SPATIAL AND TEMPORAL PATTERNS OF TREE INVASION, UPPER NANEUM WATERSHED, WASHINGTON: A COMPARATIVE STUDY OF HYDRIC, MESIC, AND XERIC MEADOW SYSTEMS

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ABSTRACT

SPATIAL AND TEMPORAL PATTERNS OF TREE INVASION, UPPER NANEUM WATERSHED, WASHINGTON: A COMPARATIVE STUDY OF HYDRIC, MESIC, AND XERIC MEADOW SYSTEMS

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Previous studies have uncovered a potential relationship between the timing and extent of tree invasion and the moisture regime of meadows. This study examined the spatial and temporal distribution of tree invasion in the upper Naneum watershed, Kittitas County, Washington, to determine if the timing and patterns of invasion vary between hydric, mesic, and xeric meadows. Additionally, this study aimed to reveal how tree establishment in these different settings has historically related to changes in climate, land use, and fire regimes. Findings suggest a relationship between tree invasion and climate variation, with snow pack potentially having a major impact on the timing of invasion in all three meadow types. A relationship was found between tree invasion and Pacific Decadal Oscillation, Palmer Drought Severity Index, snow water equivalent, cattle grazing, and fire return intervals. Findings also indicate the spatial, temporal, and species patterns of invasion are fairly similar across meadow types.

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CHAPTER I

INTRODUCTION

Problem

Meadows (i.e., parks or balds) are dynamic features found within mountainous landscapes throughout western North America. They are areas where grasses, sedges, and forbs dominate the vegetation assemblage despite being surrounded by forest (see Figure 1). These anomalous, nonforested areas have played an important role in the lives of people throughout human history. During pre-Columbian times, Native Americans used meadows as places for resource gathering and hunting. As Euro-Americans settled throughout North America, they too found meadows to be important resources and utilized them primarily as grazing grounds for livestock. More recently, people have enjoyed mountain meadows for recreation and leisure, being drawn to these areas by their beauty and abundant wildflowers (Rochefort & Peterson, 1996). Additionally, ecologists

Figure 1. Subalpine meadow, Table Mountain, Washington.

value mountain meadows for their uniqueness and rich biodiversity (Griffiths, Madritch, & Swanson, 2005).

Despite the importance and value of mountain meadows throughout time, these areas are currently threatened. The forest/meadow ecotone has migrated as trees have established in meadows causing them to decline in area. This is especially true in the Pacific Northwest, where tree invasion into meadow systems has been observed and documented throughout the 20th century (Dunwiddie, 1977; Franklin, Moir, Douglas, & Wiberg, 1971; Hadley, 1999; Magee & Antos, 1992; Miller & Halpern, 1998; Rochefort & Peterson, 1996; Woodward, Schreiner, & Silsbee, 1995). Encroachment threatens many of the resources and values of meadows, including Native American root crops, grazing grounds, visually splendid recreation areas, and biodiversity (Andersen & Baker, 2005; Griffiths et al., 2005).

Although intensive investigation has been conducted on the topic, the exact reason for meadow invasion remains somewhat ambiguous. Research points to various factors leading to tree invasion, such as changes in climate, land use, and fire return intervals, but the relationships between these factors and their relative importance remain unclear (Andersen & Baker, 2005; Coop & Givnish, 2007; Dunwiddie, 1977; Griffiths et al., 2005; Hadley, 1999; Magee & Antos, 1992; Miller & Harlpern, 1998; Norman & Taylor, 2005; Rochefort & Peterson, 1996; Woodward et al., 1995). Moreover, it appears as though not all factors operate the same in all meadows. Rather, the effects and importance of these factors vary based on environmental conditions of meadows. For example, Magee and Antos found a link between increased summer precipitation and increased levels of tree invasion on the dry margins of a subalpine meadows, while

Franklin et al. attributed peaks in tree invasion in moist subalpine meadows to warmer, drier climatic conditions. Although research has determined the relationship between factors facilitating tree invasion and environmental conditions of meadows, relatively few studies have set out to determine if the spatial and temporal patterns of tree invasion vary in meadows with differing moisture regimes (Miller, 1995; Miller & Harlpern). Additionally, no research has been done to understand how the timing of tree invasion in hydric, mesic, and xeric meadow systems in Washington State's eastern Cascade Range coincides with climate variation, land use change, and fire return intervals.

Purpose

The purpose of my research was to examine where and how tree encroachment occurs, and if encroachment changes across different meadow types in the Wenatchee National Forest's upper Naneum watershed, Kittitas County, Washington. More specifically, I (a) documented the spatial distribution of meadows; (b) determined spatial, temporal, and species patterns of invasion for hydric, mesic, and xeric meadow systems; and (c) determined how climate, land use, and fire return interval changes correlate with the timing and rate of tree invasion per each meadow type. Additionally, I used findings from this study to make meadow management recommendations for the upper Naneum watershed that are applicable to other mountain meadow sites in the region.

Significance

The information provided by my research in the upper Naneum serves as important baseline data for future studies examining meadow/forest dynamics within the watershed. The findings of my study may also aid forest managers in the Wenatchee

National Forest and throughout the Pacific Northwest in the maintenance and preservation of these unique and heavily used areas by adding to preexisting knowledge on where and how tree encroachment occurs. Additionally, this study will fill an important gap in mountain meadow research, and enhance the understanding of how site-specific characteristics may influence and impact tree invasion. This is important for gaining a better understanding of how vegetation boundaries fluctuate based on specific characteristics of ecosystems, and how plant succession occurs over time and space. Moreover, a greater understanding of vegetation dynamics and the causes of ecotone movement is important as we enter into an era of increasing climate change and changing land use, as the distribution of vegetation has the potential to impact how and where people live on, use, and move across landscapes.

CHAPTER II

LITERATURE REVIEW

Meadow Origins

The origin of mountain meadows is somewhat of a mystery. Three contradictory hypotheses are generally found throughout the literature as explanations for meadow formation: the permanent site hypothesis, the remnant hypothesis, and the replacement hypothesis (Lynch, 1998). The permanent site hypothesis postulates that meadows inhabit relatively permanent positions on the landscape (Lynch). These enduring locations are attributed to either topography or soil characteristics, such as poor drainage (Doering & Reider 1992; Lynch). The remnant hypothesis states that mountain meadows are merely remnant features from a cooler climatic period when alpine tundra was the dominant vegetation type (Kuramoto & Bliss, 1970; Lynch). As global temperatures warmed, forest vegetation moved into former alpine tundra zones, and meadows were found in areas not yet invaded by forests (Kuramoto & Bliss). Under this hypothesis, meadow vegetation existed in mountainous regions before forests became the primary vegetation assemblages. The third meadow origin hypothesis, the replacement hypothesis, attributes meadows to climate change or disturbances, such as forest fires (Coop & Givnish, 2007; Lynch; Norman & Taylor, 2005). After such disturbances, meadows are maintained for tens to thousands of years by site specific characteristics, such as soil, topography, or solar radiation, or by continued disturbance (Lynch). This hypothesis is based on the idea that meadows form in already established forest, rather than forest establishing around meadow vegetation. Although these hypotheses seem to be at odds with one another, it is likely that some combination of them can explain meadow formation and maintenance throughout the mountains of western North America, including the eastern Cascades.

