at any time and place (Ahrens and Henson, 2018). In the context of this work, prescribed burn managers must consider several elements within the weather pantheon, but the three greatest concerns are for temperature, relative humidity (RH) and wind.

Relative humidity

Atmospheric temperature and RH on a potential burn day directly modulates fire fuel moisture content in dead and living foliage. Moreover, prescribed fire managers measure temperature and RH congruently because these indices are linked. Temperature alone is only a rough indicator for fire behavior, but RH levels fluctuate closely alongside temperature levels. Ahrens and Henson describe RH is the following equation:

$$RH = \frac{water\ vapor\ content}{water\ vapor\ capacity}$$

Where:

Water vapor content denotes the actual amount of water vapor present in the air at a given temperature, and

Water vapor capacity denotes the total amount of water vapor the air can hold at the same given temperature (2018, p. 97).

Higher temperatures encourage evaporation over water bodies and transpiration over stands of vegetation, which means relative humidity can be higher in these areas. . Conversely, lower temperatures discourage evaporation and transpiration, leading fire mangers to observe lower RH levels.

According to Ahrens and Henson (2018), RH occurs because water vapor produced during evaporation and transpiration fills the space between the nitrogen, oxygen and other trace elemental molecules found in Earth's atmosphere. For example, warm air rises (expands), which in turn increases the amount of space between the molecules, which free-floating water vapor fills. Conversely, cool air sinks (condenses), which restricts the amount of space between air molecules in which water vapor can fit. When this occurs, atmospheric water vapor content can saturate the air until the atmosphere at that temperature can no longer hold that amount of water vapor, thereby elevating RH readings. At this point, clouds form and precipitation becomes likely.

Modern technology aids fire crews in collecting these data. According to the Center for Natural Lands Management Prairie Restoration Specialist Kathryn Hill, prescribed burn crews use hand-held weather meters (Figure. 2.2a) which gather the data explained in this section, and more if required, for immediate use in deciding if weather conditions promote safe/ efficient burning.

Figure 2.2a- Fire crews use Kestrals, such as this to gather pertinent weather-related information prior to each prescribed burn. Sometimes this information indicates no burns should be conducted. *Image taken from kestrelinstruments.com.*

Weather conditions cause plant tissue moisture load fluctuations. For example, hot and dry conditions accelerate plant tissue desiccation in live plants, and subdue absorption in dead plant matter. Desiccation is the process in which all moisture is removed from living tissue. This process affects all foliage (i.e., their flowers wilt and drop their petals), irrespective of its taxonomy. See this work's Chapter 3: "Plant Phenology" for more information regarding phenotypical moisture sequestration cycles.

Wind enhances dead fuels moisture absorption. Absorption, or the process in which dead floral tissues sequester atmospheric moisture, occurs regardless of wind speed, but higher wind speeds help this process function at a higher rate than what occurs at lower wind speeds. Thus, prescribed fire managers use wind more as an index for potential fire spread, and less as a fire fuel load predictor. See Chapter 5, "Results and Discussion" for wind/ fuel moisture correlation matrices generated by the author.

2.3- Climate change effects on fire behavior

Climate change models suggest the Pacific Northwest will undergo an overall warming trend as we advance through the 21st century. According to Wimberley & Liu (2014), climate change models compiled by the Intergovernmental Panel on Climate Change (IPCC) predict a 3.5^{o} C increase in overall temperatures by the 2080s. However, precipitation levels are unlikely to change in the same models over the same time period. As a result, temperature increases correlate with decreased foliar moisture (see Chapter 5). This is especially significant to South Puget Sound prairie fire operations because elevated temperatures are expected to occur during June, July and August - months during which most prescribed burns take place.

2.4- 2017 and 2018 Puget Sound fire season weather characteristics

The following figures aggregate daily weather data collected by the National Weather Service McChord Air Force Base site during the 2017 and 2018 burn seasons; burn seasons were from April – September in each year (Puget Sound Ecological Fire partnership, 2019).

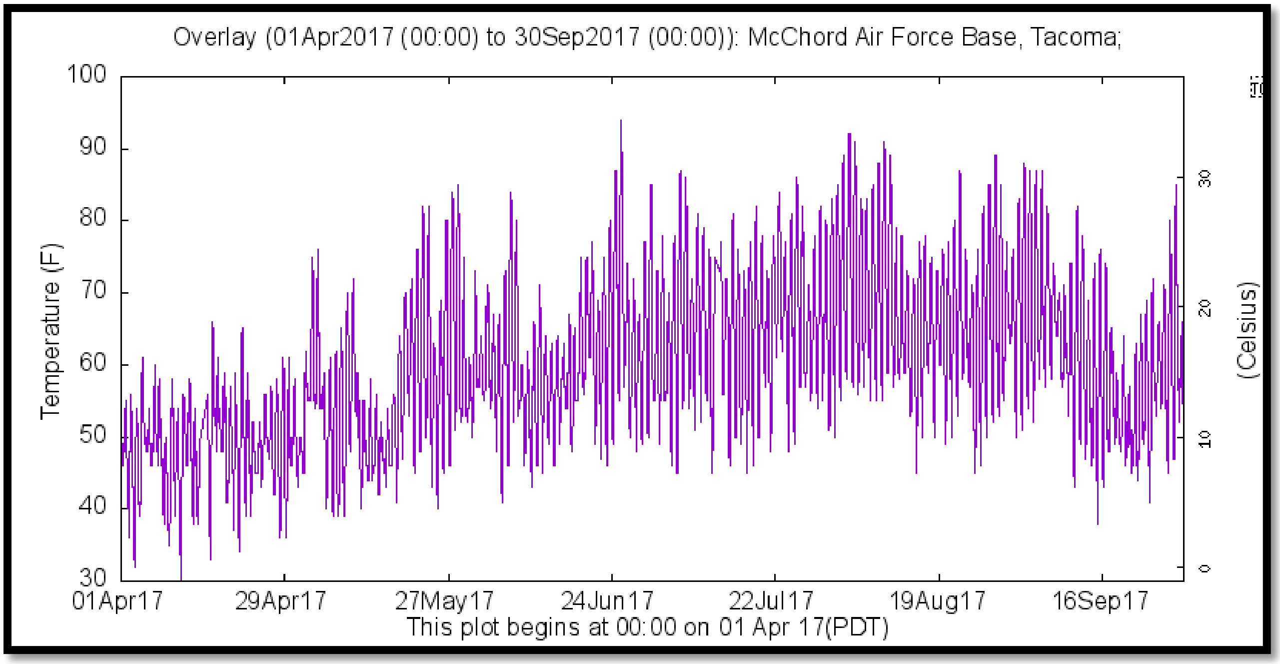

Table 2.4a- Daily temperature readings during the 2017 burn season. As temperatures increase throughout the season, dead foliar moisture levels decrease (See Ch.5 for correlations). *Graph generated in and taken from The University of Washington. "Live From Earth and Mars" website (n.d.).*

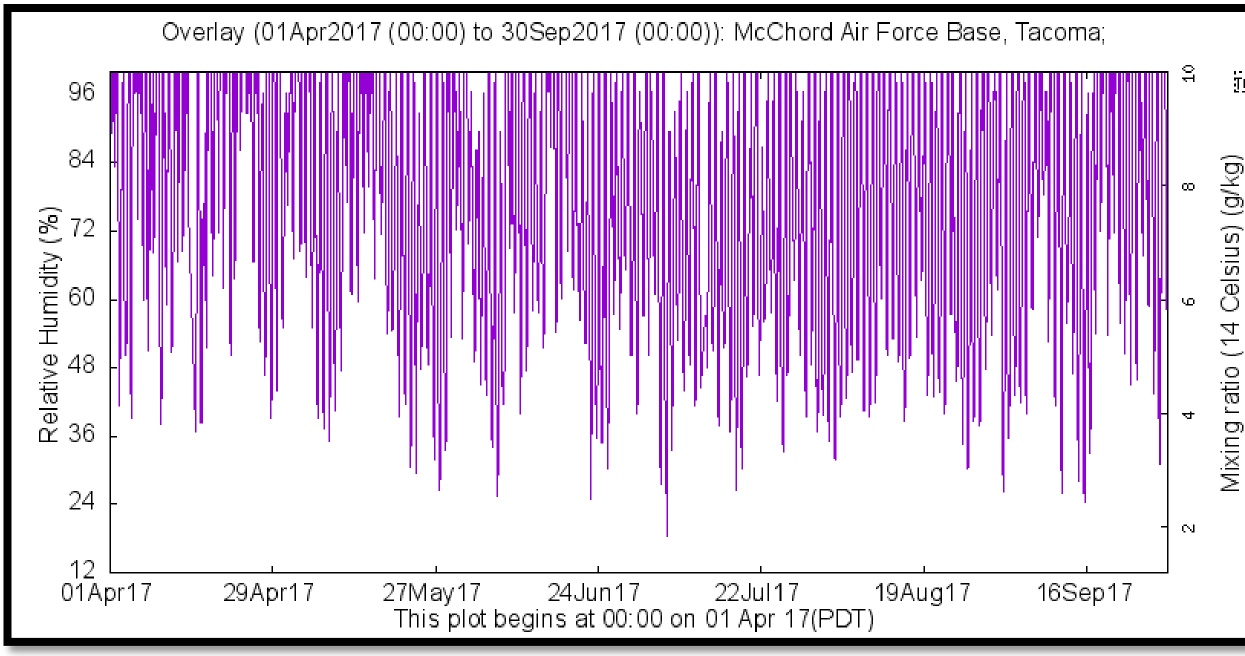

Table 2.4b- Daily RH readings from 2017 burn season. Relative humidity levels are a stronger determining data point towards the advent of a prescribed burn on a given day. RH directly influences dead fuels moisture absorption, and so if RH is low, dead foliar moisture levels are expected to be low as well. The fire sticks reduce the dependence on this "rule of thumb" by providing quantifiable data.

