USING FIRE FOR BUTTERFLIES:

SOIL CHARACTERISTICS ACROSS A BURN GRADIENT IN WESTERN WASHINGTON PRAIRIES

by

Robyn Andrusyszyn

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Robyn Andrusyszyn

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by

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Carri LeRoy, Ph.D.
Member of the Faculty

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Date

ABSTRACT

Using fire for butterflies: Soil characteristics across a burn gradient in western Washington prairies

Robyn Andrusyszyn

Prescribed burning has become an important strategy for restoring Puget lowland prairies in the Pacific Northwest. Mosaic burning is employed to create a large variety of habitat conditions to help restore populations of rare species, including the Taylor's checkerspot butterfly (*Euphydryas editha taylori*). This important pollinator species is very sensitive to microclimatic habitat conditions. To better understand the microclimatic conditions provided by fire, as well as the succession of those conditions, I evaluated surface temperature, subsurface temperature, and soil moisture across a burn gradient from 2009 to 2013 at two different prairie sites on Joint-Base Lewis-McChord. In the winter months of January through March 2013, temperatures in areas last burned in 2009 were significantly cooler than temperatures from other burn years. Soil moisture did not vary significantly among burn years. Regular burning at an interval of every three to four years provides a warmer microclimate, and supports the current estimated historic fire return interval. Maintaining these habitat conditions may provide an advantage for Taylor's checkerspot butterfly larval success.

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Chapter 1 - Literature Review

Fire Disturbances

Wildfires are a natural disturbance that regularly influences ecosystems. Fires accelerate new growth, alter community structure, and diversify available habitat (Noss et al. 2006). However, nuisance smoke, loss of natural resources, and the potential danger to people have created a fear of wildfires since the late 19th century (Dombeck et al. 2004). Recently we have begun to recognize the positive changes that fire disturbance events have on the environment. Not only are there ecological benefits from fires, but some ecosystems actually depend on fires for survival. In the African bush, fires drive ecosystem dynamics and maintain the grassland-dominant system (Parr and Andersen 2006, Ribeiro et al. 2008). Savannas in the southeastern United States depend on fires to remove competing non-native species and allow the coexistence of numerous native species (Kirkman et al. 2001, Parr and Andersen 2006). In the northwestern United States, prairies require fires to increase nutrient availability to plants and open habitat for wildlife (Agee, 1996). The alteration of natural fire regimes has modified forests and decreased prairie and oak woodland habitat in the Pacific Northwest (Hamman et al. 2011). Fire disturbance events play a crucial role in ecosystem maintenance and this has become even more apparent through anthropogenic changes to natural fire regimes.

Native Americans demonstrated an early knowledge of fire benefits through their use of fire to maintain certain ecosystems. As early as the 15th century, Native Americans in the northwestern United States burned for agriculture as well as hunting and gathering purposes (Shinn 1980, Walsh et al. 2010). A decline in Native

American populations, as well as the influence of Euro-Americans, led to a decrease in fire activity in the early 20th century. In the 1930s the United States Forest Service instituted fire suppression regulations intended to limit resource losses from wildfires (Dombeck et al. 2004, Jensen and McPherson 2008). However, these fire suppression practices are costly and largely have not been successful in preventing catastrophic fires (Neary et al. 1999, Brown et al. 2004, Jensen and McPherson 2008). The inability of fire suppression practices to prevent large-scale catastrophic wildfires has led to a loss of natural resources. Some of the largest impacts are felt in logging communities when large wildfires kill most, or sometimes all, of the trees that were available for timber harvest (Noss et al. 2006). Furthermore, the negative ecological impacts from fire suppression, including an increase in non-native species prevalence and decreases in habitat heterogeneity, demonstrate that fire disturbances are crucial components to ecosystem maintenance (Shinn 1980). Long-term fire suppression may lead to an abundance of fuel for large, intensive fires. As fuel loads increase, potential fire severity increases. When fire does come to such an area, it often burns hotter and longer, causing increased resource and ecosystem damage. The natural mosaic that would have previously prevented much of the area from being fully destroyed diminishes as fuel loads increase (Noss et al. 2006). Instead of increasing the potential for resource losses, proper maintenance of historic fire regimes can better preserve resources.

In order to find a more effective method of preventing large-scale, destructive fires, land managers have begun to reintroduce natural fire regimes to fire-dependent ecosystems through prescribed burning. Prescribed burning for ecological management became more common in the United States starting in the late 1980s (Jensen and McPherson 2008), but this practice was used as early as the 1970s by park managers in South Africa (Brown et al. 1991) and Australia (Bradstock et al. 1998). In 1995, the United States adopted the Federal Wildland Fire Management Policy. This called for improved fire management plans and recognized that fire was a fundamental ecological process (Jensen and McPherson 2008). The recognition of fire as a necessary ecological process created a new challenge to land-managers to effectively and safely incorporate burning into management plans (Stephens and Ruth 2005). Using prescribed fire, smaller and more controlled burns can maintain systems while reducing the risk of future catastrophic wildfires. Land managers have been experimenting with prescribed burning to appropriately and efficiently manage their lands and to protect ecosystems from future catastrophic wildfires. In addition to protection from future wildfires, prescribed burns can be used to achieve other management goals such as nutrient supplementation, habitat enhancement, and reduction in non-native plant species cover.

Using prescribed fire, restoration managers are attempting to further understand fire effects and how to optimize the benefits fire disturbances can provide (Dunwiddie and Bakker 2011). This destructive disturbance provides unique influences on ecosystem functions that are difficult to imitate through other techniques (Harrington and Kathol 2009). Finding a balance between obtaining fire benefits and protecting people and their property is a new challenge for ecological restoration and management. The spread of human development into fire-dependent ecosystems emphasizes the need to live effectively, and safely, with regular fire disturbances (Dombeck et al. 2004).

Prairie Degradation and Fire in Restoration

Prairies are flat, grass-covered ecosystems that are historically adapted to regular fire influences. Prairies are found in areas such as the Midwest and northwestern United States. Retreating glaciers created the Puget lowland prairies of western Washington, which are now very rare and fragmented ecosystems. An estimated 95-99% of native prairies in the Pacific Northwest have been lost to urban development and coniferous forest encroachment since the early 20th century, leaving less than 17,000 ha of fragmented habitat remaining (Hamman et al. 2011). These unique ecosystems not only benefit from fire disturbance events, but depend on them to maintain ecological functions. Native American burning historically maintained the Puget lowland prairies, using fire to improve landscapes for agriculture. This encouraged crops such common camas (*Camassia quamash*), and maintained pastures for grazing herd animals. These practices depended on regular fires to manipulate herd movements and increase nutrient availability in the otherwise nutrient-poor soils of the prairies (Boyd 2002). Frequent low-intensity fires were used to obtain the beneficial influences of fire without a large amount of destruction, maintaining a fire return interval of approximately two to three years (Agee 1996, Rook et al. 2011). The reduced frequency and extent of anthropogenic burning following declines in Native American populations, the influx of Euro-Americans, and the onset of fire suppression practices has increased the loss and degradation of this ecosystem (Walsh et al. 2010, Rook et al. 2011). Without regular burning, noxious invasive species have become widespread and there continues to be encroachment of coniferous forests (Walsh et al. 2010, Hamman et al. 2011).

The sharp decline in prairies has led to a recent increase in restoration efforts. An important component of those efforts is the re-introduction of regular fire disturbance events through prescribed burning. Regular short-interval burning of prairies stimulates plant growth, creates open habitat, and decreases the risk of catastrophic wildfires by reducing fuel accumulation (Agee 1996). Additionally, native plant species that are historically well-adapted to frequent fires may persist over non-native plant species under a frequent fire regime (Hamman et al 2011). Through this effort, the hope is to restore habitat to support populations of endangered and threatened animal species such as the Taylor’s checkerspot butterfly (*Euphydryas editha taylori*) and the streaked horned lark (*Eremophila alpestris strigata*), while preventing further decline of other increasingly rare fire-dependent and prairie-dependent species. Prescribed burning is a cost-effective and time-effective practice that provides habitat enhancement through thatch removal, invasive species removal, and snag creation (Harrington and Kathol, 2009). Regular fires at appropriate fire return intervals can reduce available fuel, maintain open space for new growth, and alter nutrient availability (Neary et al. 1999). Research continues to evaluate the effects of prescribed fires on soils, vegetation, and wildlife, creating evidence to support prescribed burning as a valuable tool in restoration from the perspective of both the public and land managers.

Prescribed burning can achieve many restoration goals at a cheaper and more effective rate than other techniques. Restoration goals include creating habitat for rare fauna and reducing the cover of non-native noxious plant species. Prescribed burning addresses both of these goals in that it can immediately top-kill non-native species including the noxious Scotchbroom (*Cytisus scoparius*) (USDA NRCS 2013), while providing nutrients and space for native species to return (Rook et al. 2011, Stanley et al. 2011). Fire surrogates such as herbicide and mowing are also used to remove non-native species, however at the cost of increased time, effort, and money. Burning can remove acres of Scotchbroom within a few hours, while the same area could take days with herbicide treatment or mowing. Additionally, burning facilitates the removal of thatch and moss as well as the conversion of nutrients in the soil (Harrington and Kathol 2009, Hamman et al. 2011). These influences provide more opportunity for fire-adapted native plant species to out-compete non-native species. Typically fire surrogate techniques are limited in their ability to provide equivalent conservation benefits and are at a higher cost per unit area of land treated compared with prescribed burning (Harrington and Kathol 2009). Maintaining regular prescribed burning events contributes the unique benefits that only fire can provide.

As prescribed fire becomes an increasingly influential restoration tool, knowledge gaps in optimal fire frequency and fire season, species-specific responses, and alternatives to burning become more apparent (Rook et al. 2011). Despite increased management experience in these prairies, there is a lack of quantitative data to support anecdotal evidence of fire effects on soil characteristics, vegetation growth, and wildlife survival (Dunwiddie and Bakker 2011, Granged et al. 2011).

Understanding the long-term impacts of fire on post-burn physical, chemical, and microbial characteristics provides a basis for management decisions. Using this knowledge to better predict future fire behavior and influences will improve the effectiveness of prescribed fires as a management tool. This information may also enhance the predictability of future prescribed burns and wildfires. In turn, the improved management of Puget lowland prairies may reduce the risk of personal injury and property loss to fires while maintaining vibrant and robust prairie ecosystems into the future.

Fire Effects

Fire disturbances have profound effects on the ecosystems they invade. These effects drastically change the landscape, starting with the soil. At first glance, burned areas epitomize destruction and eradication. However, burning transforms nutrients, opens up habitat, and increases the competitive advantage for native species to thrive over non-native species (Shinn 1980, Noss et al. 2006, Hamman et al 2011). Soil characteristics provide the basic building blocks for ecosystem structure and function. Physical and chemical properties of soil, such as temperature, moisture-holding capacity, and nutrient content, influence the recovery of ecosystems following burn events. Characteristic changes in soil microclimate following fire include: changes in surface albedo, reductions in plant density, and increases in nutrient availability. Topographical variation, patchy vegetation, and a variety of moisture levels create diversified soil microclimates across burned prairie landscapes (Gibson et al. 1990, Hart et al. 2005). These habitat variations, along with increased diversity from mosaic burn patterns, improve habitat and promote species diversity. Understanding specific fire influences in each ecosystem may promote better management and restoration of fire-dependent ecosystems.

Soil Temperature

Changes in soil temperature impact the survivability of wildlife, the development of microbial communities, and the growth of plant species. Following a burn event, plant and thatch density is reduced and the soil becomes blackened (Neary et al. 1999). These changes to the soil may create increased daytime temperatures and more rapid loss of heat at night (Kasischke et al. 2007). Seasonal differences include earlier freezing in winter and earlier warming in spring (Fisher and Binkley 2000, Hart et al. 2005). Snyman (2003) investigated differences in unburned and burned patches following a bush fire in South Africa, and concluded that burned areas showed a significant increase in soil temperature in the year post-fire. This was assumed to be partly because of a strong decrease in plant basal cover. In Alaskan black spruce forests, Kasischke et al. (2007) concluded that for the first several decades following a fire, soil temperatures remained elevated. Understanding the relationship between burn events and soil temperature may increase the predictability of plant community recovery and may directly influence prairie-dependent species.

Wildlife can be extremely sensitive to temperature conditions. Post-fire, warmer soil temperatures can increase the growth of food plants and alter winter survivability of animals. Temporary increases in bird and mouse observations occur in recently burned areas, possibly due to increases in food supplies and soil temperature changes

(Bock and Bock 1983). After a fire in the Sierra Nevada foothills, nesting bird density and large predator density increased (Lawrence, 1966). Species diversity can also change in relation to new habitat characteristics that are created from fire disturbances; fire-adapted species that thrive on a warmer, more open habitat increase in abundance after a burn, while species requiring more sheltered conditions tend to leave a burned area (Simons 1991, Tiedemann et al. 2000). Fire can also directly have a negative impact on species when animals are unable to escape an oncoming fire, most commonly rodents, small amphibians, and insects.