Meadow Moisture Regimes

Soil moisture of meadows varies based on site specific characteristics, such as climate, topography, underlying geology, and soils. Because of this, meadows are often classified in one of three meadow types based on moisture regimes: hydric, mesic, and xeric (Benedict, 1983; Doering & Reider, 1992; Miller & Halpern, 1998). These three commonly recognized meadow types may be further subdivided based on dominant vegetation and seasonality of soil moisture via various classification systems (Benedict; Debinski, Jakubauskas, & Kindscher, 2000; Kindscher, Fraser, Jakubauskas, & Debinski, 1998), but for the purpose of this discussion only the broader categories will be examined in more detail.

Hydric Meadows

Hydric meadows are commonly referred to as wet meadows. They often occur in areas of poor drainage, high water tables, and near lakes or streams (Benedict, 1983; Miller & Halpern, 1998). Topography is often a key component of these meadow types. Hydric meadows tend to occur on concave or flat slopes (Miller, 1995). Climate and topographic shading plays a pivotal role in the formation of these meadow types, as generally these areas receive more precipitation than the evapotransportation on an annual basis (Benedict). Hydric meadows are often found on north facing slopes, or areas that are shaded from afternoon sun. In western North America, including the eastern Cascades, these meadows do tend to have a summer drought period, where evapotransportation exceeds precipitation, but soil water, ground water, and stream flows keep them wet throughout this dry period (Benedict). Saturated soil conditions are the norm in hydric meadows, thus hydrophytic vegetation tends to persist in these areas. The characteristic vegetation of these meadows are wet sedges, rushes, willows, and perennial bunch grasses. Hydrophytic forbs may also be found in hydric meadows, but they tend to have low frequency and cover values (Benedict; Debinski et al., 2000).

Mesic Meadows

Mesic meadows, as the name indicates, are in the middle of the wet/dry gradient of meadow moisture regimes. Soil drainage in these meadows is relatively greater than that in hydric meadows, thus saturated soils are not typical in these sites, but may occur seasonally (Benedict, 1983). Mesic meadows are often found on gently sloping surfaces, and on moderately well drained soils (Miller, 1995). Additionally, these meadows have few rocky/gravelly areas, high vegetation cover, and are typified by soft, dense turf (Benedict). The dominant vegetation of mesic meadows throughout the western North America and in the eastern Cascades includes perennial grasses, sedges, and large amounts of forbs (Benedict; Debinski et al., 2000). Of the three meadow types discussed in this section, mesic meadows support the greatest richness of biodiversity and are most affected by seasonal and inter-annual droughts (Debinski et al.).

Xeric Meadows

In contrast with hydric and mesic meadows, xeric meadows are meadows dominated by dry conditions. These meadows are dry for one or more of the following reasons: evapotransportation exceeds precipitation, south-facing aspect, convex or steep slopes, and rocky or gravelly soils that are excessively drained (Benedict, 1983; Miller, 1995). The vegetation supported by xeric meadows tends to be more drought tolerant than other meadow vegetation, consisting primarily of sagebrush, dry sedges, and bunch grass in western North America (Benedict), including the eastern Cascades. Because of the xerophytic plants that live in these sites, xeric meadows are less impacted by drought than mesic meadows (Debinski et al., 2000).

Spatial Distribution of Meadows

The elevation distribution of mountain meadows is very diverse. Meadows inhabit basin and valley bottoms, and high subalpine zones. Depending on location and elevation, mountain meadows are classified as either montane or subalpine (Miller & Halpern, 1998). Montane meadows tend to be lower in elevation, while subalpine meadows are found in higher elevation locations, often near the upper treeline (Miller & Halpern). Despite the altitudinal ranges of mountain meadows, few have examined where meadows tend to occur across these gradients.

In addition to meadows occurring throughout a vast altitudinal range, meadows can be found on all types of topography, including all aspects, hummocky areas, concave surfaces, convex surfaces, and all slope gradients. As discussed above, the aspect and slope of a meadow likely influences the moisture regime (Benedict, 1983; Miller, 1995). These characteristics may also impact invasion (Miller & Halpern), which will be discussed later. Although meadows can inhabit various types of topography, limited research has been conducted in the Cascade Range to determine where meadows tend to occur on the landscape.

Temporal Distribution of Meadows

The temporal distribution of meadows on the landscape is not well documented and tends to vary greatly from meadow to meadow. Factors that impact the longevity of meadows include meadow origin and meadow location (Kuramoto & Bliss, 1970). Meadows created by disturbance events, such as those described in the replacement hypothesis, tend to be ephemeral features, persisting on the landscape for hundreds of years (Lynch 1998). Meadows created by more long-term trends, such as climate change, may endure on the landscape for thousands of years (Lynch). Still others are very stable features, and may persist for many thousands of years (Lynch). Additionally, meadow location plays a role in the temporal distribution of the meadow. Meadows inhabiting areas of environmental extremes, such as dry, south facing slopes or boggy, concave surfaces can endure much more environmental change and will remain on the landscape much longer than meadows that inhabit sites with moderate conditions (Kuramoto & Bliss). Little research has been done to determine the age of meadows in the eastern Cascades.

Factors Impacting Tree Invasion Into Meadows

As previously discussed, research indicates factors such as climate, fire, soils, grazing, and other types of land use may influence tree invasion. There may also be some synergistic relationships between these factors. These possible factors of tree invasion will be examined in further detail in this section, as well as the species, spatial, and temporal patterns of tree invasion.

Climate

Studies suggest that climate plays a significant role in tree encroachment into mountain meadow systems (Coop & Givnish, 2007; Franklin et al., 1971; Magee & Antos, 1992; Miller & Halpern, 1998; Norman & Taylor, 2005; Rochefort & Peterson, 1996; Woodward et al., 1995). Drought can either increase or decrease invasion, depending on whether the site is wet or dry (Coop & Givnish; Franklin et al.; Miller & Halpern; Norman & Taylor; Rochefort, Little, Woodward, & Peterson, 1994; Rochefort & Peterson; Woodward et al.). Conversely, above average precipitation can either increase or decrease invasion, depending on the dominant moisture regimes of the site (Coop & Givnish; Miller & Halpern; Norman & Taylor; Rochefort et al.; Rochefort & Peterson; Woodward et al.). For example, using dendrochronology, Franklin et al. found that peak periods of invasion tended to coincide with warm and dry climatic cycles in the moist subalpine meadows surrounding Mt. Rainier, while Norman and Taylor found peaks in invasion tended to coincide with cool, moist climatic periods in the mesic and dry meadows of the southern Cascades near Mt. Lassen. The link between peaks in invasion levels and increased/decreased moisture levels observed at many sites illustrates the importance precipitation plays in vegetation dynamics, as moisture is often a limiting factor for trees (Coop & Givnish; Miller & Halpern; Norman & Taylor; Rochefort et al.; Rochefort & Peterson; Woodward et al.).

Snowfall and snowpack might also play a significant role in tree encroachment into mountain meadow systems. It appears as though decreased late spring and summer snowpacks help facilitate tree invasion in the moist western Cascades, Oregon Coast Range, and eastern and western Olympic Mountains (Franklin et al., 1971; Magee & Antos, 1992; Rochefort & Peterson, 1996; Woodward et al., 1995). The relationship between decreased snow pack and increased invasion exists because these areas often receive such deep snow packs that young trees do not melt out from the snowpack until late summer (Rochefort & Peterson). This, coupled with early autumn freezing temperatures, greatly reduces the growing season for seedlings and saplings, leading to increased mortality (Rochefort & Peterson). It is possible that the same phenomenon occurs at meadow sites high in the eastern Cascades, where snow pack is deep, and freezing occurs early in autumn.