This graph appears upside-down because RH levels remain relatively high throughout most of the year. See section 2.2 of this work for discussion on Puget Sound humidity characteristics. *Graph generated in and taken from The University of Washington. "Live From Earth and Mars" website (n.d.).*

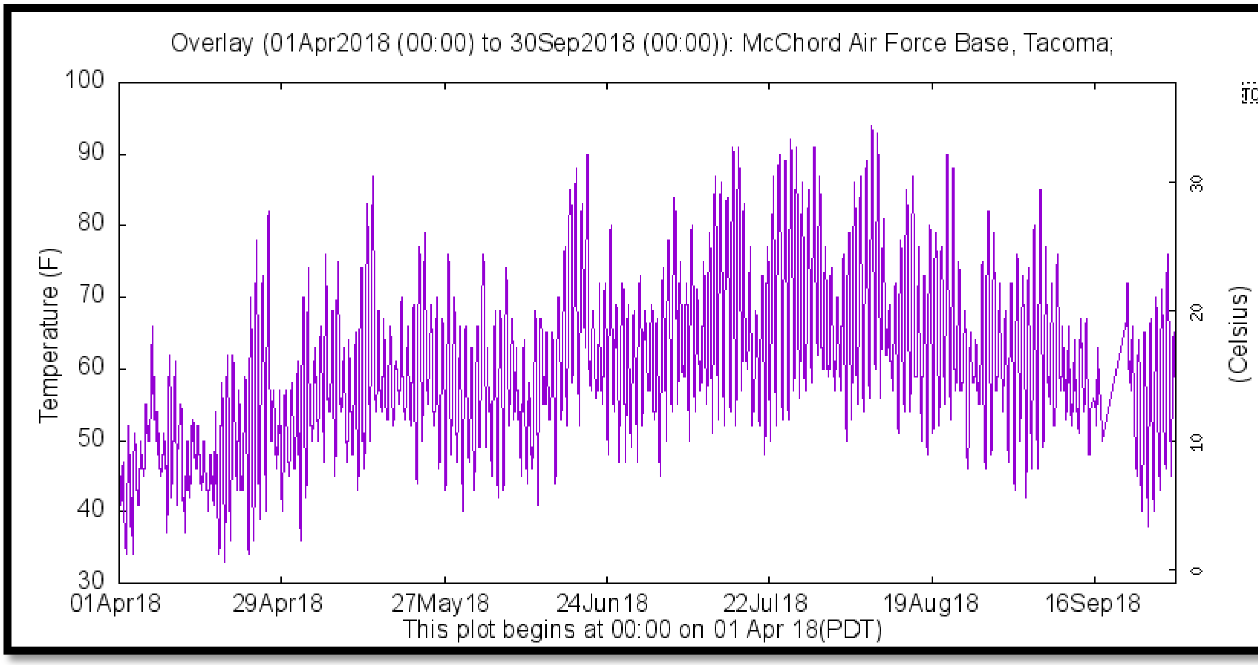

Table 2.4c- Daily temperature readings during the 2018 burn season. *Graph generated in and taken from The University of Washington. "Live From Earth and Mars" website (n.d.).*

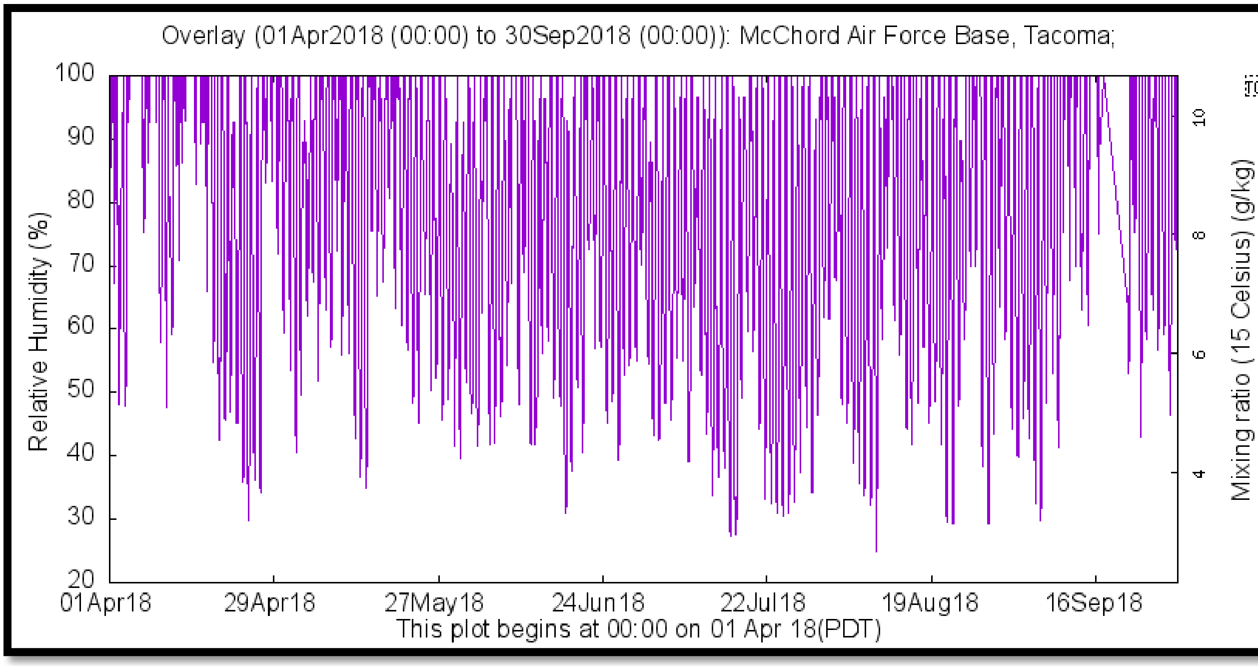

Table 2.4d- Daily RH readings from the 2018 burn season. Relative humidity levels fluctuate along seasonal changes, as expected. High early April RH levels often inhibit prescribed burns, while low mid-September RH levels dictate prescribed burn operations to be conducted with extreme care.

This graph appears upside-down because RH levels maintain relatively high throughout most of the year. See section 2.2 of this work for discussion on Puget Sound climate characteristics. *Graph generated in and taken from The University of Washington. "Live From Earth and Mars" website (n.d.).*

2.5- Conclusions

Chapter 2 provided the groundwork in understanding prevailing weather conditions in and around the South Puget Sound prairies. Section 2.2 introduced terms and concepts that are integral to this study, while section 2.3 notes climate change will likely influence local weather conditions over the next 60 years. Section 2.4 displays the daily temperature and RH recorded at the National Weather Service McChord Air Force Base station. Chapter 3 introduces plant phenology, the next critical component in this thesis.

Chapter 3

Study-Specific Plant Species Phenology

3.1- Introduction

Chapter 1 explained the history of fire ecology on the South Puget Sound prairies, and Chapter 2 examined the most common weather and their effects on fire behavior. This chapter delves into plant phenology. Three plants and their respective phenology bear greater scrutiny here because the Center for Natural Lands Management (CNLM) scientists and technicians collected their foliage for use as live fuels data in the 2017 and 2018 growing seasons: 1. Scotch broom (*Cytisus scoparius*), 2. Snowberry (*Symphoricarpos albus*) and, 3. Douglas fir (*Pseudotsuga menziesii*). Although I collected and analyzed these data, they are omitted from this work because they do not provide direct evidence for the question my Thesis answers. However, the live fuels data are important because climate change could affect plant seasonal phenology, i.e., plant tissues could dry and fall from plants earlier in the year than what is considered phenotypical for that particular species, and so adding more dead fuels to a potential burn event earlier in the burn season.

Section 3.2 provides basic definitions and introduces relevant concepts. Sections 3.3 – 3.5 each analyzes the phenology of the three plant species noted above. Section 3.6 summarizes this chapter and introduces Chapter 4.

3.2- Plant phenology defined

Phenology is, "generally described as the art of observing life cycle phases or activities of plants and animals in their temporal occurrence throughout the year" (Lieth, p.4, 1974). Lieth describes life cycles and their relationship with seasonal changes: Deer, for example, shed and re-grow their antlers on a yearly cycle and according to the season, and so this is an aspect of deer phenology. Plants also display phenology. The common Camas (*Camissia quamish,* Figure 3.2a) is a native lily cultivated for human consumption, notably by the Vancouver Island Coast Salish (Pojar & McKinnon, 2004). It tends to sprout and bloom in the early spring. By late summer, these plants have senesced, thereby dropping their seeds. These seeds lie dormant in the soil throughout the winter until the following spring.

Figure 3.2a- The common camas blooms early in the spring, which is typical phenotypical behavior for this plant.

The following section examines each of the three plants in this study in detail; information regarding why managers burn these specific plants is provided as well.