Soil microbial communities drive nutrient conversion and form mutualistic relationships with plants (Hart et al. 2005). Fire influences on microbial communities create concomitant reactions throughout plant communities. Microbial mortality can occur from increased soil temperatures during a fire event, which in turn influences the recovering plant community (Neary et al. 1999, Hart et al. 2005). Nutrient demands and mutualistic relationships vary based on both microbe- and plant-availability post-burn (Neary et al. 1999). Microbial and plant communities simultaneously depend on one another for post-burn recovery.

Surface temperatures reached both during a fire and in the months following a fire strongly influence the plant community that recovers. Increases in temperatures, especially daytime temperatures, can accelerate plant growth and productivity (Heuvelink 1989). Soil temperature can also influence the germination of plants post-fire. Native plant species that are better adapted to exposure to high temperatures are likely to be given competitive advantage over non-native plant species that become established when fire is excluded from the ecosystem. One strategy employed by fire-adapted plants is the creation of a seed bank in the soil. These dormant seeds are protected by strong seed coats that need the intense heat of a burn to break dormancy and germinate (Keeley 1987, Agee 1996). Different seeds have different temperature requirements to break dormancy, but some fires create soil temperatures that are warm enough to destroy seeds. Furthermore, topographical variation creates temperature variation both during and after a fire. Variation in burn season also typically has a strong influence on which seeds break dormancy. For example, Bradstock and Auld (1995) demonstrated that the increase in soil temperature after a summer fire could be enough to break seed dormancy for some plant species, but the same was not true following a winter fire. The plant community that recovers post-burn will depend on which seeds are able to break dormancy and the growing conditions available on a micro-scale.

Nutrient Levels

In addition to changes in temperature, soil nutrient availability changes after the passage of a fire. The intense heat modifies soil stability, alters chemical compositions, and adds new soil nutrients from burned plant matter (Neary et al. 1999). There is a tendency to lose nutrients overall during a fire, but the amount of plant-available nutrients increases (Kutiel and Naveh 1987, Vose et al. 1999). However, the variation in fire intensity, as well as spatial heterogeneity across landscapes, can produce different results in nutrient fluxes; chemical reactions in the soil are altered by variation in heat and fire residence time (Kasischke et al. 2007, Savadogo et al. 2012). Marion et al. (1991) investigated the effects of fire and ash on soil nutrients, and found an increase in availability of all investigated nutrients (NH_4-N, NO_3-N, PO_4-P, Ca, Mg and K) in surface soil post-fire. However as fire severity increases, some of those nutrients decreased, while others increased. In addition, nutrients found in dead thatch are quickly returned to the soil for the use of growing plants following a fire. Nutrient levels in the soil provide building blocks for plant growth. During a burn some carbon is transformed into charcoal for long-term storage (DeLuca and Aplet 2008). While some fires cause a decrease in soil organic matter, increases in surface soil organic matter also occur, especially in forested areas where an input of leaves and other plant materials can influence fire behavior and soil composition (Mataix-Solera et al. 2011). Scharenbroch et al. (2012) discovered burned areas had increased total nitrogen and total organic carbon levels compared with unburned counterparts. The new growth of the post-burn recovering plant community is accelerated through the help of this influx of available nutrients, and can demonstrate patchy fire effects (Hart et al. 2005).

Changes in nutrient properties also contribute to post-fire changes in soil structure and aggregate stability. Erosion becomes a concern due to decreased plant cover and altered soil texture and stability post-fire. This may mean that immediately post-fire more nutrients are available, but those nutrients may leach away as that soil erodes (Neary et al. 1999, Granged et al. 2011). Combined, these factors are important in understanding fire effects on erosion and future plant communities (Granged et al. 2011, Mataix-Solera et al. 2011).

Soil Moisture

Fires also influence soil moisture levels. The ability of a soil to hold or lose moisture changes after a burn due to changes in soil texture and water-repellency layers. Belowground hydrologic properties support vegetation growth, and in-turn affect ecosystem functioning (Neary et al. 1999). A lack of post-burn moisture availability may limit all vegetation growth, and provide a poor microclimate (Augustine and Milchunas 2009). Restoration of fire-dependent ecosystems is often contingent on native plant species being better adapted to adverse moisture levels than undesirable non-native plant species. Knowing post-fire moisture levels can indicate the success rate of rare plant species thriving and out-competing non-native species that are not as well-adapted to adverse moisture conditions (Hamman et al. 2011). Soil moisture is a valuable characteristic that can be used to predict plant species distribution and productivity as well as future fire intensity (Bekker and Taylor 2001, Lenihan et al, 2003, Augustine and Milchunas 2009). In other ecosystems, fire greatly influences soil moisture. Granged et al. (2011) found that following a fire in the Mediterranean the proportion of water-repellent soil decreased, and remained lower than pre-fire conditions for three years. Through the use of satellite imagery, Kasischke et al. (2007) concluded that fire in black spruce forests led to a decrease in soil moisture for several decades following a fire. Snyman (2003) also detected significant decreases in soil moisture for two years following a burn in South Africa. In the climate of western Washington, with very wet winters and dry summers, the importance of changing water repellency layers and moisture levels may be even more important. Summer droughts can create extreme microclimate conditions, and water-deprived plants have diminished chances for survival during a drought.

Fire Influences on Butterfly Habitat

Conservation of increasingly rare and endangered prairie-dependent species is a top priority in restoration efforts. The focus of many of these efforts concentrates on the recovery of multiple butterfly species, including the Taylor’s checkerspot butterfly and Mardon skipper (*Polites mardon*). Prairie-dependent species have become rare due to the decline in their habitat. Among others, the Taylor’s checkerspot butterfly is currently a candidate species to be listed as endangered under the Federal Endangered Species Act. Much emphasis has been placed on these rare butterflies because of their important role as pollinators. Pollinator capacity represents an important ecological function that can sustain plant reproductive resilience (Dixon 2009). Because of their high sensitivity, butterflies are often used as indicators of habitat quality on both a macro- and micro-habitat scale (Vanreusel and Van Dyck 2007, Beyer and Schultz 2010). Specifically for western Washington butterflies, recovery may also be strongly tied to the recovery of several rare plant species (Adler 2003, Caplow 2004).

The effects of fire on soil characteristics also indirectly influence dependent animal species through plant community responses to different soil conditions. The productivity of plants is a function of available moisture, temperature, and nutrient composition, all of which are altered by burning (Lenihan et al. 2003). An important characteristic of ideal butterfly habitat is not only the presence of host and food plants, but also the timing of the different stages of these plants. Changes in phenotypic plasticity in response to recent burning creates changes in flowering time, the number and size of blooms, and extended active growth phases in a variety of species in Southeastern Oregon, including modoc hawksbeard (*Crepis modocensi*), Nevada biscuitroot (*Lomatiun nevadense*), and slender phlox (*Phlox gracilis*) (Wrobleski and Kauffman 2003, USDA NRCS 2013). Anecdotally, similar phenological changes have been seen in Puget lowland prairies (Sarah Hamman, personal communication April 2012). Specifically for butterflies, differences in germination rates and the timing of senescence can limit the availability of food and host plants during the various life cycle stages (Weiss et al. 1988). Interestingly, an increase in butterfly oviposition rates has been found in prairies throughout Washington, Oregon, and British Columbia in conjunction with increases in native nectar resources post-fire (Schultz et al. 2011).

Butterfly survival throughout various life cycle stages requires specific temperature and moisture levels (Weiss et al. 1988, Beyer and Schultz 2010). Warm soil surfaces are used for basking, which allows butterflies to thermoregulate. Thermoregulation also allows for survival at larval stages and increases oviposition success in adult stages (Severns 2007). Temperature also impacts the timing of various life cycle stages, giving butterflies external cues for larval diapause, pupation, and adulthood. The highly seasonal climate of the Pacific Northwest places time constraints on butterfly development (Weiss et al. 1988). Spatial variation in soil temperature has been shown to be strongly related to reproductive success of adults, timing of flying females, and the mass and survivability of larvae (Weiss et al. 1988, Severns 2007). Areas of high local topographical variability provide more opportunities for long-term population survival. The reintroduction of regular fire events increases the diversity of available microclimates. Microclimatic and topographical variations are particularly influential for bay checkerspot butterfly (*Euphydryas editha bayensis*) populations in northern California, a subspecies similar to the Taylor's checkerspot butterfly of the Puget lowlands (Weiss et al. 1988). Spatial variation in plant communities can also provide more basking sites and native plant availability (Severns 2007).

Future Challenges to Prairie Restoration

There are numerous ecological and social questions to be answered concerning the use of fire for successful prairie restoration. Prescribed fire has been used in other systems, but there is a lack of quantitative information on fire effects specific to Puget lowland prairies (Dunwiddie and Bakker 2011). Hamman et al. (2011) demonstrated some of the first attempts to quantify short-term post-fire effects, such as fire severity and bare ground creation, finding significant differences in vegetation, moss, and thatch cover immediately after a burn. However, the long-term impacts on these habitat characteristics are typically not quantified. A better understanding of lasting effects can determine optimal fire return intervals for this threatened ecosystem. Furthermore, improving the predictability of lasting fire influences will assist land managers in creating butterfly habitat management plans.

Public perception and acceptance of prairie restoration, especially concerning prescribed burning, is essential for management success. The extreme rarity of this ecosystem can pose challenges in justifying the effort to restore it. Additionally, prescribed burning affects the public in many unavoidable ways. Nuisance smoke can be difficult to control and may pose health risks to nearby communities. While much effort is made concerning safety for both people and property during anthropogenic burn events, there are still risks to human lives and the potential for damage to nearby property. The public's perception and knowledge concerning the safety precautions taken by firefighters is imperative for burn operations to occur as numerous public complaints can prevent a burn from happening before it starts. Furthermore, the ecological need for fire disturbances is not often intuitive, and the sights, sounds, and smells of wildfires are often alarming. Another common concern of the public is the management of nearby lands. If endangered wildlife exists on private property it may not only impact the way that landowner manages his property but may also pose additional costs to the landowner; requirements to preserve habitat for an endangered species can even motivate a landowner to prevent endangered species from being found on their property by government scientists (Shogren et al. 1999). Enhancing and increasing available habitat can alter the spread of species of concern and hopefully prevent or improve the endangered status of species to eliminate the concern for both restoration managers and private landowners. Only through public cooperation can measures such as these be taken. Informing the public about the ecological benefits of fire to Puget lowland prairies and the efforts to restore them may prove to be critical to maximizing both the ecological benefits for prairies and the health and safety of people.

Reducing the likelihood of catastrophic wildfires through the use of prescribed burning is increasingly important as human populations spread to areas with a higher likelihood of wildfires. As the wildland-urban interface continues to shift, management practices in those areas need to adjust to protect people as well as the environment. Increasing development can increase habitat fragmentation and the spread of non-native species (Radeloff et al. 2005). The responsibility for protecting houses, lives, and property is also divided between private landowners and governing systems. This creates a challenge in defining how that responsibility is appropriately shared. As the number of people living within the wildland-urban interface increases, there is increased difficulty in evacuating those people safely. In these areas evacuation needs to happen more quickly due to the close proximity to fuels and the decreased defensibility of property (Cova 2005). In addition to more human lives at risk in these areas, increases in accidental anthropogenic wildfires are also likely to occur (Jensen and McPherson 2008). For protection of the ecological value of the wildland-urban interface and the people who have made these areas home, accidental wildfire protection and education is fundamental. An increasing human population creates an increased need for cooperation between restoration efforts and the public as the wildland-urban interface expands in fire-prone areas.

Another future challenge to restoration and conservation efforts, not only in prairies but in all ecosystems, is the potential complex influences of climate change. The frequency and intensity of wildfires is very likely to be affected by a changing climate, especially in synergy with increased urban development and habitat fragmentation (Lawson et al. 2012). Longer, warmer, and drier summers will extend the duration of the fire season and increase the risk of catastrophic wildfires (Brown et al. 2004, Flannigan et al. 2009). Furthermore, changes in temperature and moisture will alter the vegetation composition and productivity of ecosystems, leading to more changes in habitats and fire behavior (Lenihan et al. 2003). The forested areas of the Northwest, many of which border prairie habitat, are of particular concern for climate change impacts. Forests tend to accumulate large amounts of fuel which poses a much higher fire danger, particularly under dry climate conditions (Brown et al. 2004). Puget lowland prairies, however, may not be as disadvantaged in a warmer and drier climate as other systems; native flora may thrive in areas no longer suitable for forests in more extreme climate conditions (Bachelet et al. 2011). More difficult to predict, however, are the reactions of non-native species to climate change, many of which have already demonstrated their high-adaptability by establishing themselves in many systems (Bachelet et al. 2011). Plant community changes as a result of climate change will concomitantly influence fire regimes (Lenihan et al. 2003).