Snow deposition caused by wind has a similar impact as snowfall on the leeward sides of meadows, inhibiting invasion on meadow margins and possibly creating “snow glades,” which are linear treeless features aligned perpendicular to the prevailing wind on the lee sides of ribbon forests (Butler, Malanson, Bekker, & Resler, 2003; Doering & Reider, 1992). If wind-driven snow deposition on the lee side of meadows inhibits tree invasion, it may be possible that invasion is greater on the windward side of meadows, where snow is removed by prevailing winds.

In addition to precipitation, changes in temperature patterns might also influence tree encroachment. Research indicates that higher temperatures in the late spring, early summer, and early fall have a positive correlation with tree invasion in the cold, moist meadows of the western Cascades (Rochefort & Peterson, 1996). This increased tree invasion can be attributed to longer growing seasons (Rochefort & Peterson). Although higher early and late growing season temperatures can increase tree invasion, high midsummer temperatures may inhibit tree invasion, especially in drier areas, such as the eastern Cascades (Miller, 1995; Rochefort et al., 1994; Rochefort & Peterson; Woodward et al., 1995). This impact on tree invasion is due to soil surface temperatures, as well as increased evapotranspiration (Miller). Despite this, increased midsummer temperatures tend to aid invasion in north-facing, moist areas where snow and saturated soil conditions persist well into the growing season (Miller; Rochefort & Peterson). Although it appears that the importance and role of different climatic conditions influencing encroachment varies based on the moisture regime of the meadow, little research has been conducted looking directly at this variation. Temperature regimes might also impact invasion through geomorphic changes and soil disturbance. In areas where high variation in diurnal temperatures exists, and freeze thaw cycles are abundant, it is conceivable that frost heave could disturb seedlings and/or alter soil nutrients via soil churning.

Fire Regime

Natural and anthropogenic burns have been identified as key components of meadow maintenance (Magee & Antos, 1992; Miller & Halpern, 1998). It has also been widely recognized that altering fire regimes has affected tree encroachment into mountain meadow systems (Coop & Givnish, 2007; Hadley, 1999; Miller & Halpern; Norman & Taylor, 2005). Using dendrochronology, researchers have found fire return intervals throughout the western United States have increased significantly since the late 19th and early 20th centuries (Coop & Givnish; Hadley; Norman & Taylor). Research indicates that the eastern Cascades are no exception. Fire return intervals have increased significantly throughout this region; pre-European settlement, the mean fire return interval for midelevation Douglas fir forests was 6 to 7 years. Today the fire return interval is 38 to 43 years (Everett, Schellhass, Keenum, Spurbeck, & Ohlson, 2000). Researchers have also found a relationship between these lengthened fire intervals and the increased ability of trees to move into meadow systems (Coop & Givnish; Hadley; Norman & Taylor). This is likely because fires enhance meadow vegetation, while destroying tree seedlings and saplings that move into these areas (Coop & Givnish; Hadley; Miller & Halpern; Norman & Taylor).

Soils

Research indicates soil properties may be linked to tree invasion into mountain meadow systems. As previously discussed, several studies implicated soil moisture levels and climate variation as a cause of invasion (Coop & Givnish, 2007; Hadley, 1999; Miller & Halpern, 1998; Norman & Taylor, 2005; Rochefort & Peterson, 1996; Woodward et al., 1995). It is likely that where excessive soil moisture or soil drought limits tree growth, creating forest openings, microtopography, land use, or climate may create more moderate soil moisture conditions that are favorable for seedling recruitment in meadows.

Forest and meadow soils tend to be very different, as are the conditions in which they form (Doering & Reider, 1992; Griffiths et al., 2005). Soil differences appear in pH, temperature, nitrogen levels, litter depth, field respiration, fungal and microorganism activity, and moisture (Doering & Reider; Griffiths et al.). In addition to soil properties being a facilitating factor for tree invasion, it is likely that soils also change with tree invasion (Doering & Reider; Griffiths et al.; Haugo & Halpern, 2007). It appears as though soil properties can shift quickly from meadow soils to forest soils, and this transition might even begin to occur before invasion via spreading fungal mats (Griffiths et al.). This is especially true in areas where forest shading creates cool, moist soil conditions (Griffiths et al.). Transition back to meadow soils after a disturbance event is often slower, although these changes occur more rapidly when the disturbance event is fire (Griffiths et al.) In the dry and cool conditions that exist in the high elevations of the eastern Cascades, soil changes likely occur very slowly, similar to what Doering and Reider found in the Rocky Mountains.

Wildlife Impacts on Meadow Systems

Wildlife has the potential to greatly alter and impact their surrounding environment, and meadows are no exception to this. In the Rocky Mountains, grizzly bears (*Ursus arctos*) have been observed digging near the tree line and in subalpine meadows (Hall & Lamont, 2003; Tardiff & Standford, 1998). This digging activity occurs for food procurement: catching burrowing rodents, finding insects, and foraging for plant bulbs. The disturbance caused by grizzly bear digging has shown to have major effects on soil nutrients and vegetation patterns, with digging increasing the amount of mineral nitrogen available to plants in the soil, changing local plant assemblages, and even perhaps changing plant successional patterns within disturbed areas (Tardiff & Stanford). With the overall changes in soil and vegetation properties that bears can cause in meadow systems, it is conceivable that grizzly bear digging could impact and influence tree invasion into these systems. This is also likely true of black bears (*Ursus americanus*), which have a propensity to feed on roots in high, subalpine meadows.

Pocket gopher (*Cratogeomys spp*.) bioturbation could also impact forest/meadow dynamics. Much like grizzly bear disturbance, soils within subalpine meadows that have been subjected to pocket gopher churning have greater levels of mineral nitrogen, as well as higher levels of phosphorus (Hall & Lamont, 2003; Laycock & Richardson, 1975; Tardiff & Standford, 1998). Because of pocket gopher impacts on soil nutrients, their burrowing activities also impact the vegetation assemblages of subalpine meadows, generally increasing the diversity and cover of meadow plant species in areas of low population (Laycock & Richardson). This would likely help inhibit tree invasion because meadow vegetation might be more able to out compete forest vegetation. Despite the possible benefits of pocket gopher activity, high populations have been linked to a decline in herbaceous ground cover and livestock forage, and an increase in soil erosion (Ellison, 1946; Laycock & Richardson).

Large ungulate trampling and herbivory may also have impacts on meadow systems (Hall & Lamont, 2003; Weisberg & Bugmann, 2003). Trampling has been shown to be the greatest impact of large ungulates, such as dear and elk, on meadow systems, leading to soil surface disturbance, erosion, and compaction, which could influence vegetation dynamics and tree invasion into meadow systems (Hall & Lamont; Weisberg & Bugmann). Additionally, trampling may cause a decline in meadow vegetation covers, which could decrease species competition, leading to an increase in tree establishment. Overgrazing is also a concern for many land managers in areas where ungulate populations are high (Weisberg & Bugmann). Overgrazing may also lead to a decline in meadow vegetation covers, decreasing competition and facilitating tree invasion.