3.3- Scotch broom (*Cytisus scoparius)*

Recall from Chapter 1 why JBLM considers Scotch broom a deterrent to military training operations, particularly parachuting. It is a perennial woody shrub in the Fabaceae (pea) family that can achieve maximal heights of over 6 feet (Figure 3.3a). It establishes readily in degraded soils, recently logged areas, and in Puget Sound's prairies' nutrient-rich, well-drained soils (United States Dept. of Agriculture Natural Resources Conservation Service, 2019). Scotchbroom growth activity and moisture levels are at annual highs during the spring and summer months. A single mature Scotch broom can produce hundreds of bright-yellow inflorescence which attract pollinators. Flowers wilt and fall during mid-Summer months as the plant transfers energy from flowers to seedpod production (Figure 3.3a).

Figure 3.3a- Mature Scotch broom. Large specimens such as this one produce vast amounts of pollen and seedpods. This means that once established in a new area, eradication is virtually impossible. *Photo credit:"5454461", Coombs, Oregon Dept. of Agriculture, 2018. Image taken from www.invasive.org.*

Grove, Haubensak & Parker (2015) explain Scotch broom's peculiar seed dispersal method. Seed pods desiccate as the plant transfers less water and nutrients to the pods during the mid- to late-Summer months. The seed pod twists on itself which stores potential energy via torsion. Seed dispersal occurs when potential energy transforms into kinetic energy; the seedpod literally ejects the seeds several feet away from the parent plant. Each pod contains 3 – 12 seeds (Grove,

Figure 3.3b- Seed pods begin forming shortly after flower senescence. The bright green coloration indicates a young pod with high moisture content. *Photo credit: Coombs, Oregon Dept. of Agriculture, 2015.*

et.al., p. 2, 2015), and possesses a waxy coating that allows for long soil residence times. New plants readily germinate in the early spring months.

Land managers, such as the CNLM, must take Scotch broom phenology into consideration before implementing eradication efforts. For example, CNLM field technicians will use weed wrenches and gas-powered hand tools during early spring (March – June), to remove/destroy small, young plants before they can produce flowers and seedpods. This method will actually help disseminate viable seeds if conducted during the summer months, when seedpods are desiccated and ready to eject seeds as normal for this plant. Similarly, early spring prescribed burns may not affect mature Scotchbroom because of its high moisture content. Felling large Scotchbroom, followed by prescribed fire, is therefore more effective at reducing Scotchbroom biomass from an infested site during summer months, when foliar moisture is low.

Controlling Scotch broom is either extremely challenging or practically impossible. A seminal study, conducted in 1993 by Ingrid Parker of the University of Washington Department of Biology, quantified Scotch broom phenology according to their physical locations, and thereby determined why this plant is considered a noxious weed by modern land managers (U.S. Department of Agriculture, 2019; Zouhar, 2005). In her study, Parker examined Scotchbroom on the Upper Weir and Johnson prairies, which are parts of the larger Fort Lewis Rainier Training Area. She compared these prairie-based specimens with those in Discovery Park, the largest park in Seattle, Washington (Seattle Parks & Recreation, 2019). She tested whether or not Scotchbroom growing on the prairies, where there is little to no sustained human activity, displayed greater fecundity over those growing in Discovery Park, which experiences heavy sustained human activity. Her results concluded, "*C. scoparius* showed higher rates of population growth in prairies than in urban fields" (Parker, p. 733, 2000). In essence, Parker showed why Scotchbroom persists on Puget Sound prairies: they are free to perpetuate because of the lack of human enterprise. They also grow very large on the prairies; the largest shrubs produce the greatest amounts of pollen and seeds, and with enough time, will invade virtually every inch of a landscape, to the detriment of most other plants.

3.4- Douglas fir (*Pseudotsuga menziesii*)

Douglas fir is not considered an invasive species on the same spectrum as Scotch broom. Douglas fir is actually prized for its use in building construction material, poles (utility poles, for example), and Christmas trees (United States Dept. of Agriculture Natural Resources Conservation Service, 2019). JBLM and its surrounding Training Areas contain large Douglas fir stands, which JBLM actively harvests and sells (see Chapter 1 of this work for details). This large coniferous tree (Figure 3.4a) typically grows to over 200 feet and readily establishes in well-drained soils. New needles sprout during mid- to late-spring months, which mean the tree's overall water content is at its yearly high. Seeds are produced in cones (Figure 3.4b), which are dropped during the late summer months and dispersed by the many fauna who depend on the seeds for sustenance. The Douglas fir tree is common to the Puget Sound prairies

Figures 3.4a, 3.4b- A typical Douglas fir and its cone. *Photos taken from: https://www.nationalforests.org/blog/the-firs-the-best-christmas-trees and http://hilltromper.com/article/douglas-fir*

because of favorable soil and climatic conditions, and this is why JBLM logs it, and the CNLM targets it in prescribed burns.

Current restoration efforts resemble those of our Western Washington tribal counterparts in the millennia preceding the 1850s. Douglas fir propagation is restricted from encroaching into the few remaining open prairies, such as those depicted in Chapter 4 in this work. It is also restricted from invading Garry oak stands, which are vital components to the South Puget Sound Prairie-Oak ecosystem. A study conducted in June 2001 by Devine, Harrington and Peter showed how towering conifers and the resulting canopy severely restricts Garry oak phenology. Garry oaks are shade intolerant, and while they can survive in the shade, the study indicates they reduce foliage and acorn production (Devine and Harrington & Peter, p. 247, 2006) in shady conditions. To wit, "The overtopped oak trees in the control treatment received, on average, only 13% of the photosynthetically active radiation that would have been available under unobstructed sunlight" (Devine, Harrington & Peter, p. 250-251, 2006). Finally, with the historical encroachment of Douglas fir came non-native forbs and introduced pasture grasses, such as the aforementioned Scotchbroom; Hairy cat's ear (*Hypochaeris radicata*) and *Agrostis capillaris*, which thrived in the void left in the absence of native flora (Springer & Dunwiddie, p. 108, 2011). In short, unless managed, Douglas fir will rapidly populate the open prairies, and so it is targeted in prescribed burns.

3.5- Snowberry (*Symphoricarpos albus*)

Pojar and McKinnon note that the eponymous snowberries "are considered poisonous by aboriginal peoples" inhabiting the Washington State and British Columbia coastal regions (p. 70, 2004). Snowberry is native to the South Puget Sound prairies, and favors prairie-forest margins where soil moisture and clay contents are greater than the typically well-drained open prairie soils (United States Dept. of Agriculture Natural Resources Conservation Service, 2019).

Figure 3.5a- Snowberry is a common native shrub whose berries, shown here, serve as food for foragers during the winter months. (*Photo credit: J.S. Peterson, hosted by the USDA-NRCS PLANTS Database).*

It is a robust, woody shrub (Figure 3.5); Snowberry can attain heights exceeding 6 feet and can form dense stands throughout its habitat. Snowberry bushes are deciduous. Leaves begin forming in late spring months and are fully developed about one month later. Leaves shed during the fall season while berry production begins. Berries persist throughout the winter months and serve as food for white-tailed deer (Thilenius, 1972). Additionally, Snowberry propagates via seed dispersal as well as rhizomes; the latter allows Snowberry re-population after fire activity destroys the visible shrub (Tisdale & Hironaka, 1981).

Snowberry is not targeted for prescribed burns for the same reasons as those regarding the other two plants described here. Snowberry is a ubiquitous floral denizen throughout the prairies; so much, in fact, that fire operations routinely destroy patches as an operational by-product. Snowberry safety is rarely considered because of its robust post-fire regeneration abilities. Thus, according to CNLM Prairie Restoration Specialist Kathryn Hill, Snowberry live fuel moisture was collected in this experiment simply because the sheer abundance of this shrub necessitated data acquisition (personal communications, 2019).

Chapter three is a critical piece of this work because it explores the flora collected and examined in this experiment, which tests the question, “Do the benefits of adding a coarse fire fuel moisture load index to Fire Effects Monitoring Operations (FEMO) outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?” Section 3.2 defined and explained the importance of plant phenology, while sections 3.3 – 3.5 introduced Scotch broom, Douglas fir and Snowberry and their roles in both fire ecology and this study. Chapter 4 fully explores the data collection processes.