Predicting wildland fire behavior is a complex endeavor, made increasingly difficult by potential changes in climate (Hély et al. 2000). On a daily basis, even slight weather changes can dramatically alter fire behavior (Bessie and Johnson 1995). In a drier, warmer, and longer fire season, the ability of wildland firefighters to predict, alter, or suppress wildfires may be compromised (Hély et al. 2000). Furthermore, an altered climate that increases fire-prone areas also increases the wildland-urban interface (Dombeck et al. 2004). People that were previously not living in a high fire-risk area may unknowingly now live with increased risk. Improving our understanding of both short- and long-term fire effects can strengthen predictions concerning climate change effects as well as help managers to adapt restoration plans for the protection of both prairies and people.

Ecosystem management is influenced by fire disturbances across a landscape. In order to better understand how prescribed burning in Puget lowland prairies influences plant and butterfly habitat, I investigated changes in soil temperature and moisture across a burn gradient. Based on patterns found in other ecosystems, I wanted to understand if Puget lowland prairies also have increased soil temperature and decreased soil moisture after burning, and how long those changes persist. The primary purpose of this experiment was to determine how changes in these soil characteristics impact sensitive butterfly species; however, many plant and animal species may also be affected by these soil changes.

Chapter 2 – Manuscript (formatted for Northwest Science)

Introduction

Wildfires are disturbances that influence a variety of ecosystems across the United States. Fires provide unique and beneficial influences to those ecosystems. However, increases in human population and development within fire-prone areas led to an era of fire suppression beginning in the early 1900s (Dombeck et al. 2004). The goal of fire suppression policy was to stop all catastrophic and destructive wildfires; however, this policy was largely unsuccessful at reducing the total area of land burned every year (Stephens and Ruth 2005, Jensen and McPherson 2008). Furthermore, with the exclusion of regular fire influences from historically fire-dependent systems, the vital role of fire disturbances in ecosystem maintenance and function became increasingly clear (Parr and Andersen 2006). When fires pass through an ecosystem, they alter plant community structure, reinvigorate growth, and diversify habitat (Noss et al. 2006). Fire disturbances also contribute to ecosystem maintenance by reducing thatch cover and overcrowding (Knapp and Keeley 2006). The current policy challenge is to protect both human populations and fire-dependent ecosystems in an effective and cost-efficient manner (Harrington and Kathol 2009). Rather than attempting to suppress every fire, learning to live cooperatively with fire improves environmental, economic, and social components of sustainability (Dombeck et al. 2004).

Puget lowland prairies are fire-dependent, grassland ecosystems in the northwestern United States. The reduction of fire disturbances in this ecosystem has diminished prairie quality and quantity. Current estimates demonstrate that only 1-5%

of native prairies remain compared to the early 20th century (Lawrence and Kaye 2011, Hamman et al. 2011). The remaining prairie habitat is highly fragmented and degraded. Native Americans once maintained these glacial outwash prairies through anthropogenic fires for agricultural, hunting, and social purposes (Shinn 1980, Walsh et al. 2010); however, without regular fire influences, non-native vegetation and coniferous forests have invaded these sensitive systems (Dunwiddie and Bakker 2011, Hamman et al. 2011). Plant community and soil nutrient alterations have led to a concomitant reduction in wildlife populations. Observed changes in community structure, species decline, and native plant cover have created a need for increased management of prairies before they disappear. Recent anthropogenic managers of prairies are now attempting to restore ecological structures and native plant cover to this historically fire-dependent ecosystem.

For restoration success, prairie managers are attempting to reestablish populations of declining, threatened, and endangered prairie species. Of particular focus is the restoration of species that provide key ecological services. Butterflies fulfill a crucial ecosystem function by providing pollination services, increasing the reproductive and genetic resilience of plant communities (Dixon 2009). Priority prairie species include the Taylor’s checkerspot butterfly (*Euphydryas editha taylori*), which is currently a candidate for endangered species listing under the Federal Endangered Species Act (ESA). These highly sensitive butterfly species serve as indicators of macro- and micro-habitat quality (Vanreusel and Van Dyck 2007, Beyer and Schultz 2010). Furthermore, the successful restoration of pollinating butterfly species is also predicted to be directly tied to the restoration of several endangered plant species including golden paintbrush (*Castilleja levisecta*; ESA status: threatened, WA state status: endangered) (Adler 2003, Caplow 2004, USDA NRCS 2013). Successful butterfly populations help to maintain healthy plant communities and increase the overall sustainability of prairie ecosystems. Established and reproducing butterfly populations can also provide crucial feedback about the ability of current restoration strategies, including prescribed fire, to create high quality habitat.

The recent re-introduction of fire to Puget lowland prairies through prescribed burning demonstrates enormous potential as a key strategy for restoring and preserving the few remaining prairies in the Pacific Northwest (Hamman et al. 2011). Fire influences several important habitat factors for sensitive species. For the Taylor's checkerspot butterfly, important influences of fire include altered phenology of food and host plants and microclimatic variation in temperature and moisture (Weiss et al. 1988). One of the primary uses of prescribed burning is for removal of noxious non-native species, such as Scotchbroom (*Cytisus scoparius*, USDA NRCS 2013), which can alter the habitat structure of these short-grass prairies. Without fire influences, increased thatch and tall non-native plants negatively impact butterfly behaviors including basking, puddling, and oviposition (Lawrence and Kaye 2011). Through experiments using a chronosequence of burns, we hope to find an optimum fire return interval, or fire frequency, for prairie sustainability. Currently estimated at every 2-5 years, an appropriate fire return interval may maximize biodiversity and habitat availability while still providing ample time for post-burn recovery (Agee 1996, Rook et al. 2011). The long-term benefits from fire can be maximized through mosaic burn patterns and maintaining an appropriate fire return interval. Establishing more frequent, but smaller and less intense fires can actually decrease the likelihood of catastrophic wildfires that damage property and risk human lives (Brown et al. 2004). This may also increase ecosystem resilience while simultaneously creating microhabitat heterogeneity that is ideal for butterflies.

The most dramatic fire influences on a landscape often involve soil. Soil characteristics are the building blocks of an ecosystem and drive the available habitat for plants and rare species such as the Taylor’s checkerspot butterfly. Both physical and chemical changes to the soil after a burn influence plant community recovery. Variation in soil temperature and moisture influence the germination and growth of seeds in the post-burn community (Wrobleski and Kauffman 2003). The altered plant community determines which wildlife populations succeed. For butterfly restoration, the availability of host and food plants, as well as the phenological timing of those plants, determines the reproductive success of each population (Weiss et al. 1988). Chemical changes and soil blackening create temperature variation (Neary et al. 1999). Butterflies depend on warm soil surfaces for basking and thermoregulation at multiple life stages (Weiss et al. 1988, Stinson 2005, Beyer and Schultz 2010). Thermoregulation improves larval growth and survival as well as adult butterfly oviposition success (Severns 2007). A common strategy for Taylor’s checkerspot butterfly restoration is to release captive-bred larvae following a burn, assuming that this provides larvae with advantages such as increased temperatures. Establishing the long-term temperature pattern as a community recovers from a burn may indicate when and where ideal butterfly habitat conditions exist.

The importance of butterflies to restoration success and the increasingly widespread practice of prescribed burning led us to investigate the soil characteristics created by mosaic burning that may influence butterfly distribution and reproductive success. In order to investigate the physical characteristics of the ground surface during the approximate larval stage of Taylor's checkerspot butterflies, we addressed several research hypotheses: 1) prairie surface temperature would be warmer and more variable following recent burns. 2) subsurface soil temperature at a depth of 5 cm would be warmer and more variable following recent burns. 3) soil moisture would be lower following recent burns.

Study Area

This study took place on two of the remaining Puget lowland prairies: Johnson prairie and Upper Weir prairie. These prairies are located on Joint Base Lewis-McChord near Rainier, Washington, and are approximately 1 km apart. Both areas have similar topographical variation and are military training sites. These short-grass prairies are presently managed through the use of prescribed burning and native seeding for restoration and habitat enhancement. Burning occurs in a mosaic pattern (Figure 1) to maximize the diversity of micro-habitats. On each prairie we established eight 40 m^2 plots (Figure 2), two plots per burn year (2009, 2010, 2011, and 2012) at close proximity to minimize travel time among plots. At Upper Weir prairie we established two additional plots for 2013 when a section of prairie was burned in February 2013.

Prairie Burn Mosaic

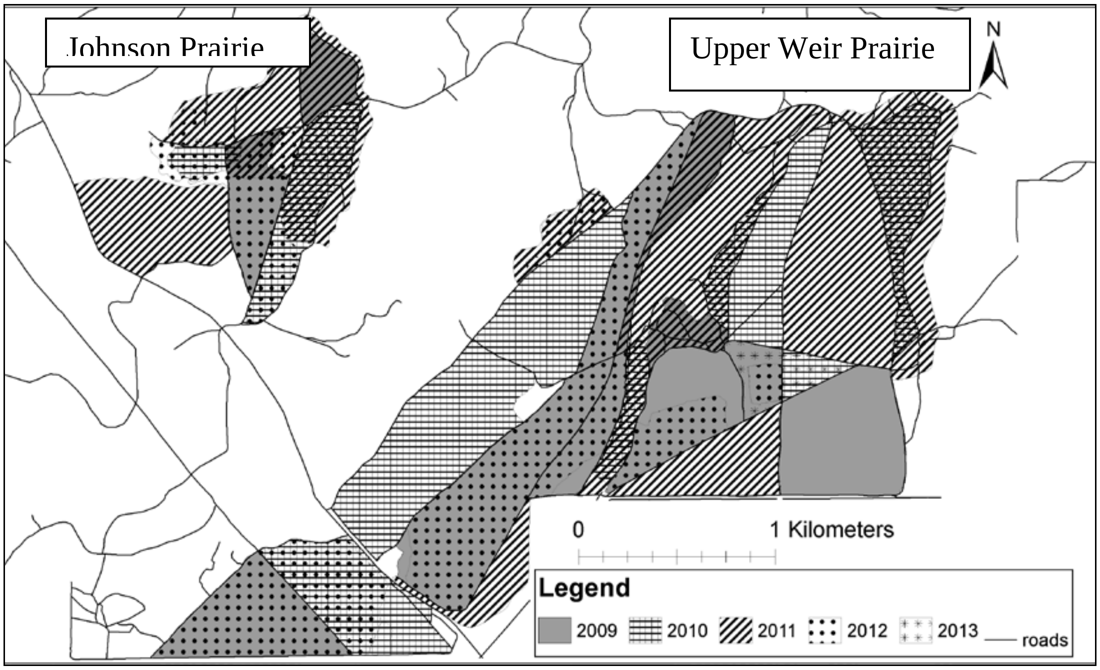

Figure 1: Burn mosaic patterns of Johnson prairie and Upper Weir prairie. Areas coded by burn year: 2009 (■), 2010 (▦), 2011 (▨), 2012 (⁙), 2013 (⁘).

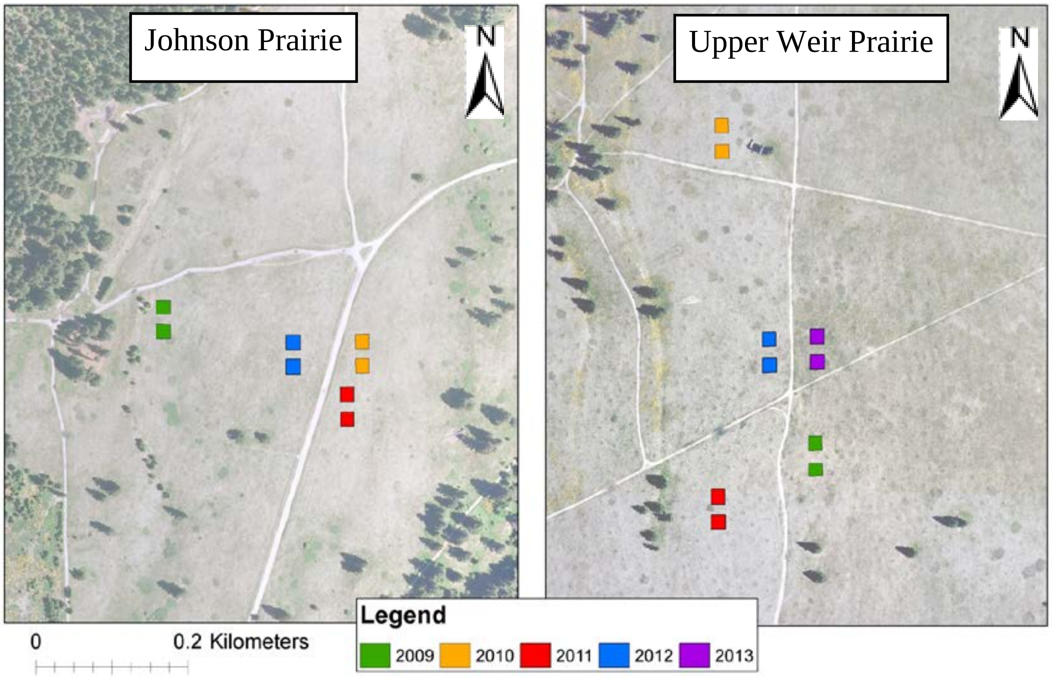

Figure 2: Modified-Whittaker plot locations at Johnson prairie and Upper Weir prairie. Plot color coded by burn year: 2009 (green), 2010 (orange), 2011 (red), 2012 (blue), and 2013 (purple).