In addition to the abovementioned animal species that may impact tree invasion, it is possible the insect herbivory or infestation, as well as plant disease could effect tree invasion. It is feasible that these could cause stresses to either invading trees or meadow vegetation, which could decrease or increase invasion. Despite this possibility, little research has been conducted examining the impacts of insects and plant disease on tree invasion.

Land Use

Fire Suppression and Anthropogenic Burns

As previously discussed, human-caused fires have been recognized as a meadow maintenance technique, as fire within mountain meadow systems tends to cause seedling mortality (Magee & Antos, 1992; Miller & Halpern, 1998). It is commonly recognized that Native Americans throughout the western United States, and likely within the eastern Cascades, used fire as a tool to maintain meadows, increase game fodder, and enhance food plants gathered within these systems (Coop & Givnish, 2007; Griffiths et al., 2005; Hadley, 1999; Haugo & Halpern, 2007; Magee & Antos; Norman & Taylor, 2005). It appears as though Euro-Americans also used fire as a tool in mountain meadows. At Rigdon Meadow, Oregon, it was found that anthropogenic burns occurred in high frequency shortly after the arrival of Euro-Americans, from 1850 to 1868 (Hadley). This increase in fire frequency is attributed to road building activities during this period (Hadley).

As discussed in previous sections, fire return intervals have increased over the past 100 to 120 years, which has had major influences on tree invasion (Hadley, 1999; Norman & Taylor, 2005). This elongation of the fire return interval is likely due to land management practices, such as fire suppression (Hadley; Miller & Halpern, 1998; Norman & Taylor). Fire suppression in the western United States and the eastern Cascades began around 1890 with the establishment of federal forest reserves; it peaked in the 1920s, and remained high throughout most of the 20th century (Hadley; Norman & Taylor). Recently, there has been a policy shift in fire suppression. Over the past 2 decades, reintroduction of fire to the landscape has occurred through prescribed burns and by allowing some wildfires to burn (Stephens & Ruth, 2005).

Resource Extraction

Meadows have been resource extraction sites for thousands of years. As previously mentioned, Native American groups hunted and gathered food crops within meadows long before the arrival of Euro-Americans. Root gathering practices may have had great impacts on the vegetation and soils of meadow systems (Suttles, 1987). Traditionally, camas and other root and bulb crops were dug in the eastern Cascades from spring though summer (Suttles). This digging caused soil disturbance by mixing surface and subsurface horizons (Suttles). This soil churning may have increased mineral nitrogen, which would have enhanced meadow vegetation, similar to the impacts of grizzly bear and burrowing rodent digging in these systems (Suttles; Tardiff & Stanford, 1998). Enhanced meadow vegetation may make it more difficult for seedlings to germinate and may increase competition for vital water, light, and nutrients (Norman & Taylor, 2005).

Euro-Americans also used these areas for resource extraction, primarily in the form of livestock grazing (Andersen & Baker, 2005; Coop & Givnish, 2007; Dunwiddie, 1977; Hadley, 1999; Miller & Halpern, 1998; Norman & Taylor; 2005; Rochefort & Peterson, 1996). Livestock grazing began in western meadows around the 1860s, with sheep grazing later shifting to cattle grazing (Coop & Givnish; Norman & Taylor). Grazing in most meadow areas peaked around the late 1800s and early 1900s, and began to decline to the modest levels that exist today (Coop & Givnish; Dunwiddie; Hadley; Norman & Taylor; Rochefort & Peterson).

Like large ungulate impacts noted above, evidence suggests that livestock have had major impacts on meadow maintenance, and tree encroachment. Many studies indicate that in the Pacific Northwest with grazing reduction and cessation, tree invasion is increasing (Coop & Givnish, 2007; Hadley, 1999; Miller & Halpern, 1999; Norman & Taylor; 2005; Rochefort & Peterson, 1996). This suggests that trampling and browsing might prevent trees from establishing within meadows (Coop & Givnish; Miller & Halpern; Norman & Taylor). Others have viewed livestock grazing as facilitating invasion by disturbing meadow soils and vegetation, thus providing niches for trees to germinate (Andersen & Baker, 2005; Franklin et al., 1971). Dunwiddie (1977), based on observations made in the Wind River Range, Wyoming, theorizes that intensive grazing prevents invasion via seedling browsing and trampling, while moderate levels of grazing facilitate invasion by disturbing vegetation and soils, but not causing seedling mortality. Additionally, ungrazed meadow vegetation prevents tree invasion by providing ground cover and competition. In addition to the impacts grazing may have on browsing, trampling, and vegetation and soil disturbance, livestock grazing may also impact meadow vegetation by altering the hydrology of meadows through soil compaction. Little research has been conducted to determine how grazing might impact meadows in the eastern Cascade Range.

Tree Species

Research has implicated several tree species as major players in tree invasion. Invading species vary from site to site based on species morphologies and the specific environmental characteristics of meadows. For example, in the western and eastern Olympic Mountains of western Washington, Woodward et al. (1995) found western hemlock (*Tsuga heterophylla*) invading in more moist meadow sites and subalpine fir (*Abies lasiocarpa*) invading slightly drier meadows. This can likely be attributed to the moisture tolerance of hemlock as compared to subalpine fir, and the greater drought tolerance characteristics of subalpine fir (Woodward et al.). Invading tree species also depend on the forest series surrounding meadows, mainly because of seed availability (Miller, 1995). Additionally, light and nutrient needs may make some species more likely to invade mountain meadows than others (Miller). For example, a species that prefers shade, such as grand fir (*Abies grandis*) might be less likely to invade a meadow than a species that can tolerate full sun, such as subalpine fir (Miller). Table 1 summarizes the various invading species, surrounding forest series, and meadow

Table 1

Species of Invasion, Surrounding Forest Series, and Meadow Moisture Regime for Tree Invasion Studies in the Cascade and Rocky Mountain Regions

Species of invasion	Forest species	Meadow moisture regime	Reference
Grand fir, lodgepole pine	Grand fir/Douglas fir/ lodgepole pine	Mesic	Haugo & Halpern, 2007
Grand fir, lodgepole pine	Grand fir/Douglas fir/ lodgepole pine	Mesic	Griffiths, Madritch, & Swanson, 2005
Lodgepole pine, subalpine fir	Lodgepole pine/subalpine fir/Engelmann spruce	Mesic	Jakubos & Romme, 1993
Lodgepole	Lodgepole pine	Xeric	Jakubos & Romme, 1993
Douglas fir	Ponderosa pine/Douglas fir/incense cedar	Mesic	Hadley, 1999
Engelmann spruce, lodgepole pine, whitebark pine	Subalpine fir/lodgepole pine/whitebark pine, Engelmann spruce	Wet-mesic	Dunwiddie, 1977
Lodgepole pine	Lodgepole pine/subalpine fir/Engelmann spruce	Mesoxeric	Doering & Reider, 1992
Subalpine fir	Subalpine fir/hemlock/ Alaskan yellow cedar/ whitebark pine/ Engelmann spruce	Mesic	Rochefort & Peterson, 1996
Douglas fir, lodgepole pine	Douglas fir/lodgepole pine/Engelmann spruce	Mesoxeric	Miller & Halpern, 1998
Grand fir, Douglas fir	Grand fir/Douglas fir/ lodgepole pine/ Engelmann spruce	Mesic	Miller & Halpern, 1998
Subalpine fir, Engelmann spruce, hemlock	Subalpine fir/Engelmann spruce/hemlock/Douglas fir/lodgepole pine	Hydric	Miller & Halpern, 1998

moisture characteristics for tree invasion studies conducted in the western Cascades and Rocky Mountains of the United States. Little research has been conducted on invading species in the eastern Cascades.