Chapter 4

Study Design and Data Collection Processes

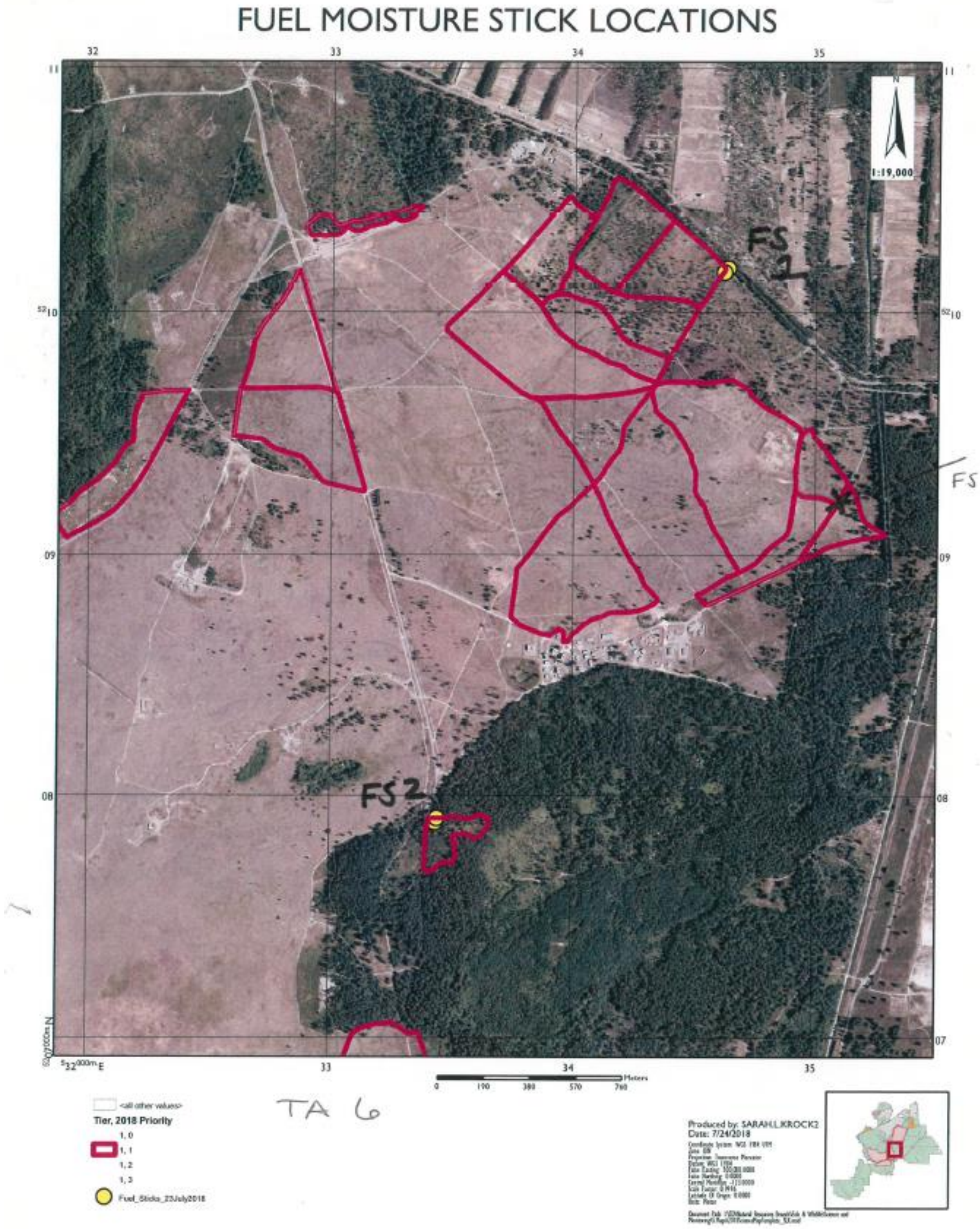
FUEL MOISTURE STICK LOCATIONS
1:19,000
FS 1
FS
FS 2
TA 6
Meters
<all other values>
Tier, 2018 Priority
1, 0
1, 1
1, 2
1, 3
Fuel_Sticks_23July2018
Produced by: SARAH.L.KROCK2
Date: 7/24/2018

Figure 4.1a.

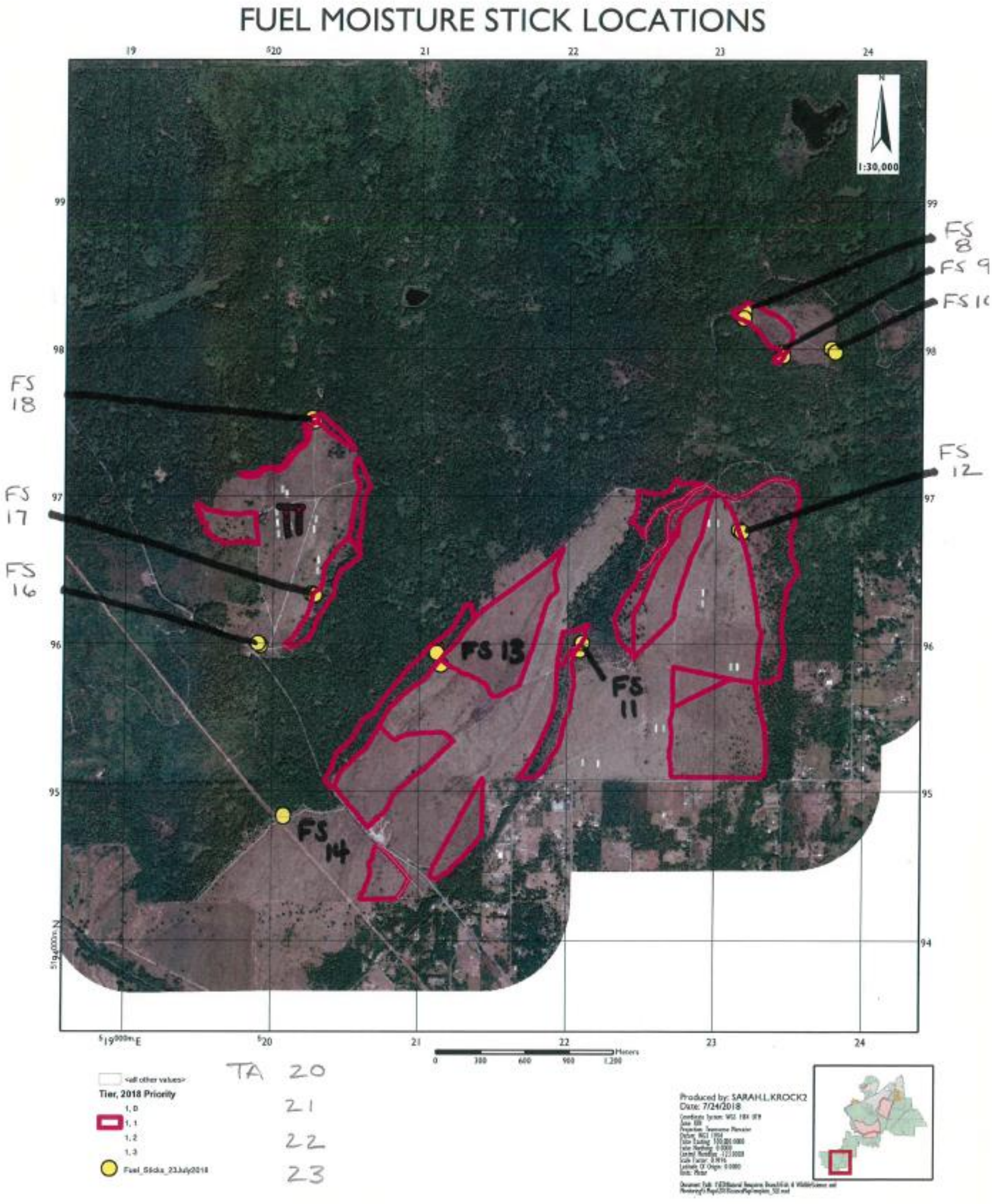

Figure 4.1b

Figures 4.1a and **4.2b** depict fuel moisture analogs (also known as 'fire sticks') locations throughout JBLM-controlled prairies as yellow dots. Red-lined polygons are areas which had high-burn priority during the 2018 prescribed burn season. Maps created with Arc GIS software by Krock, (2018).

4.1- Introduction

In Chapter 1, I covered the history of prescribed burns on the South Puget Sound prairies. In Chapter 2, I discussed weather and its relation to fire ecology in general and its specific role in target plant species phenology. Chapter 3, "Study-Specific Plant Phenology", examined why three specific plants have been burned, according to their phenology. This chapter ties these critical components into a cohesive fire fuel moisture data collection and analysis plan. In essence, the first three chapters explained why the data in this project is important; this chapter explains how the data was collected and analyzed. It also illuminates gaps in the fuel moisture stick data collection; although data should be collected and analyzed daily, only 18 days out of the approximately three-month long, 2018 fire season saw actual field work. This is critical, and underpins the question this work attempts to answer: "Do the benefits of adding a coarse fire fuel moisture load index to Fire Effects Monitoring Operations (FEMO) outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?"

4.2- Data collection procedure: Dead fire fuels

Burn time indicates the time fire takes to completely burn the fire fuel. The U.S. Forest Service (2005), classified fire fuels according to the amount of time it takes for 2/3 of a given fuel to establish equilibrium with the atmosphere. Equilibrium, in this case, refers to fuel moisture content and atmospheric moisture content being equal. Dead fire fuels are binned according to their diameter and referenced according to their equilibrium time: 1-hour, 10-hour, 100-hour and 1,000-hour. The fuel moisture sticks referenced throughout this work represent 10-hour fire fuels.

Dead fire fuels vary in their composition, size, decomposition state, etc., all of which can inhibit accurate moisture load measurements. The Utah Bureau of Land Management's Fuel *Moisture Sampling Guide* (2007) recommended using an analogy with known dimensions and similar moisture sequestration properties as dead floral tissues. That analogy is the fuel moisture stick (Figure 4.2a).

Beginning in 2017, the Center for Natural Lands Mangement Prairie Restoration Specialist Kathryn Hill deployed fuel moisture sticks throughout the areas depicted at the beginning of this chapter in Figures 4.1a and 4.2b (Hill, personal correspondance, 2018). Hill selected sites according to burn priority. Priority was assigned to sites that had not burned within the previous five burn seasons. Hill positioned the fuel moisture sticks close to live fuels collection points (covered in the following section). A separate control fuel moisture stick was sited beneath a mature Douglas fir tree immediately adjacent to the JBLM Fish and Wildlife office. The fuel moisture sticks reside approximately four inches above the target detrtus in a wire bracket that prohibits fuel moisture stick contact with the ground. This ensures the sticks sequester atmospheric moisture, rather than ground moisture. Ground moisture persists temporally, and may not reflect atmospheric conditions. Thus, a fuel moisture stick resting on the ground will absorb more moisture than what it would have absorbed if it had no contact with the

Figure 4.2a- Wooden dowels of consistent composition, length and height suspended from the ground are useful analogs for dead fuel moisture loads. *Image taken from: forestrysuppliers.com*

ground, resulting in misleading data. Additionally, fuel moisture sticks were allowed approximately two weeks acclimation time in the study site. Hill replaced them on a bi-weekly basis because of diminished moisture sequestration capacity; the fuel moisture sticks became either too dry or too saturated to provide accurate measurements. Damaged fuel moisture sticks were also replaced as needed.