Methods

Soil Temperature

Several methods were used to record soil temperature. An infrared thermometer (Cen-Tech Model #96451) was used to measure surface temperature. Six measurements were taken following a grid pattern in each plot (Figure 3), with a maximum distance between points of 10 m to account for the suspected maximum daily travel distance of butterfly larvae (Weiss et al. 1988). Simultaneously, two soil thermometers spaced 15 m apart were used to record subsurface temperature at a depth of 5 cm (Figure 3). Each measurement was recorded weekly (with the occasional exception of Upper Weir when military training prohibited access to the site) and within the hours of 1100 and 1400. One HOBO datalogger (Model # UA-002-08) per burn year was located centrally between each burn year plot to record continuous surface temperature and relative light intensity every 10 minutes (Figure 3). Due to the limited availability of dataloggers, there were several weeks when we did not have a datalogger for every burn year at each site. In this case, the datalogger most central to all the plots was referenced.

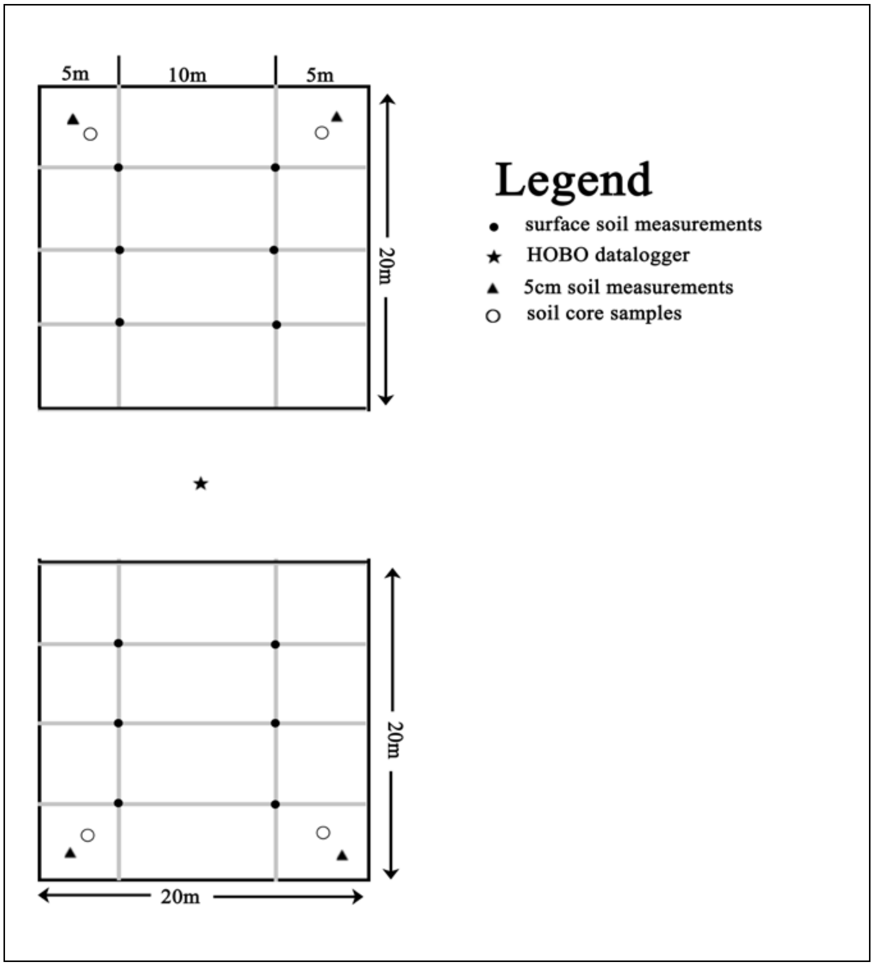

Figure 3: Plot layout per year, including measurement locations for surface temperature, subsurface soil (5 cm depth) temperature, soil moisture, and dataloggers.

Soil Moisture

Soil cores, with a diameter of 1.5 cm and 5 cm deep, were taken from Johnson prairie in early February 2013 and from both sites in early March 2013. Soil moisture content was calculated using gravimetric water content protocols (Black 1965). Within each plot two cores were taken, 15 m apart. A 15 mL subsample from each soil core was weighed in its “wet” state, and then dried in a 105°C oven for 48 hours. Each sample was re-weighed in its “dry” state to determine percent moisture. The moisture content within each plot was then averaged for analysis.

Statistical Analysis

Weekly soil surface temperatures were standardized to the corresponding HOBO datalogger light and temperature data as if they were all recorded at 1200. Subsurface soil temperature at 5 cm was assumed to be negligibly affected by the change in sunlight and surface temperature over the course of the two hours during which the measurements were recorded due to increased insulation from moss and thatch layers. Results from the 2013 plots located in Upper Weir were not included in statistical analyses because they were not replicated at the time of this study.

Repeated measures ANOVA was used to evaluate relationships found between surface temperature and plots over time. The average surface temperature, maximum surface temperature, and surface temperature standard deviation for each plot at each site for eight weeks were analyzed. Similarly, a repeated measures ANOVA was used to investigate the influence of the fire chronosequence on average subsurface temperature and subsurface temperature standard deviations. Post-hoc orthogonal contrast comparisons were used to further investigate patterns. The influence of average daily air temperature (as recorded by the Ft. Lewis weather station via <http://www.wunderground.com>) on surface and subsurface temperatures, was evaluated through a regression analysis. Furthermore, we evaluated the influence of light intensity on surface temperature through a regression analysis of measurements from the dataloggers.

We used a regression analysis to compare average soil moisture variation with burn year in March (February measurements were omitted from regression analysis due to limited replication). A student’s t-test was used to compare differences between February and March measurements.

Results

Surface Temperature

When comparing average surface temperatures across the burn chronosequence using a repeated measures ANOVA, burn year had a significant influence on average surface temperature ($F_{(3,4)}=30.4225$, $p=0.0033$; Figure 4). Orthogonal contrast comparisons demonstrated that 2009 temperatures were significantly colder than all other burn years (Figure 4, Appendix A). Surface temperatures for 2010, 2011, and 2012 were all relatively similar. Midday surface temperatures from infrared thermometer measurements were supported by continuous datalogger measurements (Appendix B). Average daily air temperature had a positive correlation with surface temperature, accounting for approximately 19% of the variation in surface temperature ($R^2=0.1875$, $p<0.0001$, Appendix C). Average surface temperature was more strongly positively influenced by light intensity ($R^2=0.4649$, $p<0.0001$; Figure 6). Light intensity accounted for approximately 46% of the variation in surface temperature.

There were also significant differences in maximum surface temperature among burn years ($F_{(3,4)}=11.3678$, $p=0.0199$; Figure 5). Similar to average surface temperatures, orthogonal contrast comparisons of maximum surface temperatures demonstrated that 2009 temperatures were significantly cooler compared to all other burn years and maximum surface temperatures for 2010, 2011, and 2012 were all relatively similar (Figure 5, Appendix A). Average air temperature also had a positive correlation with maximum surface temperature, but only accounted for approximately 13% of the variation in maximum surface temperature ($R^2=0.1292$, $p<0.001$, Appendix C).

Standard deviation of surface temperature within each plot ranged between 0.2°C and 3.4°C. Burn year did not significantly influence the variation of surface temperature within each plot ($F_{(3,4)}=0.6656$, $p=0.6156$). Standard deviations also did not show a strong response to average daily air temperature ($R^2=0.0123$, $p=0.1451$, Appendix C).

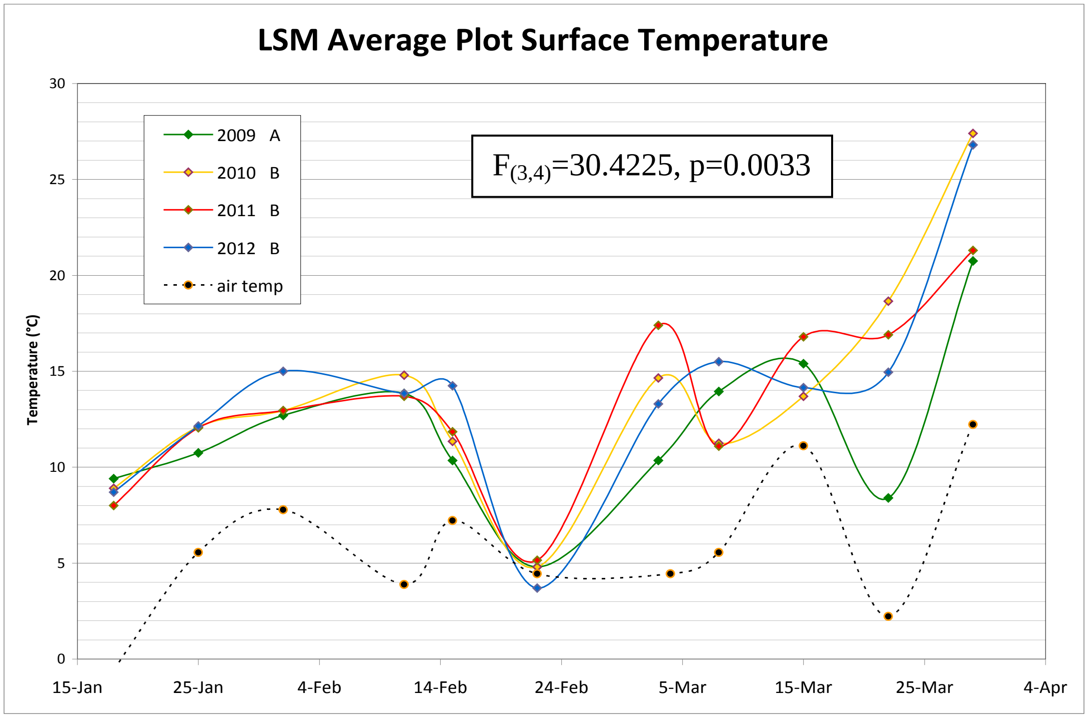

Figure 4: Results from a repeated measures ANOVA for average plot surface temperature compared with burn year, represented by least squares means ($F_{(3,4)}=30.4225$, $p=0.0033$). Years are coded as follows: 2009 (green), 2010 (orange), 2011 (red), and 2012 (blue). Average air temperature is shown as a dotted black line.

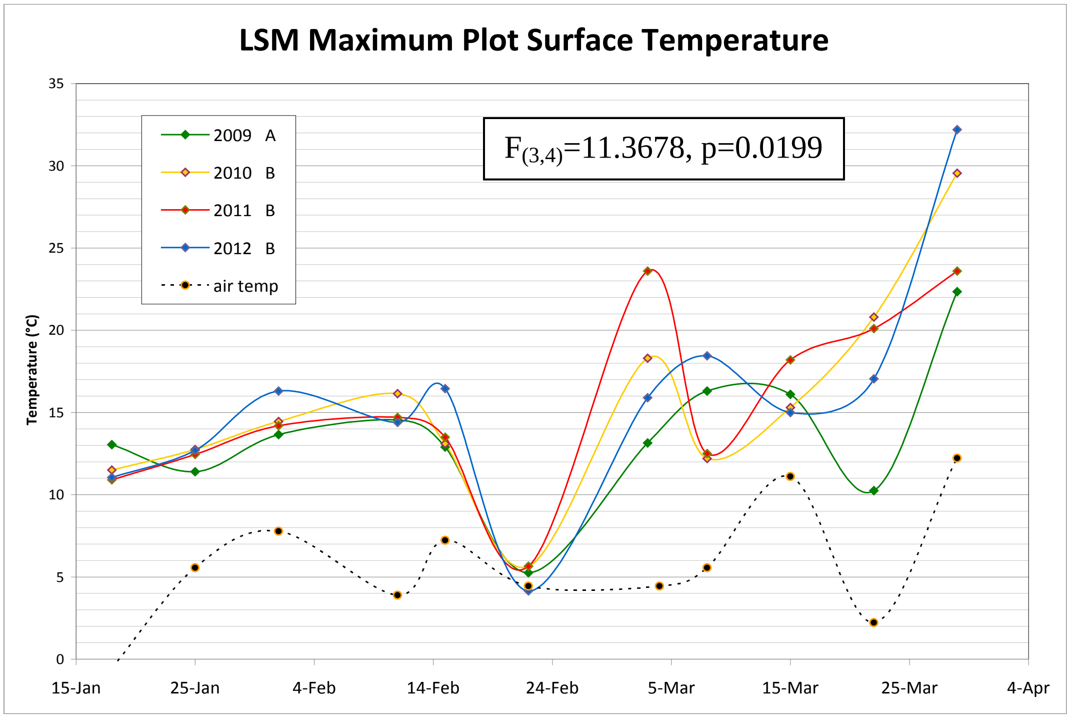

Figure 5: Results from a repeated measures ANOVA for maximum plot surface temperature compared with burn year, represented by least squares means ($F_{(3,4)}$=11.3678, p=0.0199). Years are coded as follows: 2009 (green), 2010 (orange), 2011 (red), and 2012 (blue). Average air temperature is shown as a dotted black line.