Spatial Patterns of Tree Invasion

Elevation

The literature indicates that meadow invasion occurs across elevational zones (Coop & Givnish, 2007; Franklin et al., 1971; Miller & Halpern, 1998). Not only does tree invasion occur throughout the elevation distribution of mountain meadow systems, but also, elevation may be a contributing factor to tree invasion (Coop & Givnish). In a study conducted in the grasslands of the Valles Caldera, New Mexico, researchers found that tree invasion tends to be greater in higher elevation locations (Coop & Givnish). They suggest that frequent inversion layers may contribute to this spatial phenomenon, with cold temperatures killing tree seedlings and saplings in the lower elevations. This implicates cold temperatures as a limiting factor to invasion in this mesic setting. One might also see such a pattern as a result of climate change causing warmer temperatures at higher elevations. A similar pattern of invasion might exist in the cool, dry climate of the eastern Cascades.

Aspect

As noted above, meadows exist on slopes of all aspects. Despite the varying aspects of meadows, some research suggests that meadow aspect influences tree invasion. Many researchers have found that statistically significant relationships exist between aspect and tree invasion, although what aspect best facilitates tree invasion seems to depend on soil moisture properties, and local climatic variations and microclimate (Miller & Halpern, 1998; Rochefort & Peterson, 1996; Woodward et al., 1995). It appears as though south-facing slopes support tree invasion in wet areas, while limiting tree encroachment into meadow systems in more xeric locations (Miller & Halpern; Rochefort & Peterson; Woodward et al.). On the other hand, north-facing slopes support tree encroachment in drier locations, while limiting it in more moist locations (Miller & Halpern; Rochefort & Peterson; Woodward et al.). These findings suggest that shading may play an important role in meadow invasion by influencing soil moisture through evapotransportion or snowmelt. This is likely the case in the eastern Cascade Range. Given this, it is conceivable that shading by surrounding forest might also shape the spatial patterns of invasion within a meadow.

Slope

Slope, and its impacts on microclimate and soil moisture, might also be a determining factor for tree encroachment into mountain meadow systems. In fact, Rochefort and Peterson (1996) suggest that it may be among the most important factors relating to tree invasion, and found that trees tend to establish on convex surfaces as opposed to concave surfaces in the moist subalpine meadows surrounding Mt. Rainier. The same could be true in hydric meadows of the eastern Cascades.

Miller and Halpern (1998) found that, in wet montane meadows, flat sites are not nearly as susceptible to invasion as gently sloped sites. In these settings, excessive soil moisture is likely the limiting factor of tree growth. In hydric sites, when the distance to water table is reduced because of topography it is likely to impact the ability of seedlings to establish by reducing the capability of tree roots to respire (Miller & Halpern). They also found that invasion is less likely in mesic and “mesoxeric” meadows that occur on steep slopes (Miller & Halpern). Steep slopes inhibit tree invasion because of shallow soil depth and excessive water drainage (Miller & Halpern). Despite their findings, Coop and Givnish (2007) and Andersen and Baker (2005) found that tree invasion is greater on steep slopes in the mesic meadow sites they studied. It is possible that this could be attributed to inversion layers, or spatial variation in the fire regime (Coop & Givnish).

Proximity to Forest Edge

Most tree invasion tends to occur along the margins of the forest/meadow ecotone (see Figure 2) (Andersen & Baker, 2005; Coop & Givnish, 2007, Magee & Antos, 1992; Moore & Huffman, 2004; Norman & Taylor, 2005; Rochefort & Peterson, 1996). Previous research reveals seedling establishment and survival is greatest near the forest edge, making it logical that this is where invasion tends to occur (Andersen & Baker; Coop & Givnish, Dunwiddie, 1977; Griffiths et al., 2005; Magee & Antos). This increased survival is likely related to soil characteristics, such as presence of symbiotic fungi, soil moisture, and soil nutrients (Coop & Givnish; Griffiths et al.; Magee &

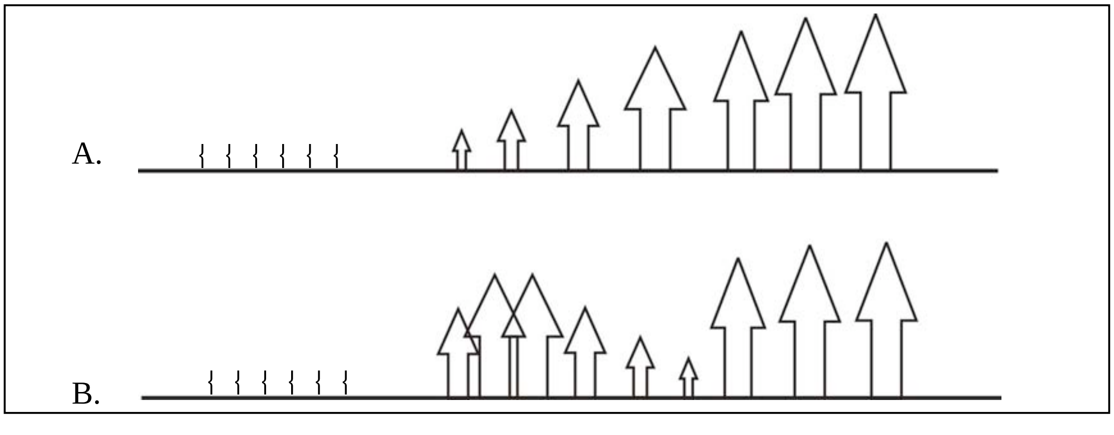

Figure 2. Spatial patterns of tree invasion. A illustrates gradual invasion pattern, while B illustrates leap-and-fill invasion pattern. The size of the trees indicates their relative age.

Antos). This invasion pattern may also be attributed to distance from seed source. Investigations into the spatial pattern of tree invasion in abandoned fields reveal that seedling establishment exponentially declines with distance from seed source (Myster, 1993). It is logical to conclude that the same may be true in mountain meadow systems.

Even though invasion often occurs at the meadow/forest ecotone, this is not always the case. Seedling establishment has been observed at distances from meadow edges (Magee & Antos, 1992). Additionally, patterns of “leap-and-fill” invasion (Figure 2) have been found to be dominant in some locations throughout the Cascade Mountains (Franklin et al., 1971; Norman & Taylor, 2005). This is where lone trees, or groups of trees known as tree islands, establish far from meadow margins, and backfill toward the margins (Norman & Taylor). One explanation for these patterns may be disturbance of the seedbed (Magee & Antos; Norman & Taylor). Seedlings may establish where there has been soil disturbance and damage to competing organisms (Magee & Antos; Norman & Taylor). These instances of tree island formation and “leap-and-fill” invasion may also be attributed to topography, especially in moist subalpine meadow settings, with trees establishing on convex surfaces away from the meadow/forest ecotone, where drainage and soil moisture is optimal (Rochefort & Peterson, 1996). In either scenario, once trees establish within the meadow negative site characteristics, such as excessive soil moisture or high competition with meadow vegetation, may be ameliorated allowing seedlings to backfill toward the forest edge. Little research has been conducted to determine the spatial pattern of tree invasion within the eastern Cascade Range.