Figure 4.2b- Fire stick weight is determined *in situ* with a portable spring scale. *Image taken from: forestrysuppliers.com*

Hill, along with AmeriCorps and Veteran Conservation Corps prairie science technicians, weighed fuel moisture sticks daily, or as often as time and personnel allowed, beginning in April and concluding in October. Dry fuel moisture sticks weigh 100g; moisture load was then determined by weighing a deployed fuel moisture stick *in situ* with a spring scale with a 200g capacity (Figure 4.2b). and comparing that weight to the base weight. The following equation results in percentage net weight:

$$\frac{(Wet\ weight - Dry\ weight)}{Dry\ weight} * 100 = \%\ moisture$$

Where:

Wet weight= The fuel moisture stick's observed weight with a moisture load

Dry weight= The fuel moisture stick's standardized weight with no moisture load

% moisture content= The desired data

EXAMPLE:

The observer discovers a fuel moisture stick weighs 115g. Plugging this value into the equation reveals the fuel moisture stick's moisture content equals 15 percent.

This value indicates low-moisture content and corresponds to a low fire ignition point (requires less direct contact time with the fire before igniting).

Other data, including temperature, RH and wind speed (see Chapter 2) at collection time, were also included as contributing factors in the fuel moisture stick moisture content. Chapter 5 discusses the ramifications of these data and how they answer the core question around which this work revolves.

4.3- Data collection procedure: Live fire fuels

Figure 4.3a- Technicians collected live samples from Scotch broom, Douglas fir and Snowberry, which was then sealed in aluminum sample containers **Figure 4.3b**. ***Fig. 4.3a*** *photo taken from U.S. Forest Service "Fuel Moisture Collection Methods- a Field Guide" (2011).* ***Fig. 4.3b*** *taken from specialtybottle.com.*

Live fire fuel samples originate from living plants located within study sites (Figures 4.1 and 4.2), and often spacially coincided with fuel moisture sticks sites. Technicians collected foliage from Scotch broom (*Cytisus scoparius*), Snowberry (*Symphoricarpos albus*) and Douglas fir (*Pseudotsuga menziesii*) on a bi-weekly basis so that each sample would indicate how the foliage adapted to local atmospheric conditions during the previous two weeks. Chapter 3 of this work analyzes the phenology of these plant species. Using pruning shears, technicans collected specimens from shaded and unshaded portions of target flora. Clippings amounted to approximately 4 – 6 ounces, and represented foliage from different sections of the plants. Bulkly foliage, such as seed pods and pinecones, were omitted from the study because of their latent high water content (See Chapter 3). Live foliage moisture (leaves and needles) is a more important index for plant adaptation to local atmospheric conditions because transpiration occurs in these extemities. Figures 4.3a and 4.3b provide examples of what field technicians collected throughout this study.

Foliage with visible moisture (dew) was eliminated from sample consideration. Sample containers were to remain dry and closed to reduce moisture accumulation on the interior surfaces. Once collected, the lids were immediately replaced to prevent further moisture sequestration by the foliage as well as along sample container interior surfaces. Excess moisture could result in misleading data. Care was also taken to ensure foliage samples maintained their moisture content until the next step in the data collection phase. Full sample containers were weighed *in situ* and secured within a cooler for transport to the JBLM Fish and Wildlife Office for further processing..

At JBLM, sample container lids were removed and the container bottoms and samples were placed in a drying oven at 100^{o} C for 24 hours. Dessicated samples were weighed again for comparison against their wet weight; percent moisture content was calculated using the following equation:

$$\frac{wet\ foliage\ weight}{dried\ foliage\ weight}(100) = \%\ moisture\ content$$

Where:

Wet foliage weight = foliage weight at time of clipping from plant

Dry foliage weight = foliage weight after 24-hour drying period.

Container weight (31.8g) was factored out of the equation by taring the scales before weighing each sample.

EXAMPLE:

The observer discovers a Snowberry sample weighs 47.03g at collection time. The 24-hour drying period reduces foliar weight to 38.52g. Plugging these values into the equation reveals the plant's moisture content at time of collection was 122.1%. Values exceeding 100% is counterintuitive until we remember live fuels transrespire atmospheric moisture, and so a given sample will weigh more if it contains greater water amounts.

4.4- Conclusions

Chapter 4 provided a detailed look at how dead and live fuels were collected during the 2017 and 2018 fire seasons. Section one explained the need for fuel moisture sticks and their correpsonding collection procedures. Section two provided the same type of information for live fuels. Each section highlights the basic equations technicians and the author used to determine fuel moisture content in foliar samples. Chapter 5, "Study Statisics and Discussion" details the statistical analyses used in determining the usefullness of the dead fuels data when answering the question: "Do the benefits of adding a coarse fire fuel moisture load index to Fire Effects Monitoring Operations (FEMO) outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?"

Chapter 5

Study Statistics and Discussion

5.1- Introduction

Chapters 1, 2, and 3 provided relevant background information regarding fire ecology on the South Puget Sound prairies. Chapter 4 outlined the data collection processes. This chapter details how and why I have decided fuel moisture sticks should be integrated into the Center for Natural Lands Management's Fire Effects Monitoring Operations (FEMO).

Section 5.2 includes a series of graphs generated in R Studio showing the correlations between specific data. The third section acts as a cost-benefit analysis; each fuel moisture stick has a monetary value, but analyzing them requires time and manpower. I use correlations in section 5.2 to test my hypotheses:

$H_{0=}$ The costs of adding a coarse fire fuel moisture load index to FEMO outweigh the benefits of new data that could be used by fire managers before a prescribed burn event.

$H_{a=}$ The benefits of adding a coarse fire fuel moisture load index outweigh the costs, and the new data should be used by fire managers before a prescribed burn event.

5.2- Fuel moisture stick correlations

I compiled dead fuels (fuel moisture stick) field data in Microsoft Excel 2010 and analyzed them in R Studio (v. 3.5.0). I omitted data collected on field day 1 from the analysis because the field technicians did not correctly annotate the data; i.e., recording wind speed as a range of value, rather than as a precise decimal value. I also omitted the "Fish & Wildlife Office" fire moisture stick data because these were rarely collected in either year. The value “0” appears in wind speed column at infrequent intervals. I did include these data in the analysis because “0” is a possible wind speed value. There are no zeroes in the RH or temperature columns; zero percent relative humidity is physically impossible except in laboratory-controlled environments, and zero degree temperature is just as impossible during Puget Sound summer months. Thus, I determined the relationships among the following pairs of data found for the fuel moisture stick field data:

- Relative humidity and fuel moisture stick percent moisture levels – SHADED and UNSHADED
- Temperature and fuel moisture stick percent moisture levels – SHADED and UNSHADED
- Wind speed and fuel moisture stick percent moisture levels – SHADED and UNSHADED

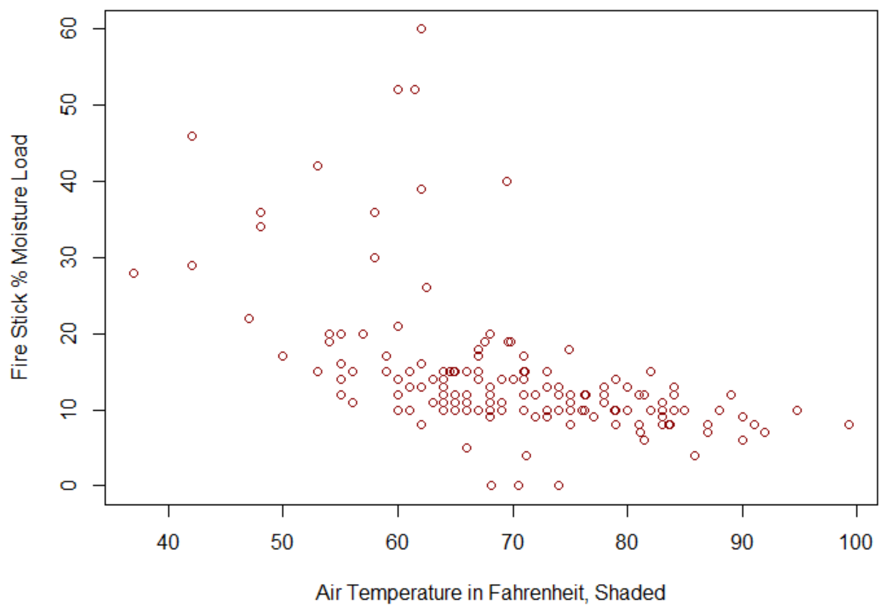

Table 5.2a- Correlation: Shaded temperature (F°) and percent fire stick moisture loads. A standard Pearson's product moment correlation. Where, t = -7.5551, df = 156, and a p-value = 3.318e-12, shows a moderately to moderately-strong negative correlation (-0.52, 95% CI: -0.6233371, -0.3932071) between air temperature and fire stick moisture levels in the shade. In other words, fire sticks will absorb atmospheric moisture as intended, partially irrespective to prevailing temperatures.