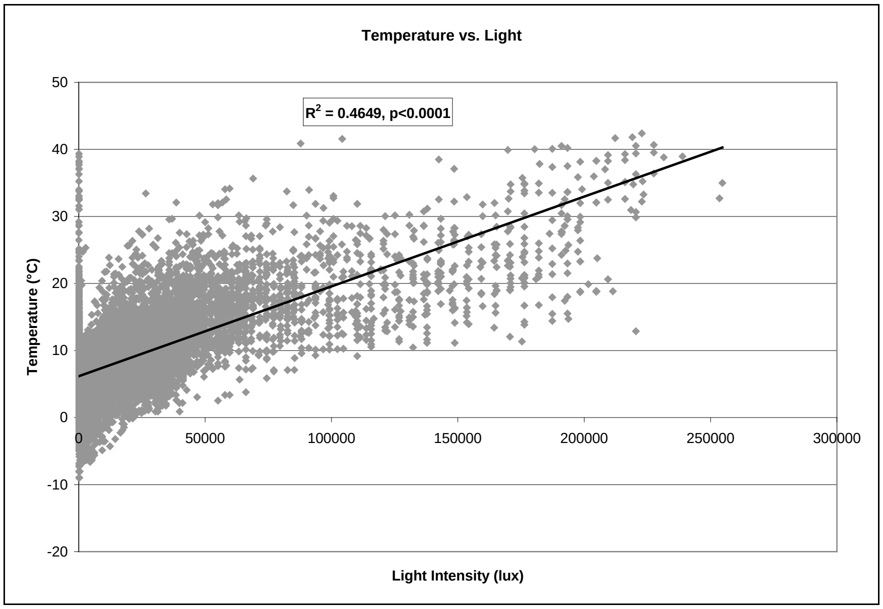

Figure 6: Influence of light intensity (lux) on prairie surface temperature (°C), as measured by HOBO data loggers from January through March 2013.

Subsurface Soil Temperature

Comparing the influence of a burn chronosequence on subsurface temperatures throughout time using a repeated measures ANOVA demonstrated that burn year had a significant influence on average subsurface temperature ($F_{(3,4)}$= 8.891, p=0.019, Figure 7). Plots burned in 2009 or 2010 tended to be cooler than plots burned in 2011 and 2012 (Figure 7). Statistically significant differences were found between 2009 and 2011 (p=0.0051, Appendix A), and 2009 and 2012 (p=0.0138, Appendix A). Average daily air temperature had a positive correlation on average subsurface temperature (R^2=0.7434, $p<0.0001$, Appendix C). This was a very strong correlation, with average air temperature accounting for approximately 74% of the variation in subsurface temperature.

Within-plot variation in subsurface temperatures did not vary significantly among burn years ($F_{(3,4)}$= 0.3013, p=0.8241). Standard deviation of subsurface temperature only ranged between 0.03°C and 1.15°C throughout the study, likely due to the increased insulation provided by moss and thatch layers and less influence from sunlight compared with surface temperatures. Average daily air temperature was not significantly correlated with subsurface temperature standard deviation (R^2=0.0039, p=0.4416, Appendix C).

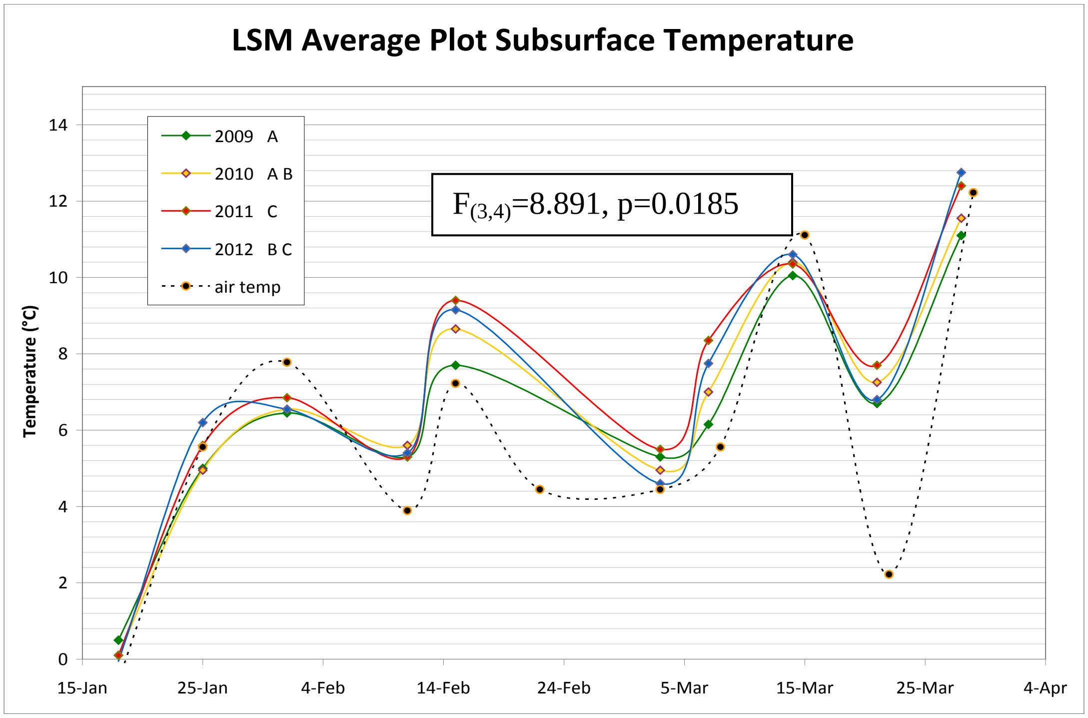

Figure 7: Results from a repeated measures ANOVA for average subsurface temperature compared with burn year represented by least squares means ($F_{(3,4)}$=8.891, p=0.0.0185). Years are coded as follows: 2009 (green), 2010 (orange), 2011 (red), and 2012 (blue). Average air temperature is shown as a dotted black line.

Soil Moisture

Soil moisture ranged from 34-42% in February and 37-53% in March. No distinct linear relationships between soil moisture and burn year were found (Table 3); however, a t-test demonstrated that soil moisture in March was significantly higher than soil moisture in February (difference=9.721%, p<0.0001).

Discussion

Temperature

Observations made over the course of this study demonstrate a significant influence of a burn chronosequence on both surface and subsurface temperature. Areas last burned in 2009 were significantly cooler than other burn years during the winter season. These observations support the estimated historic prairie fire return interval of every 2-5 years. Approximately four years post-burn, microclimate conditions vary significantly, and may not provide a warmer temperature advantage to sensitive species of concern.

Moisture

The burn chronosequence was unexpectedly not correlated with soil moisture. Anecdotal observations suggest that small topographical variations have a surprisingly large influence on soil moisture. Furthermore, typical fire influences on soil that limit water infiltration, such as altered water repellent layers and collapsing soil structures (Neary et al. 1999), may be less apparent on the already shallow, well-drained, rocky soils of Puget lowland prairies (Dunwiddie and Bakker 2011).

Overall Trends

Observed temperatures demonstrated the anticipated pattern that regular short-interval burning in Puget lowland prairies provides improved habitat and microclimate conditions for sensitive species. Differences between burn years became more apparent over the course of this study. As the growing season begins, we expect these differences to become even more pronounced. The influence of sunlight was very apparent, accounting for nearly half of the variation in surface temperature recorded by dataloggers (Figure 6). The increase in available sunlight during the spring and summer months may provide an increase in temperature variation along the burn chronosequence. Similar temperature patterns were found in other fire-dependent grassland ecosystems in southeastern Australia (Bradstock and Auld 1995), South Africa (Snyman 2003), and the eastern U.S. (Iverson 2005). Observations from this study suggest that maintaining a fire return interval of four years or less in Puget lowland prairies provides warmer temperatures that may provide an advantage for butterfly larvae.

Study Limitations and Future Research

In order to better evaluate the variation of soil temperature and moisture within each burn year, an increased number of plots spread throughout larger burn areas may be more representative. Although there was not a significant difference in temperature standard deviation among burn years, the variation within each plot was still large enough to imply that larger sampling areas may be more representative of landscape-level conditions. Employing continuous measurements throughout the landscape may also capture temporary increases in temperature due to sunbreak variations. Because species, such as the Taylor's checkerspot butterfly, are extremely sensitive, even short variations in temperature throughout the day can mean the difference between a sustainable, healthy butterfly population and a waning population. Such variations may not be appropriately represented through snapshot measurements.

Recommendations

One of the biggest challenges to prairie restoration is difficulty evaluating microclimate conditions across the landscape, information important for maintaining sensitive and rare species. Differences in soil temperatures may result in important heterogeneity for butterfly survival. Increased variation provides more opportunity for vulnerable butterflies to appropriately thermoregulate, escape from predators, and find food and host plants. Fire return intervals providing the most opportunity for butterflies to utilize a variety of habitat characteristics may then become a primary management objective to optimize entire prairie locations. Reestablishing successful populations of this sensitive species may indicate where other prairie-dependent species will be successful. Based on observations from this preliminary study, maintaining a fire return interval of approximately four years provides for the warmest microclimate temperatures for wintering butterfly species. After butterfly release, maintaining this interval may provide crucial habitat characteristics that support sustainable populations.

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Chapter 3 – Project Significance and Interdisciplinary Connections

Extended Discussion

Surface Temperature

Observations made over the course of this study demonstrate a significant relationship between surface temperature and a burn chronosequence. Areas burned in 2009 had significantly cooler surface temperatures than other burn years, a relationship demonstrated both by average temperatures and maximum temperatures. The general pattern observed was an increase in surface temperature for more recently burned areas; however, the only statistically significant differences were observed between 2009 and other burn years (Appendix A). This pattern appeared to be stronger in March compared with January, which may imply that as the growing season proceeds, the influence of the fire chronosequence on temperatures will become more pronounced. Because light intensity accounted for approximately 47% of the variation in surface temperature (Figure 6), increased sunlight during the spring and summer may further influence these temperature differences (Weiss et al. 1988).

Recommendations based on study observations indicate that a fire return interval of four years is appropriate to maintain warmer microclimates. This may be especially important for the Taylor's checkerspot butterfly during the diapause and post-diapause larval stages, approximately lasting from December through the end of March (Stinson 2005). If areas that are not being burned more often than four years provide colder habitats, butterfly larvae may not be getting the temperature advantage they require for survival. If these temperature patterns continue throughout the growing season, the success of reproducing adults may be compromised several years after burning if there are insufficient temperatures for thermoregulation (Weiss et al. 1988, Severns 2007, Beyer and Schultz 2010).

Relationships between soil temperature and burning have been more pronounced in other similar fire-dependent ecosystems. Soils in eastern U.S. forests maintained warmer daily soil temperatures in burned areas compared to unburned plots for several months post-fire (Iverson 2005). The South African bush, another grassland-based ecosystem, showed higher surface temperatures up to two years post-burn compared with unburned areas (Snyman 2003). In Snyman's (2003) study, however, the strongest patterns between temperature and burning were found during the growing season. The season of this study, from January to March, concluded at the start of the growing season for Puget lowland prairies. The relatively small, nevertheless significant, patterns found over the winter season may become more pronounced through year-long observations.

Subsurface Soil Temperature

Average subsurface soil temperatures were warmer in recently burned plots than those burned in earlier years. The indirect influence of subsurface temperatures on the plant community is imperative for the survival of butterfly larvae. Warmer microclimates typically provide earlier germination and early senescence of butterfly host plants (Weiss et al. 1988). Larger differences in subsurface temperature among burn years were found compared with those seen in surface temperature. Increased plot-level replication would improve our understanding of the effects of burn history on soil temperatures.