Temporal Distribution of Tree Invasion

The temporal distribution of tree invasion tends to be described as either continuous or episodic, or, in many cases, both. Continuous tree invasion occurs steadily throughout time (Miller & Halpern, 1998). This type of tree invasion has been observed in the western Cascades, and is likely the result of incremental environmental change (Miller, 1995; Miller & Halpern). Conversely, episodic tree invasion is invasion that occurs periodically, peaking one or more times throughout history (Miller & Halpern). Episodic invasion has been found at a variety of locations throughout western North America (Franklin et al., 1971; Hadley, 1999; Miller & Halpern; Norman & Taylor, 2005). Additionally, episodic and continuous tree invasion may occur in different areas of the same meadow (Coop & Givnish, 2007; Franklin et al.; Magee & Antos, 1992; Woodward et al., 1995). These differences in temporal distribution patterns have been attributed to a variety of possible environmental differences, such as moisture, disturbance events, and climate over time (Coop & Givnish; Magee & Antos; Woodward et al.).

Episodic peaks in tree invasion have occurred throughout most of the 20th century in western North America (Coop & Givnish, 2007; Haugo & Halpern, 2007; Miller & Halpern, 1998; Woodward et al., 1995). Most episodic peaks have been linked to specific weather, fire, or land use disturbance (Coop & Givnish; Hadley, 1999; Magee & Antos, 1992; Miller & Halpern; Norman & Taylor, 2005; Woodward et al.). In addition to these episodic peaks, cyclic peaks (peaks that occur every 3-5 years) have been observed in the Cascades and Rocky Mountains (Dunwiddie, 1977; Franklin et al., 1971).

These cyclic peaks may be related to the reproductive cycles of trees, such as masting, which influence seed availability (Franklin et al.). No studies have been conducted to determine the temporal characteristics of tree invasion in the eastern Cascades.

Current Management Practices

Because of the previously mentioned benefits, forest managers have been working toward preserving mountain meadow systems. Some practices that have been employed to help combat the encroachment of trees into these areas include cutting pioneer trees and burning areas of tree establishment (Coop & Givnish, 2007; Griffiths et al., 2005; Miller & Halpern, 1998; Rochefort & Peterson, 1996). Research conducted by Griffiths et al. suggests that burning is likely the best way to preserve mountain meadow systems. This research found cutting to be less effective, with more seedlings reestablishing after cutting than after burning (Griffiths et al.). This is likely because pioneer trees change site characteristics, making them more inhabitable for tree seedlings, but burning enhances meadow vegetation, which increases competition, and kills fungal mats that may aid in seedling reestablishment (Griffiths et al.). Additional knowledge on how and why tree invasion occurs may help managers to understand and maintain meadow systems.

In addition to management techniques that have been employed to reduce tree invasion, managers have also taken steps to improve the ecological conditions of mountain meadow systems. Policies and procedures have been put into place throughout the eastern Cascades and the rest of the western United States to minimize damage to meadow soils and vegetation. Some of these management practices include limiting or excluding livestock grazing, building wildlife exclosures, restoring meadows through plantings, and limiting recreational uses (United States Forest Service [USFS], 1995).

CHAPTER III

STUDY AREA

Location

Lying east of the Cascade Crest, in the Wenatchee Range of Washington State, the upper Naneum watershed is situated on the margins of Table Mountain in northern Kittitas County (see Figures 3 and 4). Located approximately 30 km north of Ellensburg and 22 km southwest of Wenatchee, the study area consists of 6,041 ha. The study area encompasses all areas drained by Naneum Creek above 1,200 m, and is bounded by an unnamed ridge that forms the boundary between Kittitas and Chelan counties to the north, the Wilson Creek watershed to the south, an unnamed ridged separating the upper Naneum and lower Naneum basin to the east, and the summit of Table Mountain to the west.

Geology and Geomorphology

The upper Naneum watershed is predominately south to southeast facing, and ranges in elevation from 1,200 m to 1,900 m. The topography of the area is rugged and somewhat benched because of the basalt cliffs, basalt flow tops, and talus slopes that dominate the landscape. This topography tells a story of a varied and active geologic past.

The main underlying geology of the study area consists of uplifted basalt flows, belonging to the Grand Ronde group of the Columbia River Basalts, occurring over Chumstick and Swauk sandstones (Tabor et al., 1982). These rocks were uplifted via folding creating the southeast trending Table Mountain monocline, and a syncline

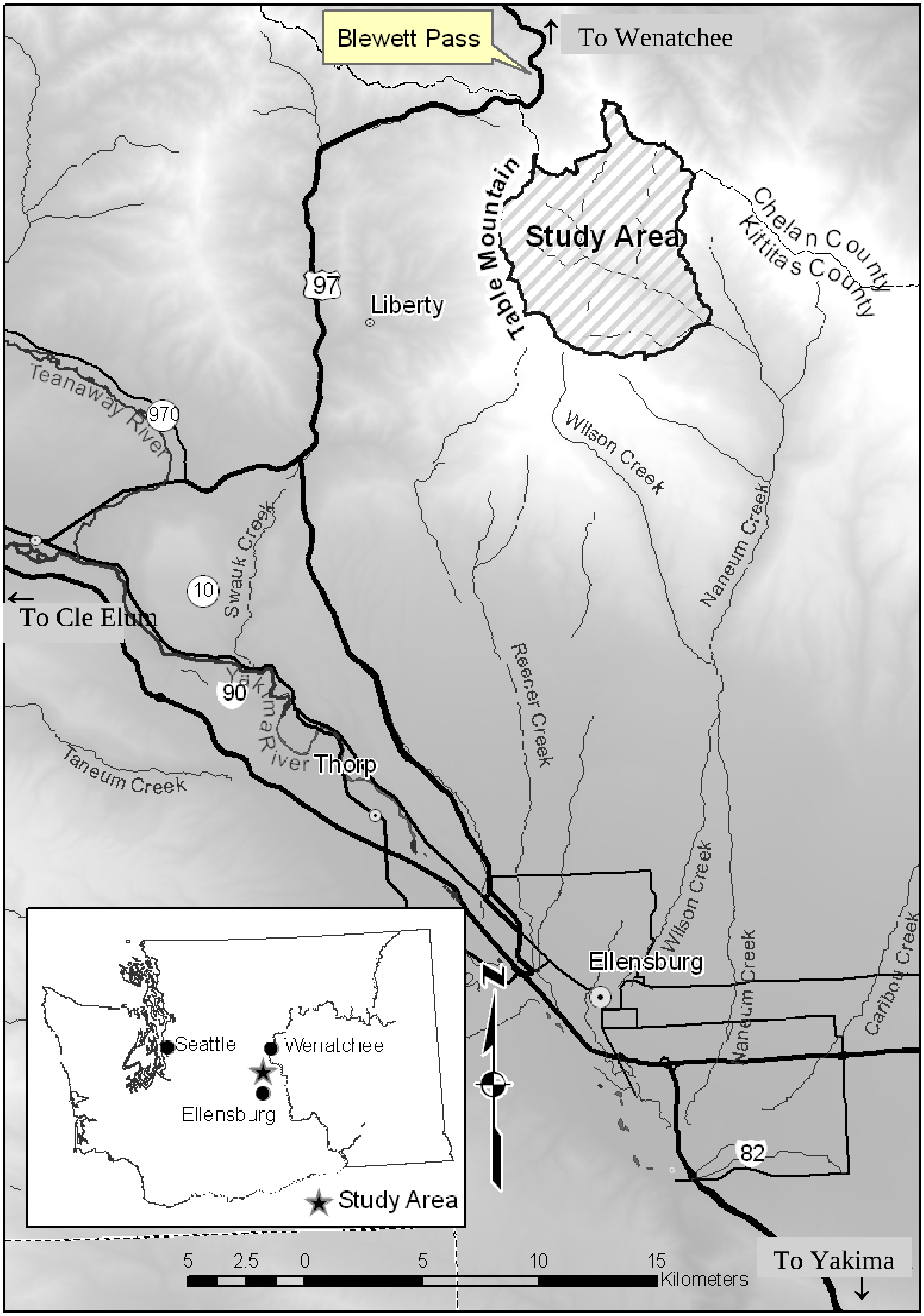

Figure 3. Location of the upper Naneum watershed, Kittitas County, Washington.