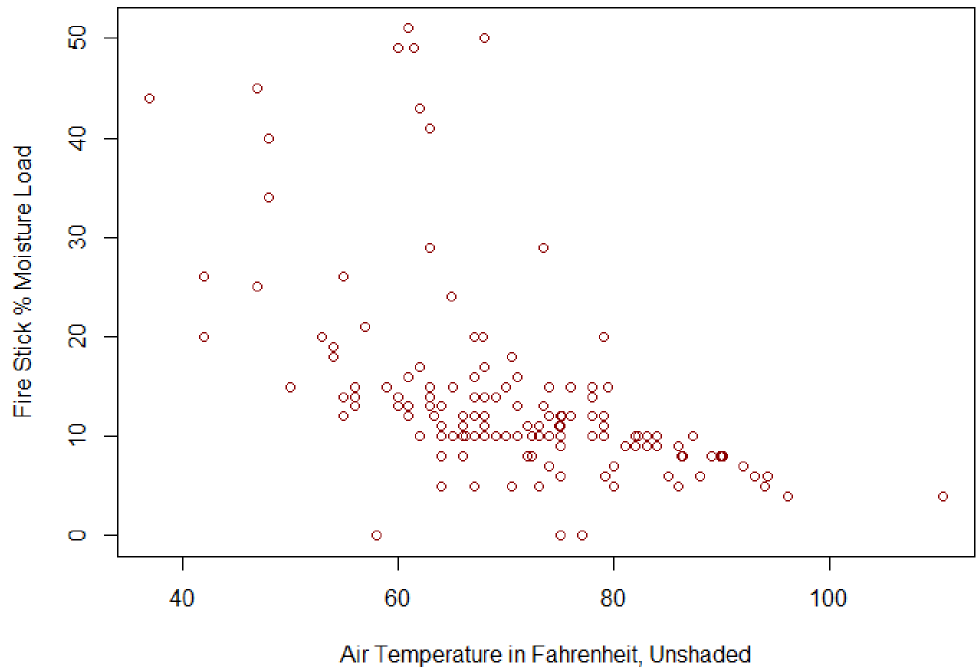

Table 5.2b- Correlation: Unshaded temperature (F°) and percent fire stick moisture loads. - A standard Pearson's product moment correlation. Where, t = -8.0034, df = 156, p-value = 2.586e-13, shows a moderately to moderately-strong negative correlation (-0.54, 95%CI: 0.4998497, 0.6982933) between air temperature and fire stick moisture levels in areas with no shade. In other words, fire sticks will absorb atmospheric moisture as intended, regardless of prevailing temperatures, and the presence or absence of shade makes no statistically or practically significant difference in this test.

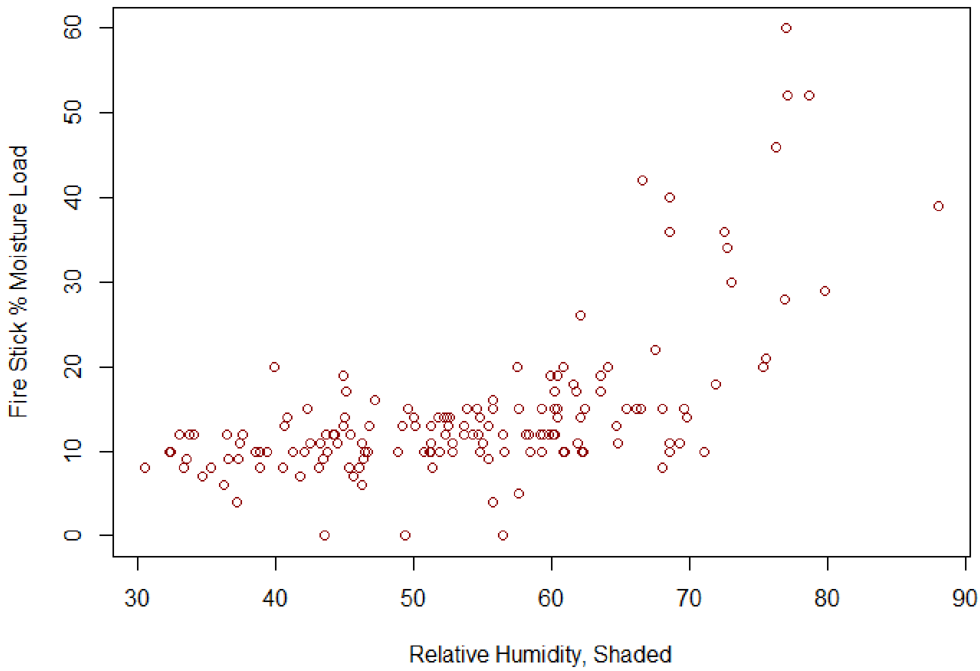

Table 5.2c- Correlation: Shaded RH and fire stick percent moisture loads. A standard Pearson's product moment correlation. Where, $t = 9.5773$, $df = 156$, p-value $< 2.2e-16$, shows a moderately strong positive correlation (0.61, 95% CI: 0.4857753, 0.6886440) between RH and fire stick moisture levels in the shade. A fire manager can expect this reading from their fire stick because it means the fire stick is absorbing atmospheric moisture as designed by the manufacturer. This metric is better than temperature because it is RH, not necessarily temperature, which drives dead and live foliar moisture levels. See Chapter 2 for more discussion on this point.

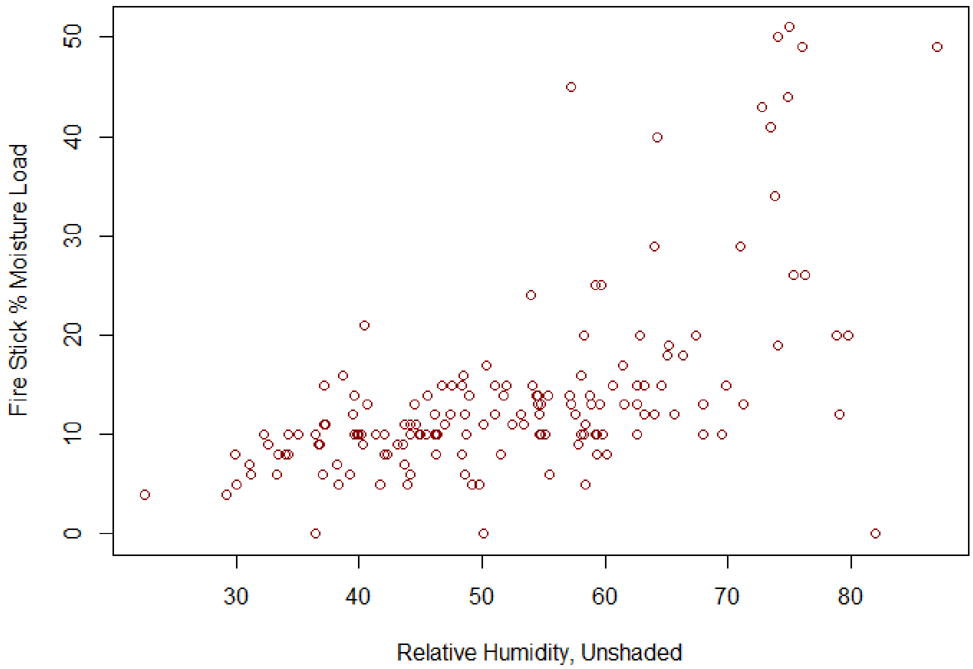

Table 5.2d- Correlation: Unshaded RH and fire stick percent moisture loads. A standard Pearson's product moment correlation. Where, t = 9.2864, df = 156, p-value < 2.2e-16, shows a moderately strong correlation (0.6, 95% CI: 0.4857753, 0.6886440) between RH and fire stick moisture content in the shade. RH, not air temperature, drives absorption to a far greater extent. The somewhat higher temperatures out of the shade will slightly accelerate the absorption process.

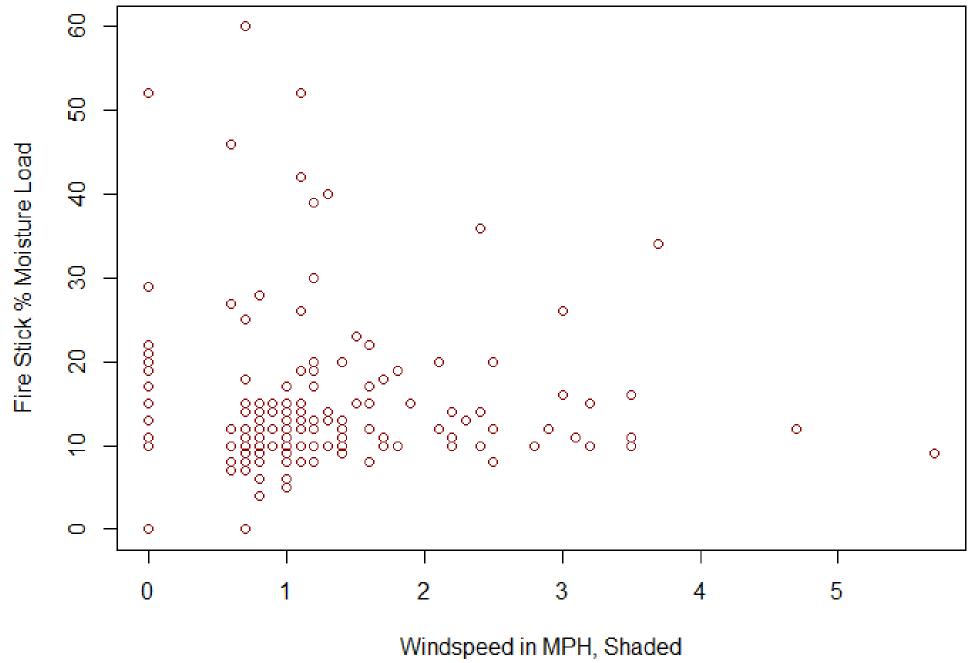

Table 5.2e- Correlation: Shaded wind speed (MPH) and fire stick percent moisture loads. A standard Pearson's product moment correlation. Where, t = 0.024702, df = 161, p-value = 0.9803, shows a minute positive correlation (0.002, 95% CI: -0.1518191, 0.1556207) between wind speed and fire stick moisture content in the shade. I included these data because they support the narrative regarding wind speed and the absorption process, which is found in Chapter 2 of this work.