Subsurface temperatures varied less than surface temperatures throughout the season, likely due to increased insulation from layers of moss and thatch. Moss and thatch layers are found throughout Puget lowland prairie landscapes, with Johnson and Upper Weir being no exception. Moss provides insulation for the soil and reduces the warming impacts from sunbreaks. While fires often alter and destroy these layers, much of the thatch in the study sites appeared intact throughout the burn chronosequence. Seasonality of a burn alters the intensity of a burn (Knapp and Keeley 2006) and lower intensities often create reduced and patchy burns (Augustine and Milchunas, 2009). For example, the 2012 burn plot on Johnson prairie had distinct thatch patches remaining after being burned. Areas with remaining thatch also appeared to have lost less of their moss layer. Replicate plots accounting for various burn seasons for each burn year may demonstrate stronger patterns in subsurface soil variation. In other ecosystems, burn season has had a large influence on fire effects. Post-fire soil temperatures in southeastern Australia varied strongly with burn season, with a summer burn having significantly higher subsurface soil temperatures compared with a winter burn (Bradstock and Auld 1995). These differences were large enough to influence germination rates of legume species, as only the summer burn had warm enough post-burn temperatures to break seed dormancy. Compared to a case study following a bush fire in South Africa, subsurface temperatures deeper than 200 mm also did not demonstrate significant variation between burned and unburned areas; however, differences in shallower soil temperature appeared stronger during the growing season (Snyman 2003).

Measurements in Johnson prairie and Upper Weir prairie were observed during the winter season. While differences in temperature were found during this timeframe, variation in temperature may become more pronounced when investigated over the growing season, or throughout an entire year. Because post-burn subsurface temperatures can vary strongly enough in other systems to alter seed germination, further investigation of this pattern in Puget lowland prairies is still warranted.

Soil Moisture

Although soil moisture ranged from 34-42% in February and 37-53% in March, this variation was unexpectedly not significantly influenced by burn year. Variation within plots, as represented by standard deviation, also did not vary significantly among burn years. The shallow soil of remaining Puget lowland prairies is rocky and well-drained (Dunwiddie and Bakker 2011), providing a challenge for measuring soil moisture. The strongest differences in winter soil moisture may only be apparent immediately following rain events, as water may drain more quickly from recently burned areas. In other fire-prone ecosystems, more distinct patterns between soil moisture levels and burning have been found; soil moisture across an entire landscape in interior Alaskan forests proved significantly higher at a site that had been burned five years earlier than the control (Kasischke et al. 2007). Long-term fire influences on Mediterranean soils included lower soil moisture levels and variation in water-repellent layers (Granged et al. 2011). Due to the minimal variation in soil moisture within each 40 m^2 plot at both Johnson prairie and Upper Weir prairie, we would recommend sampling moisture across a larger surface for each burn year. The welldraining, rocky soils of Puget lowland prairies make soil moisture challenging to evaluate. We would expect that further studies may indicate that overall soil moisture is similar across burn years, but recently burned areas with less vegetation and more heavily altered soil composition would drain moisture at an accelerated rate.

Extended Future Research

In order to better evaluate the variation of soil temperature and moisture within each burn year, an increased number of plots spread throughout larger burn areas may be more representative. Although there was not a significant difference in temperature standard deviation among burn years, the variation within each plot was still large enough to imply that larger sampling areas are needed.

Continuous monitoring of temperature may capture the highly variable effects of sunlight and other weather variations. Snapshot measurements may lack the ability to capture more extreme differences across the prairie landscape. Daytime surface temperatures (as recorded by HOBO dataloggers placed on the prairie surface) varied by as much as 14°C in 30 minutes. This wide-ranging variation is due to rapid temperature increases during sunbreaks. Observations from infrared thermometers could detect increases in surface temperature of 6°C or more in only a few seconds during a sunbreak. Because sampling across plots takes a considerable amount of time, variation in solar radiation caused by intermittent sunbreaks may have confounded average temperature differences across spatial scales. Midday temperatures did demonstrate differences between burn years, but recording average temperature throughout the entire day may better capture more dynamic changes in blackened soil. Continuous measurements may also better reflect species needs because some species are sensitive enough to react to small variations that would go unnoticed in a single daily measurement of microclimatic conditions. Short temporary differences in temperature due to sunbreaks may provide more opportunity for butterflies to appropriately thermoregulate.

Further replication of plots across all burn years may reduce impacts from topographical variation. Puget lowland prairies have widespread topographical variation. While plots were chosen to utilize relatively flat areas, the variability in minor slopes and aspects across Johnson prairie and Upper Weir prairie may have influenced temperature and moisture differences. Distances between plots were minimized when possible; however, the Johnson prairie 2009 plot and the Upper Weir prairie 2010 plot were located farther away from other plots due to the burn mosaic patterns (all plots were located within approximately 100 m of another plot, with the exception of Johnson 2009 and Upper Weir 2010 which were approximately 200 m from the nearest plot).

The nested impacts of burn season within each year may demonstrate more variation in temperature and moisture. Varying weather conditions impact the intensity and behavior of prescribed burns; changes in season lead to changes in burn effects. Cooler, more humid burns in spring tend to have less intensity than burns during the hotter and drier summer (Knapp and Keeley 2006). As seasonal conditions change, fire behavior varies significantly, with varying residence times for critically high burn temperatures (Savadogo et al. 2012). For Puget lowland prairies, this translates into differences in thatch, moss, and plant cover in accordance with burn season. However, burn season was unable to be accounted for in this study due to insufficient records. In addition to burn season, burn history may influence the recovering community. Depending on how frequently an area was burned, there may be corresponding changes in fire behavior and fire influences. Variation in recovery time between burns will further increase heterogeneity across prairie landscapes, influencing plant communities, thatch levels, and moss layers.

Future studies should continue to evaluate microhabitat conditions specific to sensitive species. Microclimate is crucial to butterfly survival at all life cycle stages. One of the benefits of prescribed fire is that it can cover a large section of landscape relatively quickly; the challenge is how to maximize the amount of necessary microclimate for butterfly survival. Measuring temperature and moisture along a scale of tens of meters across an entire ecosystem is not often an efficient use of resources, and smaller scale projects are difficult to generalize across larger scale prairies. The highly fragmented nature of Puget lowland prairies lends to enormous variation among habitat sites. Because it contains the largest, most continuous, and most pristine of the remaining Puget lowland prairies, Joint-Base Lewis-McChord has the potential to create the standard for prairie restoration success. Some of the few remaining natural Taylor's checkerspot butterfly populations are found on the base, implying that there must be some habitat quality there that is providing opportunity for survival. Restoring the unique ecological functions provided by rare species is crucial to restoring the few remaining Puget lowland prairie ecosystems. Our advice to future projects would be to utilize continuous measurements whenever possible and attempt to characterize variability in microhabitats for keystone species.

Restoration Impacts

The rarity of Puget lowland prairies unfortunately means a lack of quantitative evidence to support anecdotal ecological patterns (Dunwiddie and Bakker 2011). Studies designed to test observed and assumed patterns are important to influence management practices. Prescribed burning needs to be used effectively, as there is not much prairie land left to lose to mistakes. This study is one of the first to directly measure temperature changes in the Puget lowland prairies, and it will serve as a pilot study for further research. An important consideration for future studies is long-term landscape characteristics. Throughout the succession of an ecosystem post-fire, the beneficial influences of fire begin to fade. Increases in moss and thatch cover, along with increased cover of non-native plants, can diminish the habitat quality for prairie-dependent species. In the sensitive Puget lowland prairies, frequent burning may maintain essential ecological function by maintaining appropriate soil microclimate conditions. Many restoration goals can be met by maintaining a fire return interval that maximizes a diversity of beneficial effects for the longest amount of time.

Fire management plans need to adapt to a number of challenges with regard to predicting and utilizing fire influences. Variation in landscape, weather, and seasonality are all characteristics that influence fire effects. Adaptive management is especially important when utilizing fire disturbances for endangered species. Altering the plant community through regular burning and maintaining long-term temperature increases affects all prairie wildlife. In addition to the Taylor’s checkerspot butterfly, another candidate species for protection under the Federal Endangered Species Act, (ESA) the streaked-horned lark (*Eremophila alpestris strigata*) thrives on open habitat created by burning (Pearson and Altman 2005, Stinson 2005). Increasing open habitat and native forb diversity also benefits the Mazama pocket gopher (*Thomomys mazama*), a third ESA candidate species (Stinson 2005). For a landscape as topographically variable and fragmented as the remaining Puget lowland prairies, adaptive management and feedback learning are valuable restoration strategies for understudied rare species. Adjusting to new research-based information on fire influences is crucial to endangered species restoration as well as improving human safety and reducing catastrophic fire potential (Stephens and Ruth 2005).

Adaptive management can also be utilized to improve ecological resilience. Long-term fire suppression in historically fire-dependent ecosystems may hinder the ability of those systems to recover from disturbances. Frequent, low-intensity fires allow plant and wildlife species to adapt and build stronger defenses against future fires. Ecological resilience is especially important as climate change potentially alters fire behavior and plant communities. Degradation of prairies may be exacerbated under new climate conditions; however there is also the possibility of prairie expansion into former agricultural and forest lands in a new climate regime (Bachelet et al. 2011). The potential expansion of prairies may force human populations to manage lands for resiliency against regular fire influences.

Stakeholders

A variety of stakeholders are involved in and influenced by restoration practices in Puget lowland prairies. The fragmented nature of this habitat means prairies are found on private, state, and federal lands. Private landowners are not required to participate in management practices; however, they are impacted by federal legislation if candidate species are granted protection under the federal Endangered Species Act (as of the date of this thesis, Taylor's checkerspot butterfly and Mazama pocket gopher are proposed federally endangered species, and the streaked-horned lark is a proposed federally threatened species). The prairies found on Joint Base Lewis-McChord are often considered the most pristine of the remaining habitat, which creates a rather unique concern. Management of these areas is a concern for both ecological reasons and to maintain military training. Classifying species as endangered impacts the training strategies of the military; for some of the candidate species, the few remaining successful populations exist almost exclusively on military property. The United States Department of Defense has become an enormously influential stakeholder with their financial power and physical means to maintain the prairies that exist on their property as well as a strong motivation to establish healthy wildlife populations and high-quality habitat in other locations. Ironically, military training involving explosives is likely the reason why the most pristine prairies are found on the base; while other areas were highly impacted by fire suppression, regular fires still occurred on military property. Joint Base Lewis-McChord provides ample learning opportunities for ecologists and land managers to define high-quality prairies. While sensitive species-of-concern still persist, observations of optimal habitat attributes can create standards for restoring other prairie areas that historically also housed these species. In addition to military interest, several non-profit organizations and private landowners are important stakeholders. Collaboration between stakeholders, including the Department of Defense, the Center for Natural Lands Management, the

Department of Natural Resources, the Evergreen State College, and others, has increased collective understanding of Puget lowland prairies through quantitative and qualitative research and management. Partnerships with private landowners have also increased available land for prairie restoration and conservation, providing opportunities to increase connectivity between available prairie habitat locations.

Interdisciplinary Practices

Successful restoration and management of any ecosystem requires effective interdisciplinary work. Fire ecology requires knowledge of multiple disciplines to truly understand the impacts fire has on a landscape, including: soil science, chemistry, botany, wildlife ecology, climatology, physics, human health and safety, economics, entomology, and more. Collaboration between these various disciplines improves fire management success in maintaining the ecological benefits of fire while still providing for human health and safety.

Impossible to ignore are the economic impacts of fire disturbances. Regardless of whether the policy for an area is full suppression of every wildfire or routine use of prescribed fire, there is a financial cost. Economic costs come from hiring personnel, damaged property, lost natural resources, and health-related issues. Firefighters require specialized training and personal protective equipment for their own safety, as well as equipment such as fire trucks, hoses, and water pumps. The financial burden of this equipment often falls upon state budgets. Fire suppression practices were implemented in the United States in the 1930s because of the desire to not only save lives but also to save resources (Dombeck et al. 2004, Jensen and

McPherson 2008). In the Pacific Northwest, many communities depend on logging and timber industries to provide employment opportunities. Forest fires were thought to destroy valuable timber products and have even contributed to unemployment in entire towns (Noss et al. 2006). Interestingly, fire suppression practices often cost more than the resources that would have been lost if the fire was left to burn on its own (Jensen and McPherson 2008). Encouraging lower intensity fires may have actually benefitted timber industries by improving tree and ecosystem health and function.

Maintaining defensible property in the wildland-urban interface has a personal cost to private landowners. Costs associated with personal property protection, including insurance, tools, and appropriate landscaping, merit consideration. Another large financial burden is the ecological consequence of years of fire suppression. As fire-dependent ecosystems, such as the Puget lowland prairies, are deprived of fire disturbances, management costs increase and sustainable practices become more difficult to achieve (Brooks et al. 2004). As these ecosystems are altered and become rare, so do the species that depend on them. Species that are granted endangered or threatened status under the Federal Endangered Species Act bring on additional protective costs. Managers need to protect remaining populations and preserve habitat. In turn, private landowners also become responsible for federally endangered species if populations exist on their property. Economic incentives, such as fines or increased management costs, can shape human behavior in ways that may actually inhibit endangered species recovery (Shogren et al. 1999).