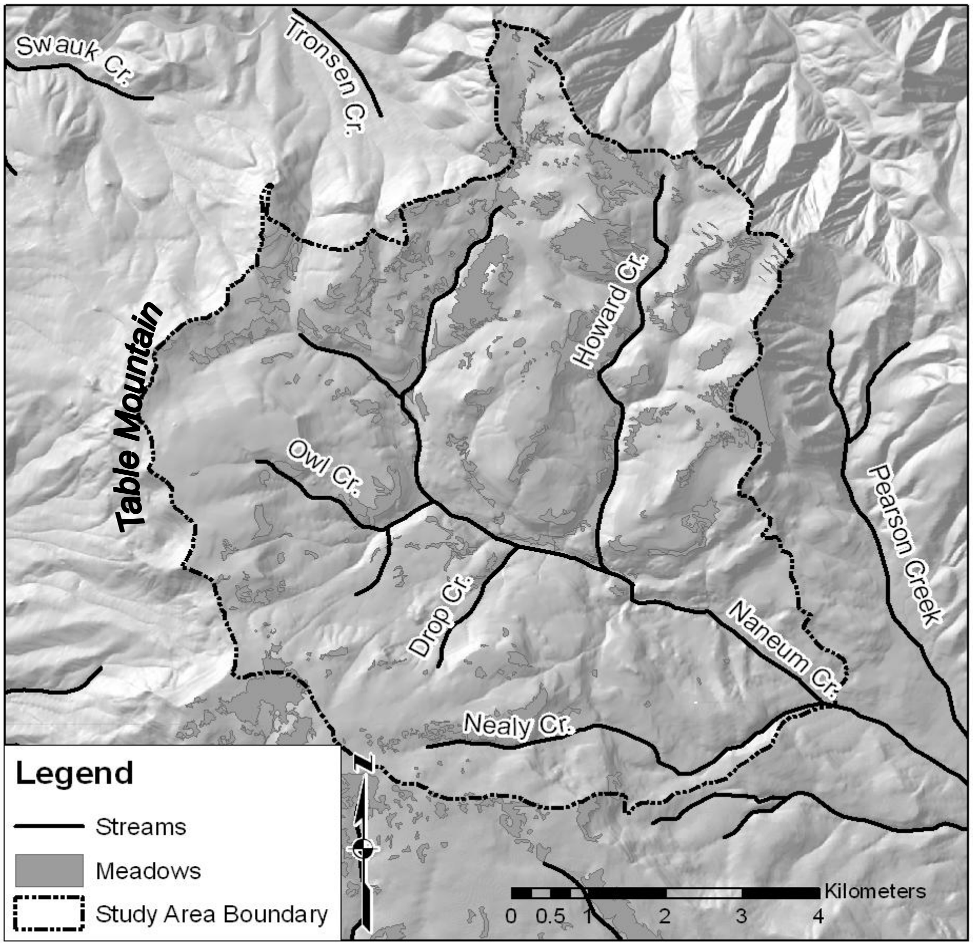

Figure 4. Upper Naneum watershed, Kittitas County, Washington.

forming the structure of the Naneum watershed (Tabor et al.). The geologic beds of the study area dip slightly to the southeast to southwest (Tabor et al.), reflecting the monocline and syncline structures.

The geomorphology of the upper Naneum was likely shaped by glacial and periglacial processes during the Pleistocene. Glaciation may have occurred near the headwaters of Naneum Creek (Tabor et al., 1982). The apparent till and moraines left behind by these ice masses and rock has likely influenced the development of wet meadows within the study area. For example, directly downstream from Lower Naneum

Meadow is a moraine (Tabor et al.). It is believed that this moraine has impeded the flow of Naneum Creek, leading to alluvial deposition and the high water table that formed the Naneum and Lower Naneum meadows (King, 1997). Relict rock glaciers have also been identified in the southwestern portion of the watershed (Powell, n.d.).

Following glaciation, the main geomorphic activity within the study area has been mass wasting. This is a result of basalts occurring over the weaker Chumstick and Swauk sandstones. Over time, these weaker sandstones weathered and eroded, resulting in numerous landslides (Tabor et al., 1982). The western and central portions of the watershed have been heavily shaped by these mass wasting events (Powell, n.d.).

Climate

The upper Naneum watershed's climate is determined by the seasonal migration of the Aleutian Low and Hawaiian High pressure systems (Mass, 2008). The Aleutian Low brings cold, wet winters, while warm, dry summers result from the dominance of the Hawaiian High. These weather patterns, coupled with the topography and elevation of the upper Naneum, result in cold, snowy winters and hot, droughty summers within the study area.

The average summer temperature of the study area is approximately 14 °C and the average winter temperature is approximately –2 °C (Natural Resource Conservation Service [NRCS], n.d.). Diurnal temperatures in this area can be extreme and can have major impacts on vegetation, soil, and geomorphic processes, especially during the summer months when the ground is not insolated with snow. The average diurnal temperature range is 15 °C during the summer months, and 12 °C during the winter months (NRCS).

Approximately 90 cm of precipitation falls in the upper portions of the watershed, with 70% falling in the winter months creating a considerable snowpack (NRCS, n.d.). The average annual April 1 snowpack at Blewett Pass, located 5 mi west of the study area (Figure 3), is 101 cm (NRCS). The study area is also very windy, with prevailing westerly winds. Additionally, mountain/valley breezes blow from the southeast and northwest following a diurnal pattern.

Hydrology

The hydrology of the study area is very much connected to the geology discussed previously. The angular basalt and numerous landslides within the study area determine the overall drainage pattern of surface water (USFS, 1995). The watershed slopes upward gently, almost to the abrupt cliffs leading into the Swauk and Tronson drainages. The major surface drainages of the study area are Owl Creek, Drop Creek, Nealy Creek, Howard Creek, West Fork Naneum Creek, and Naneum Creek (Figure 4). Naneum Creek flows out of the study area and down the lower Naneum basin into the Kittitas Valley, where it eventually drains into the Yakima River. The topography of the study area also influences its hydrology, especially in terms of wetlands and wet meadows. Several wet meadows are found throughout the study area in concave areas with high water tables. Many of these wetlands and wet meadows are found near Naneum Creek or one of its tributaries.

The geology of the study area impacts the groundwater activity and, ultimately, stream discharge levels as well. The fractured basalts of the study area allows precipitation to seep into the bedrock, and flow into the sedimentary interbeds separating the basalt flows (USFS, 1995). This groundwater slowly seeps out of springs found throughout the watershed, helping to ameliorate surface flows throughout the summer, when flows would otherwise be extremely low (USFS).