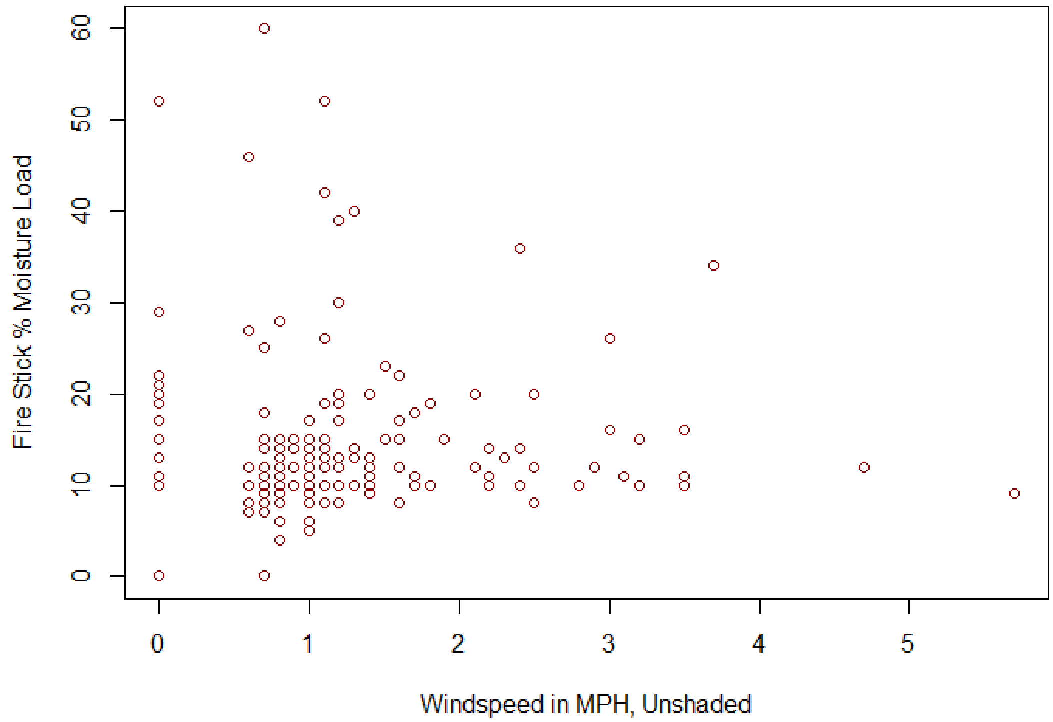

Table 5.2f- Correlation: Unshaded wind speed (MPH) and fire stick percent moisture loads. A standard Pearson's product moment correlation. Where, t = -0.18481, df = 161, p-value = 0.8536, shows an almost non-existent negative correlation (-0.01, 95% CI: -0.1679081, 0.1394692) between wind speed and fire stick moisture content when unshaded. This is further evidence that wind speed is the weakest factor in absorption regardless of shade, as stated in Chapter 2 of this work.

These graphs, and the statistical analyses behind them, provide sufficient enough evidence to reject the null. Fuel moisture sticks detect dead fuels moisture levels with practically significant accuracy to fulfill their originally stated purpose, to "determine a relationship between 10-hour dead fuel moisture measured using fuel [fire] sticks… to create a coarse and easily accessed reference point on the morning of a burn" (Kronland, p.1, 2017).

The next section outlines equipment costs, specifically those of fuel moisture sticks, and weighs these costs against the benefits of safe fire operations from my perspective as a professional firefighter.

5.4- Costs for Fuel moisture stick integration into FEMO

According to the CNLM Prairie Restoration Specialist Kathryn Hill, a bundle of 10 fuel moisture sticks from costs approximately $33.00. Fuel moisture sticks were deployed through various JBLM in shaded and unshaded areas at 27 individual locations. Fuel moisture sticks were replaced bi-weekly because of moisture sequestration capacity losses (the untreated wooden dowels are susceptible to decay). Thus:

$$3\ bundles\ of\ 10\ fire\ sticks\ @\ \$33.00\ per\ bundle = \$99.00$$

$$3\ replacement\ bundles\ of\ 10\ fire\ sticks\ @\ \$33.00\ per\ bundle = \$99.00$$

$$\$99.00 + \$198.00 = \$297.00\ total\ for\ fire\ sticks.$$

Each bundle rests on a cradle in the field to prevent ground moisture sequestration (see Figure 4.2), and each cradle costs approximately $18.00 (Forestry Suppliers, 2019), for approximately $486.00 total for cradles. Finally, a hanging scale (Figure 4.6) to weigh the sticks costs approximately $59.00 (Hill, personal correspondence, 2019). Therefore, estimated equipment cost for an effective fuel moisture stick study equals $842.00.

Personal correspondence with Hill also revealed she became overwhelmed because she lacked the time to drive to each site and then collect and process data in a timely manner. The JBLM Fish and Wildlife office hosts interns and students from Americorps, Veterans Conservation Corps, Washington Conservation Corps, and various colleges. Each organization compensates their interns in accordance with their own guidelines, and so CNLM's manpower costs are limited to paying the project leader. Fuel costs for movements throughout the training areas vary according to vehicle make, model, fuel type, and engine capacities and so are not quantified here.

Experienced prescribed fire managers are well aware of the dangers fire ecology pose, which means they are also open to the idea of attaining more data, as long as the data are useful and reliable. The costs outlined here can be even further reduced if fuel moisture sticks are deployed only in training areas in which prescribed burning is imminent. Fuel and manpower costs only accrue if crews actually deploy or replace fuel moisture sticks as necessary, and as long care is taken during data collection (e.g., ensuring fuel moisture sticks are secured in their cradles, not broken during weighing, *et cetera*), FEMO should be able to absorb initial costs with minimal concern for cost overrun.

5.5. Discussion

Author's note- The following section contains my expert opinion on fire safety and equipment protocols. I am a fully-credentialed, Department of Defense (DoD)-trained Firefighter Driver/Operator. I have 16 years of structural, wildland and aircraft fire fighting experience on various military bases in the United States and in Afghanistan.

Safety is paramount in all fire operations. Personal experience helps me understand how the presence of proper equipment on a fire scene will determine effective fire operations.

An enemy rocket directly impacted the fuel depot at Kandahar Airfield, Afghanistan in July, 2010. Standard procedure for petroleum fires requires vast quantities of Aqueous Film-Forming Foam (AFFF) mixed with water and discharged from the Airport Rescue and Fire Fighting (ARFF) apparatus' water turrets. Unfortunately, the only apparatus capable of this attack was out-of-service and located at the repair shop on the other side of the base. We had other ARFF apparatus, but none of them carried AFFF. Each of our two remaining ARFF apparatus carried 3,000 gallons of water, which they quickly discharged onto the 150,000 gallon JP-8 (kerosene) fire. However, because water alone cannot extinguish petroleum fires, we dumped well over 10,000 gallons of water onto the blaze and made zero progress.

In the meantime, mechanics scrambled to release the apparatus with foam capacity back into service. Two hours after we received the first emergency call, the foam-carrying apparatus arrived on scene and used the appropriate agent to extinguish the fire within minutes. When I recall the sheer quantities of water we used before we had access to the correct firefighting agent, I think of a firefighter rule-of-thumb: It is better to have everything you need and not use it, than to need something you do not have. In other words, it is logical to have all available tools on hand and ready for use in all situations.

This Chapter quantifies the need for an additional metric that can be used by prescribed fire managers on the morning before a fire event. The non-profit nature of the CNLM means that every dollar spent on actions and motives must be justified for their various grant holders and other cash sources. As a DoD Firefighter, I am well aware of the potential for disaster when attempting an action before gathering all possible data and tools. The statistics are sound, and the logic is clear: I reject the null in favor of the alternate hypothesis. I conclude the Center for Natural Lands Management should include dead fire fuel analogs, also known as fuel moisture sticks, for the purpose of creating a coarse and readily available fuel moisture load index that can be used to enhance fire behavior predictive abilities. The Center for Natural Lands Management conducts more prescribed burns with each passing year. 117 burn operations were conducted through Washington and Oregon's prairies in 2018 (Puget Sound Ecological Fire partnership, 2019). Maintaining safe fire operations is always the top priority, and the data shown here indicates that the addition of fuel moisture sticks will enhance safe prescribed fire operations. Thus, when viewed through this lens, I submit that the CNLM should integrate fuel moisture sticks into their fire effects monitoring operations.