Social concerns that impact fire policy include public health and safety. Even controlled prescribed fires have inherent unavoidable risks (Stephens and Ruth 2005). Unpredictable fire behavior can lead to lost lives and damaged property. Especially in very dry and windy conditions, fires can travel very quickly. A fire a mile away can suddenly be at your door in minutes. While wildland fire-fighting knowledge and experience have increased over the last few decades, one of the most important lessons learned is that fire can be very unpredictable. The timing of evacuation orders for people living within the wildland-urban interface is crucial to save lives (Cova 2005). Flames can travel quickly, and smoke can block visibility on roads. Cooperation of ecologists, public officials, fire-fighters, and residents is needed for effective evacuations, public education, and maximum protection of human lives.

Even if a nearby fire is not a direct threat to a community, nuisance smoke from both wildfires and prescribed fires can create serious health problems, especially in sensitive populations. Inhalation of small particulate matter can create breathing difficulties (Bowman and Johnston 2005). Smoke can contain a variety of noxious chemicals that have the potential to cause health damage. Carbon monoxide exposure can lead to headaches, and in extreme cases death (Reinhardt and Ottmar 2000). Communities that are particularly susceptible to regular fires also require appropriate medical facilities to manage those who are impacted by smoke inhalation or burns (Cova, 2005). Firefighters are at the highest risk of having severe health issues due to their close proximity to flames and smoke. The safety of firefighters, as well as their success at controlling a fire, depends on shared knowledge of weather predictions and ecological conditions. Regardless of the fire policy, humans and their property are put at risk with both anthropogenic fires and wildfires.

Political challenges are often created by concerns for public safety and financial costs. Fire management policies need to simultaneously protect the welfare of people and property within management areas, the economic stability of affected communities, and ecosystem services. These issues create a considerable need for interdisciplinary cooperation when prescribed burning is proposed. Obvious concerns about the safety of surrounding communities and firefighting personnel may make intentional fires seem unnecessarily dangerous at first glance. However, prescribed burning places personnel at a considerably lower risk than fighting wildfires, and provides control over when and where a burn occurs to utilize optimal weather and environmental conditions. By reintroducing smaller, controlled, and less intense burns into fire-dependent systems, the risk of catastrophic and unpredictable wildfires is greatly reduced. Justifying the risks of prescribed burning through the ecological, social, and financial benefits gained by better protecting ecosystems from catastrophic wildfires is the challenge for ecological burn managers. Nevertheless, negative media attention, as well as the conspicuous nature of fires, often challenges public acceptance prescribed burning.

Fire Ecology and Sustainability: Case Studies

Embracing fire disturbances in historically fire-dependent ecosystems promotes environmental, economic, and cultural sustainability. A prime example of sustainable fire practices occurs in Kruger National Park, South Africa. Kruger National Park relies on mosaic burning to maintain habitat for elephants, leopards, and other sensitive species. As part of a management plan, fire has helped restore African elephant (*Loxodonta africana*) populations, improving their IUCN (International Union for Conservation of Nature) red list category from “endangered” to “vulnerable” in 2004 (Blanc, 2008). Wildlife adaptations to regular fire disturbances become apparent within days of a burn. Emergent grass shoots attract grazing animals, such as zebras. The improved habitat within Kruger National Park also serves the important function of containing large and dangerous animals. Preventing animals from damaging crops, destroying property, and threatening human safety protects local communities and economics interests. Fire regimes create strong connections between environmental, social, and economic sustainability that are crucial to maintaining coexistence between humans and wildlife at Kruger National Park.

Fire ecology also helps create sustainability in farming communities. In South America, charcoal is used as an inexpensive, environmentally-safe form of fertilizer (Glaser 2007). Economically, farmers benefit from increased agricultural yield after supplementing soil with ash (Glaser 2007). While intensive farming depletes soil nutrients, using charcoal as a soil amendment in conjunction with other sustainable practices can be particularly effective in maintaining soil fertility (Glaser 2007). The improvement of agricultural yields through burning and charcoal soil amendments can also increase social capital in farming communities by providing a means to maintain trade connections and cooperation (Glaser 2007). Furthermore, increased food availability may improve public health (Glaser 2007). In addition to facilitating sustainable agricultural practices, charcoal fertilizer can contribute to nutrient availability in restoration areas (Barrow 2011). The utilization of charcoal may also have global implications. Long-term atmospheric carbon dioxide sequestration can occur through the creation of charcoal (Barrow 2011). Embracing this aspect of fire improves sustainability on several scales: higher agricultural yields locally, reduced environmental degradation regionally, and atmospheric carbon dioxide mitigation globally

Reintroducing the historic fire regime to Puget lowland prairies is an opportunity to preserve Native American heritage. Historically, prairies provided indigenous food crops, such as camas (*Camassia quamash*, USDA NRCS 2013) bulbs (Walsh et al. 2010). Native populations used fire as a hunting strategy; anthropogenic burning created habitats attractive to large game and edible insects (Shinn 1980). Furthermore, burning opened landscapes and decreased the effort required to acquire game. Anthropogenic prairie fires also played a role in social interactions between tribes. Tribes used fire as a signal for organizing convocations or migrations (Shinn 1980). Native populations also used anthropogenic fires as a war tactic to create a barricade against enemies (Shinn 1980). Whether in South Africa, South America, or the west coast of the United States, prescribed burning has enhanced the environmental, economic, and cultural sustainability of local communities.

Conclusion

Increasing available prairie habitat in the Pacific Northwest will hopefully increase the spread and success of endangered species, and decrease their need for federal protection. It is crucial to gain stakeholder cooperation in order to reduce the management requirements, financial costs, and ecological costs of species decline. Every ecological dilemma needs to consider social, political, and economic components to improve the health, resilience, and sustainability of ecosystems. For many communities, fire can play an important ecological role that can provide a more sustainable lifestyle.

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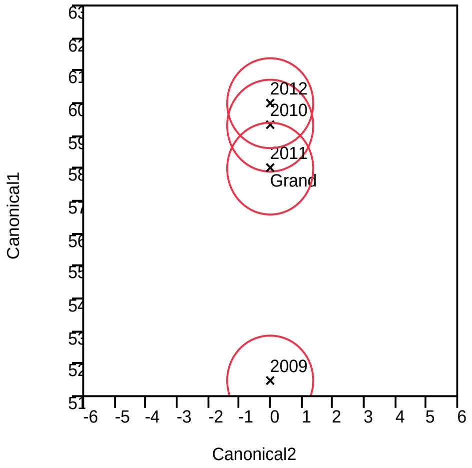
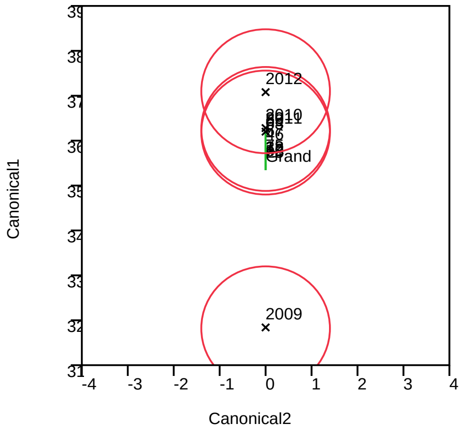
Appendix A: Contrast Pairwise Comparison Results



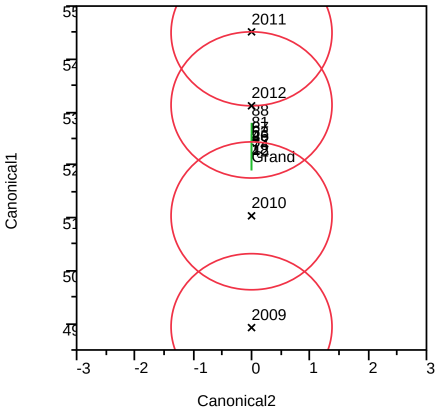
pair		F	p
2009	**2012**	**72.7548**	**0.001**
2011	2012	4.1168	0.1123
2009	**2010**	**61.1599**	**0.0014**
2010	2011	1.7419	0.2574
2009	**2011**	**42.2584**	**0.0029**

Figure A1: Pairwise contrast results for average surface temperature. Bolded rows indicate significant differences. A Bonferroni correction indicated that p-values less than 0.01 were significant.



pair		F	p
2009	**2012**	**27.8496**	**0.0062**
2011	2012	0.8244	0.4152
2009	**2010**	**19.7474**	**0.0113**
2010	2011	0.0056	0.9440
2009	**2011**	**19.0884**	**0.0120**

Figure A2: Pairwise contrast results for maximum surface temperature. Bolded rows indicate significant differences. A Bonferroni correction indicated that p-values less than 0.01 were significant.



pair		F	p
2009	**2012**	**17.5489**	**0.0138**
2010	2012	4.3872	0.1043
2011	2012	1.8796	0.2423
2009	2010	4.3872	0.1043
2010	2011	12.0102	0.0257
2009	**2011**	**30.9152**	**0.0051**

Figure A3: Pairwise contrast results for maximum surface temperature. Bolded rows indicate significant differences. A Bonferroni correction indicated that p-values less than 0.01 were significant.

Appendix B: Sample Datalogger data

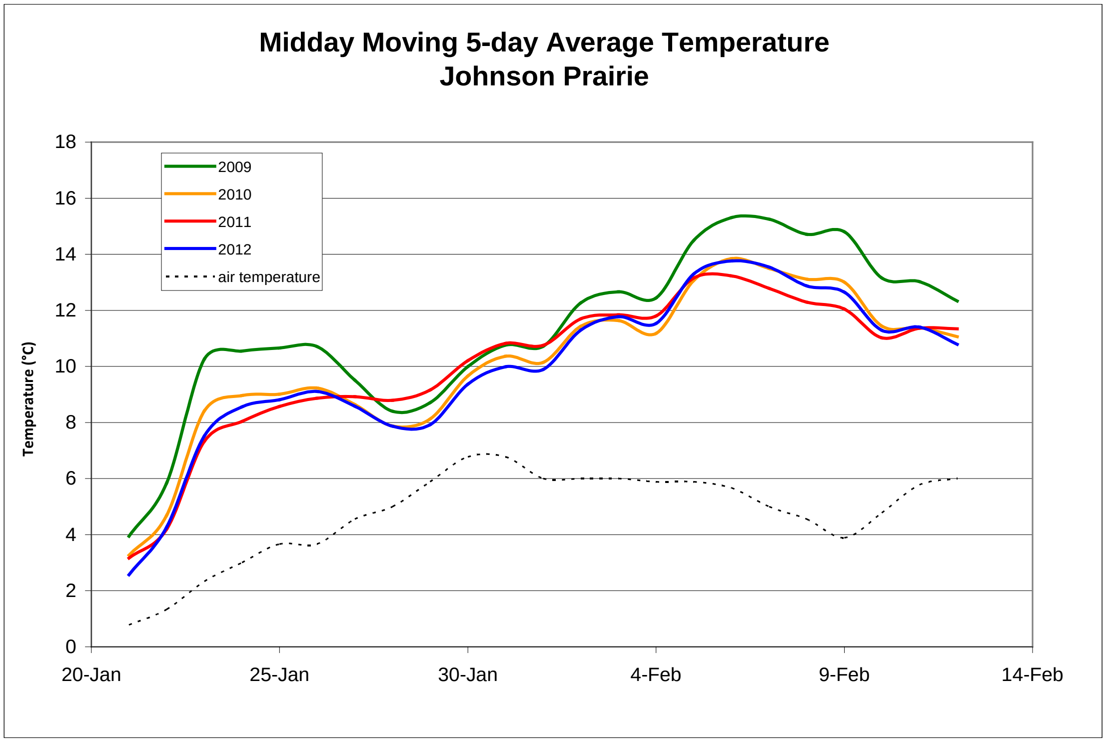


Figure B1: Sample 5 day moving average surface temperature (recorded from dataloggers) from Johnson prairie from January 19th to February 14th 2013. Average air temperature was recorded from Ft Lewis weather data (http://www.wunderground.com/history/airport/KGRF/2013/2/15/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA).

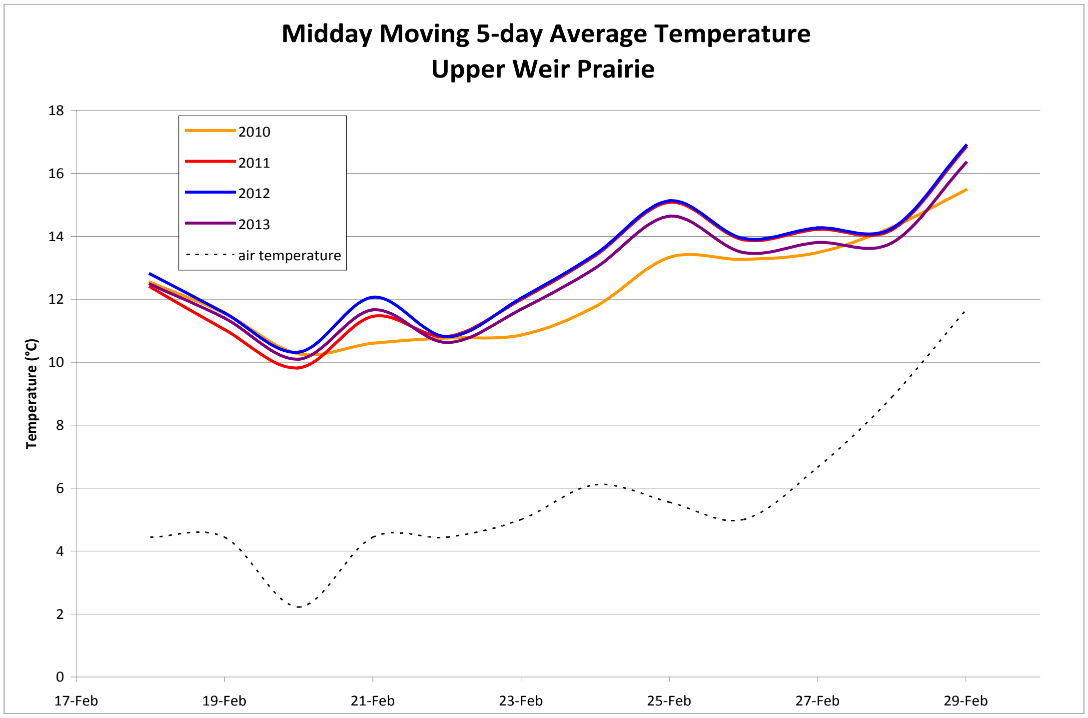


Figure B2: Sample 5 day moving average surface temperature (recorded from dataloggers) from Upper Weir prairie from February 16th to March 3rd 2013. Average air temperature was recorded from Ft Lewis weather data (http://www.wunderground.com/history/airport/KGRF/2013/2/15/DailyHistory.html?req_city=NA&req_state=NA&req_statename=NA).

Appendix C: Average Daily Air Temperature Influence

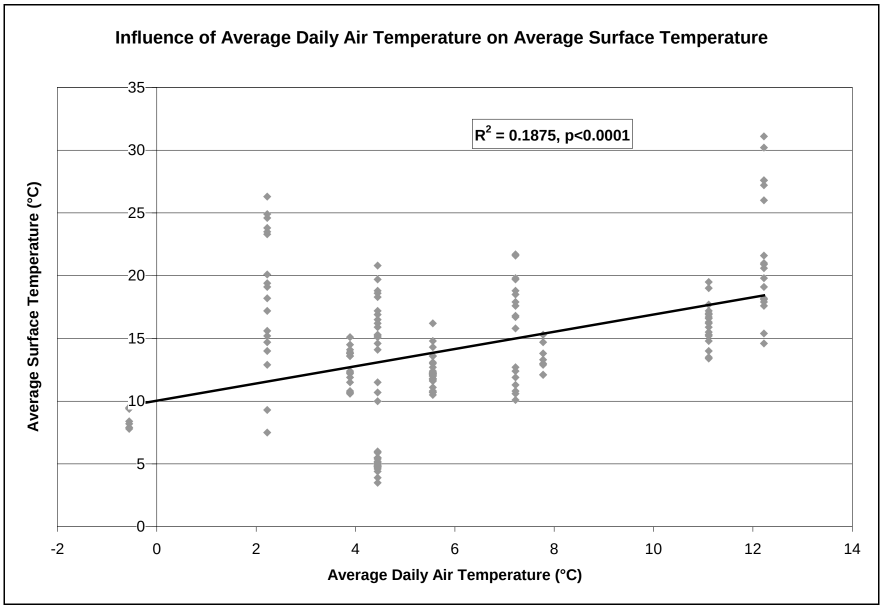


Figure C1: Regression analysis of the influence of average daily air temperature on average surface temperature. Air temperature has a significant positive influence on surface temperature, accounting for approximately 19% of the variation ($R^2 = 0.1875$, $p<0.0001$).

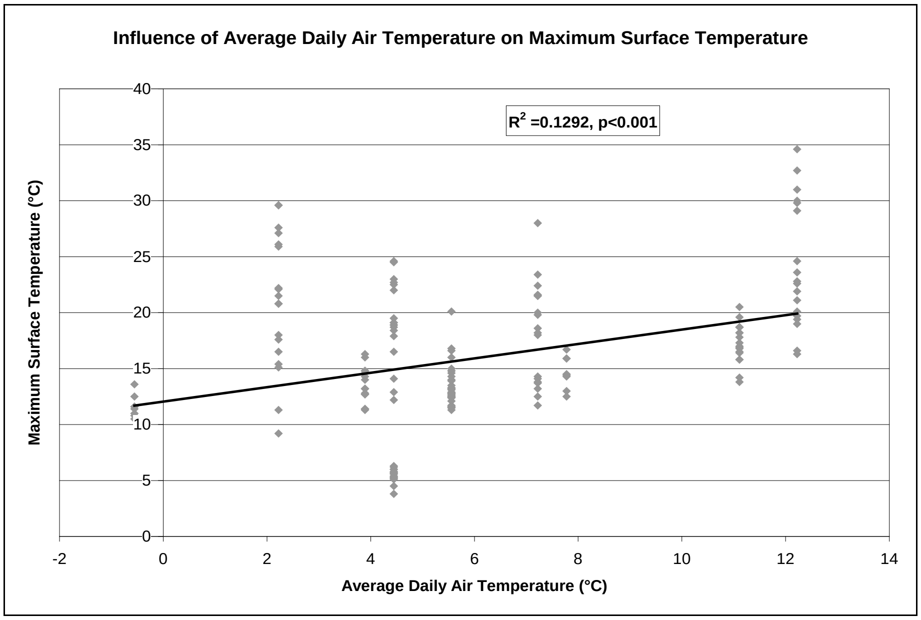


Figure C2: Regression analysis of the influence of average daily air temperature on maximum surface temperature. Air temperature has a significant positive influence on surface temperature, accounting for approximately 13% of the variation ($R^2 = 0.1292$, $p<0.0001$).

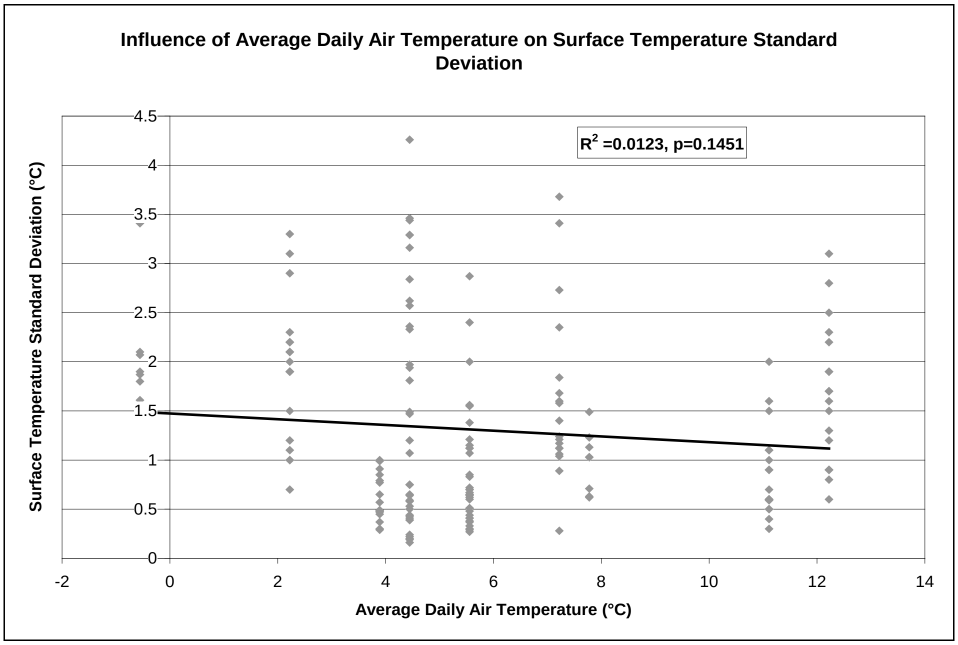


Figure C3: Regression analysis of the influence of average daily air temperature on surface temperature variation within each plot, represented by standard deviation. Air temperature did not significantly influence surface temperature variation ($R^2 = 0.0123$, p=0.1451).

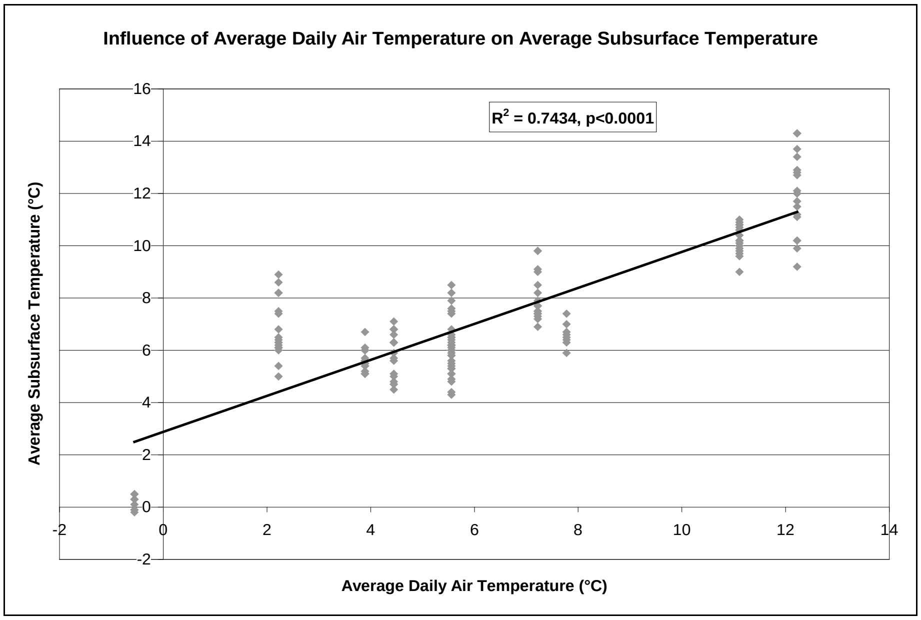


Figure C2: Regression analysis of the influence of average daily air temperature on average subsurface temperature. Air temperature has a significant positive influence on surface temperature, accounting for approximately 74% of the variation ($R^2 = 0.7434$, p<0.0001).

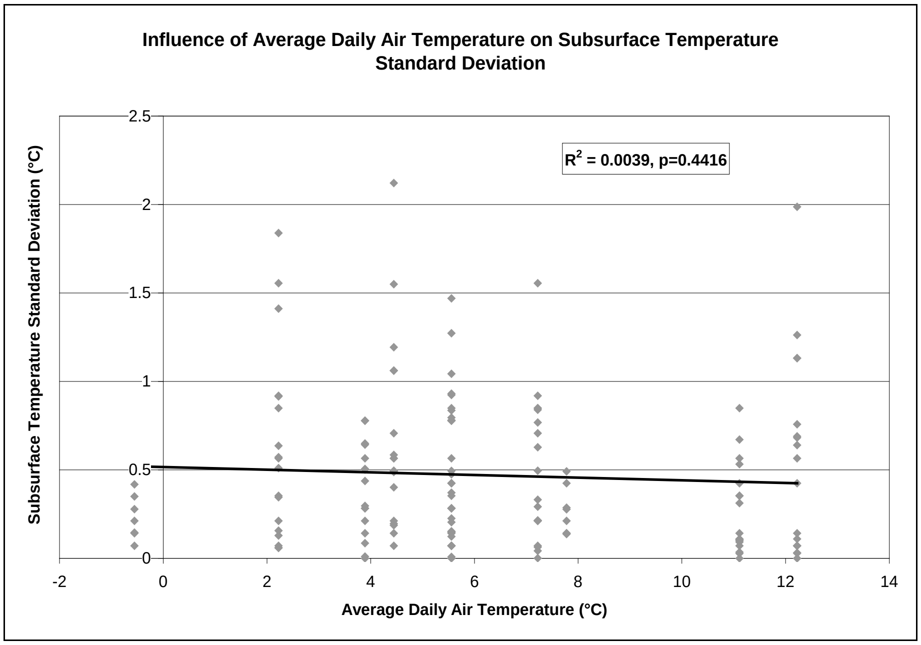


Figure C3: Regression analysis of the influence of average daily air temperature on subsurface temperature variation within each plot, represented by standard deviation. Air temperature did not significantly influence subsurface temperature variation ($R^2 = 0.0123$, $p=0.1451$).