Conclusion

Chapter review and procedural recommendations

My Thesis explores a specific, but crucial data gap. The CNLM already knows of the existence of fuel moisture sticks and their successful role in other fire ecology programs, but the question I explored here is one of worth. In essence, will CNLM burn managers benefit from the data fuel moisture sticks provide? With the use of statistics, I have concluded that the addition of fuel moisture sticks are worth the monetary and time commitment because the data they yield will only enhance fire behavior prediction abilities, which translate into safer fire operations.

Chapter 1 is a chronological timeline of the evolution of fire ecology on the South Puget Sound prairies. I also showed how societal views on how the prairies are considered valuable; value is dependent on what a given society assigns. Native Americans valued the prairies because they attracted game while the U.S. Army valued the land for training soldiers. Currently, the prairies are restored to pre-European settlement conditions because those conditions harbor greater biodiversity than the conditions found in most of the modern prairie remnants.

Chapter 2 discussed South Puget Sound weather because of its paramount role in all aspects of life on the prairies, including plant phenology and fire ecology. I explained how our climate is classified by its hot, dry summers and mild, moist winters. I then introduced temperature, relative humidity and wind speed because of their immediate relationship to this study.

Chapter 3 explores the phenology of the three plants targeted for live fuels moisture data. I must point out here, as I did in Chapter 3, that although these data are omitted from the analysis I performed to answer my question, they are nonetheless important for FEMO. Live fuels moisture loads, if tracked over the course of several years, should reveal a trend in foliar moisture dependent on seasonal climate changes. If this turns out to be the case, then this data will become extremely important in determining future prescribed burn operations.

Chapter 4 simply illuminated the data collection processes and procedures. Fuel moisture sticks were used as analogs for 10-hour deal fuels, and according to the study protocol, should have been collected daily throughout the fire season. However, only 18 days' worth of viable data was actually collected because of time and personnel constraints. This limitation is a core consideration of whether fuel moisture sticks are worth the additional time and effort their use entails.

Chapter 5 answers the question, "Do the benefits of adding a coarse fire fuel moisture load index (fuel moisture sticks) to Fire Effects Monitoring Operations (FEMO) outweigh the monetary costs to deploy, monitor and use them on the mornings prior to prescribed burns?" I set my null and alternate hypotheses to the following for testing:

$H_{0=}$ The costs of adding fuel moisture sticks to FEMO outweigh the benefits of new data that could be used by fire managers before a prescribed burn event.

$H_{a=}$ The benefits of adding fuel moisture sticks outweigh the costs, and the new data should be used by fire managers before a prescribed burn event.

Using R Studio, I established correlations among the following variables:

- Relative humidity and fuel moisture stick percent moisture levels – SHADED and UNSHADED
- Temperature and fuel moisture stick percent moisture levels – SHADED and UNSHADED
- Wind speed and fuel moisture stick percent moisture levels – SHADED and UNSHADED

I found moderately-strong negative correlations between temperature and fuel moisture stick moisture loads in both shaded and unshaded locations. Relative humidity and fuel moisture stick moisture loads showed nearly-identical significant, moderately-strong correlations between shade and unshaded conditions. Wind speed in either shaded or unshaded places and fuel moisture stick moisture loads had no statistically or practically significant correlation. These results demonstrate that fuel moisture sticks can be used as originally intended and as outlined in the study protocol. Fuel moisture sticks are designed to absorb atmospheric moisture in the same manner as dead foliage that was recently dropped by the host plant. The correlations between RH and fuel moisture stick moisture loads was strong enough for me to decide that CNLM fire managers will benefit from fuel moisture sticks as a readily accessed fuel moisture load data point, and I recommend fully integrating them into Fire Effects Monitoring Operations for future use.

Notes

I, Jason M. Keyes, do hereby declare all information contained in this Thesis is true and correctly stated to the best of my knowledge. All references are cited; any errors are mine and mine alone.

I have not received monetary compensation for any portion of this study.

Inline citations referencing personal correspondence with Kathryn Hill indicate E-mail transmissions.

I also analyzed the live fuels moisture data that was explained in Chapter 4, but decided against including those results here. The live fuels moisture data are intended for another project that will attempt to track changes to the target plants' phenology as climate change progresses at current rates. Chapter 2 briefly mentions that Puget Sound summers may become warmer and summer-like conditions (hot temperatures and low RH) may persist later into the year.

Finally, I do hereby declare my participation in the data collection processes was minimal. This is my second attempt at a Thesis for the Master of Environmental Studies program. My first project, which involved reptiles, failed because of a lack of data (the reptiles were not attracted to the coverboards, and so I could not establish herpetofaunal population counts). The data used in this Thesis was furnished to me by Dennis Buckingham via Fayth Shuey, the original field leader. I did, however, enter all data into the Excel spreadsheets and performed all R analyses on my personal computer.

And remember, no matter where you go, there you are.

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Appendix A

This is the first page of the project protocol. It lists four objectives CNLM hopes to achieve through this study. The first objective is the establishment of a coarse fire fuel moisture load index within their Fire Effects Monitoring Operations; my Thesis answers the gap in this specific data.

JBLM Burn Program: Woody Fuels and Duff Moisture Monitoring

Current JBLM fire effects monitoring (FEM) is focused on open prairie burn units (mainly in or near Priority Habitat), tracking how fuel conditions affect temperatures, severity, and post-burn vegetation in mostly thatchy fine fuels (Kronland et al. 2017). There remains a lack of data on how moisture in woody fuels and duff within edge or woodland units (as well as woody or shrubby areas of prairies) varies with phenology and weather – and how these changes affect fire behavior and effects. A woody-fuels monitoring project will be initiated to address these information gaps, with pilot data collected in 2017 informing future years of fuels monitoring.

Objectives

1. Determine a relationship between 10-hr dead fuel moisture measured using fuel sticks at the JBLM F&W office and moisture measured in specified burn units of interest, to create a coarse and easily accessed reference point on the morning of a burn.
2. Assess how moisture of 10-hr dead fuels, live shrubs, and live conifer needles change over the course of the burn season (i.e., spring – fall) and in response to weather events.
3. Relate moisture measurements to specified elements of interest in fire behavior (e.g, likelihood of torching or self-extinguishment) and fire effects (e.g., shrub consumption).
4. Develop protocols for a pilot FEMO program for South Sound habitats that includes observations on fire behavior and first-order effects for designated burns, which will be implemented on a trial basis throughout the 2017 burn season.

Protocol

For the fuel moisture pilot project, data will be collected from several potential 2017 burn units from April – October (or until they are burned), at the following frequencies:

Fuel type	Frequency
10-hr dead fuel moisture – shaded and unshaded	Daily, or as available
Live woody fuel moisture – Scotch broom	Every two weeks
Live woody fuel moisture – snowberry	Every two weeks
Conifer foliage moisture	Every two weeks

Dead fuel moisture for 10-hr fuels can represent moisture in non-living Scotch broom (or other shrub) detritus and stubble which carry fire through shrub patches or at ground level; as close to a daily measurement as possible would be ideal for tracking responses to weather changes. Live woody fuels and foliage also affect fire behavior, but have slower response times – a 10- to 15-day monitoring interval should be sufficient to capture moisture trends (Pollet and Brown 2007); however, if a precipitation event occurs after the biweekly monitoring but before a burn, additional sampling should be conducted prior to the burn. Data collection should take place at a similar time each day (e.g., mid-morning or mid-day).

Appendix B

Field data were collected and hand-scribed into a printed Excel 2010 spreadsheet. Data were tabulated in pencil for immediate error correction. Completed data sheets were maintained until all data were entered into the electronic Excel spreadsheet. These data were then configured to be compatible with R Studio.

10-hour dead fuel moisture								
Observer(s):					Date:			
Fire Stick Location	Fire Stick Name	Type	Temp (^{o}F)	RH (%)	Wind speed (mph)	[A] Wet weight	[B] Dry weight	Percent moisture [(A-B)/(B)] *100
		Shaded						
		Unshaded						
		Shaded						
		Unshaded						
		Shaded						
		Unshaded						
		Shaded						
		Unshaded						
		Shaded						
		Unshaded						

Appendix C

My Department of Defense firefighter certifications, along with my extensive firefighting career, make me qualified to discuss safe fire operations.

DEPARTMENT OF DEFENSE
FIRE & EMERGENCY SERVICES CERTIFICATION PROGRAM
LOOKUP SYSTEM

Lookup System | Performance Test Notification | Mail Tracking System | Related Links | About the Program

To print a copy of this certification record, use CTRL + P keys simultaniously.
Click on the TITLE or SEAL NUMBER link to open the certificate and print it locally.

PLEASE DO NOT BOOKMARK THIS PAGE IN YOUR BROWSER

DOD CERTIFICATION CERTIFICATES ISSUED TO KEYES 4937

Title	Edition	IFSAC Seal Number	Date Certified
Airport Firefighter		353929	13 Nov 2000
Driver/Operator ARFF		578859	23 Sep 2003
Driver/Operator Mobile Water Supply		1668466	16 Mar 2012
Driver/Operator Pumper		583356	28 Oct 2003
Firefighter II		353928	13 Nov 2000
Hazardous Materials Operations		353930	13 Nov 2000
Public Telecommunicator I/II		577420	11 Sep 2003
Firefighter I		Implied	
Hazardous Materials Awareness		Implied	