Soils

The soils within the watershed vary greatly depending on parent material, topographic position, and microclimate, and range from shallow and skeletal to deep, fine textured and organic rich. Most of the soils within the upper Naneum watershed are derived from alluvium, colluvium, residuum, and loess.

Xeric meadows within the watershed tend to be associated with rubble land-rock complex, 10%-90% slope; Darland stony loam, 30%-70% slope; and Ganis variant very cobbly loam, 5%-25% slope. All are fairly shallow, well-drained soils (NRCS, n.d.). Mesic meadows within the watershed are associated with Naxing loam, 25%-45% slope and Ganis silt loam, 7%-25% slope (NRCS). Cryaquepts, 0%-3% slope, a soil that forms under wet, cool conditions, is the soil type most commonly found under wet meadows within the watershed (NRCS).

Soil erosion is a serious concern on the hillslopes and in riparian areas in the upper Naneum because of human land use practices and the density of wild ungulate grazing (USFS, 1995). Additionally, recreation and grazing has led to soil compaction issues throughout the watershed, especially in wet meadows (USFS).

Flora

Forest covers most (approximately 4,480 ha of 6,041 ha) of the study area (Lillybridge, Kovalchik, Williams, & Smith, 1995; USFS, 1995). The subalpine fir series is the main forest type found in the upper Naneum watershed, with an association supporting not only subalpine fir (*Abies lasicarpa*), but also Engelmann spruce (*Picea engelmannii*) and lodgepole pine (*Pinus contorta*) (USFS). Subalpine fir is found throughout the watershed, because of its ability to endure high elevations, extreme temperature regimes, drought, and excessive moisture (USFS). Other principal forest series found within the watershed include the moist grand fir series in sites that sustain wet soil conditions during the growing season (USFS). This series consists of grand fir (*Abies grandis*), western larch (*Larix occidentalis*), Engelmann spruce, and Douglas fir (*Pesudotsuga menziesii*) (Lillybridge et al.; USFS). The dry forest series is found in the more droughty portions of the watershed and consists of ponderosa pine (*Pinus ponderosa*), dry lodgepole pine, dry Douglas-fir, and dry grand fir (Lillybridge et al.; USFS).

Other coniferous tree species that have been identified within the study area include Pacific silver fir (*Abies amabilis*) and white pine (*Pinus monticola*), both of which inhabit high-elevation sites (Camp, Oliver, Hessburg, & Everett, 1997). Additionally, several species of deciduous trees are found within the study area, and tend to inhabit spring sites, including quaking aspen (*Populus tremuloides*.), alder (*Alnus spp*.), and dogwood *(Cornus sericea*) (Camp et al.). Typical forest understory in the upper Naneum includes pine grass (*Calamagrostis rubenscens*), snowberry

(*Symphoricarpos oreophilus)*, huckleberry (*Vaccinium spp.*), columbine (*Aquilegia spp*.), and various mosses (USFS, 1995).

Using a definition where meadows have less than 10% tree cover (Camp et al., 1997; USFS, 1995), approximately 6% (378 ha) of the upper Naneum watershed consists of meadow vegetation. The vegetation associations of these meadows vary greatly depending on the moisture regime of the meadow. Hydric meadows primarily support hydrophilic plants and facultative hydrophytes. Within the watershed, several sedge species (*Carex spp*.) can be found in hydric meadows along with alpine timothy (*Phleum alpinum*), tufted hairgrass (*Deschampia caespitosa*), Baltic rush (*Juncus balticus*), waterleaf (*Hydrophlum spp*.), western false hellebore (*Veratrum californicum*), buttercup (*Ranunculus orthorhynchus*), larkspur (*Delphinium spp*.), and Canada thistle (*Cirsium arvense*) (USFS). Additionally, it is believed that these areas were rich in root crops, such as camas (*Camassia spp*.), before Euro-American grazing altered wet meadow vegetation (USFS). Mesic meadow communities support plants that can tolerate both moist and dry conditions, and tend to be dominated by forbs and grasses (Miller, 1995). The vegetation found in the mesic meadows of the upper Naneum include pine grass (*Calamagrostis rubenscens*), elk sedge (*Carex geyeri*), fescue (*Festuce spp*.) needlegrass (*Stipa spp*.), bluegrass (*Poa spp*.), lupin (*Lupinus spp*.), yarrow (*Achillea millefolium*), Indian paintbrush (*Castilleja spp*.) balsamroot (*Balsamorhiza sagittata*), wild strawberry (*Fragaria spp*.), and fleabane (*Erigeron spp*.) (USFS). In the upper Naneum watershed xeric meadows tend to support big sage (*Artemisia tridentata*), stiff sage (*Artemisia rigida*), and buckwheat (*Eriogonum spp*.) (USFS).

Fauna

The upper Naneum watershed supports a variety of terrestrial and aquatic wildlife. Terrestrial animal species found within the study include, grouse, migratory birds, elk, deer, bears, voles, mice, shrews, weasels, pocket gophers, squirrels, beavers, lynx, and martins, just to name a few (Pacha, Clark, Williams, Carter, & Scheffelmaier, 1987). There is also evidence that bighorn sheep (*Ovis canadensis*) were native to the area, but exterminated by exposure to domestic sheep and the diseases they carried (USFS, 1995). This is also true of Roosevelt elk (*Cervus elaphus roosevelti*), which were the native elk to the area (Couch, 1935). It is believed that these elk disappeared from the landscape around the turn of the 20th century. After the exclusion of Roosevelt elk from the landscape, Rocky Mountain elk (*Cervus elaphus nelsoni*) were introduced in 1915, and now have a very large population. Elk, deer, black bear, and burrowing rodents likely have the greatest impacts on meadows within the study area because of grazing and/or soil disturbance (USFS).

Historically, the streams of the upper Naneum watershed supported several salmonid species: coho salmon (*Oncorhynchus kisutch*), steelhead/rainbow trout (*Oncorhynchus mykiss*), and cutthroat trout (*Oncorhynchus clarki*) (USFS, 1995). Since agricultural irrigation began in the lower Naneum watershed, several barriers have been constructed that have excluded anadromous salmonid species from the upper Naneum (King, 1997). Additionally, several nonnative game fish, such as brook trout (*Salvelinus fontinalis*) and stock rainbow trout, have been introduced to the system (USFS).

Land Use

It is believed that Native Americans used the upper Naneum watershed for thousands of years as an area to gather resources (Hollenbeck & Carter, 1986). The wet meadows of the study area supported the culturally and nutritionally important camas plant (USFS, 1995). Other culturally important plant resources found within watershed include yampah (*Perideridia gairdneri*), wild onion (*Allium spp*.), balsamroot, violet bulbs (*Viola spp.*), lomatium, yarrow, sedges, western false hellebore, and buttercups (Hollenbeck & Carter; King, 1997). The meadows within the upper Naneum watershed are still used to gather these culturally important plants (USFS).

Elk, deer, and bighorn sheep are other important resources that likely drew Native Americans into the watershed. Evidence of Native American hunting can be found on the ridges and slopes of the area, and include rock fences, hunting blinds, and food storage pits (Hollenbeck & Carter, 1986; USFS, 1995), but there is no documentation of these uses within the meadows of the upper Naneum.

The first Euro-Americans in the upper Naneum watershed were likely fur trappers, utilizing the area to trap beavers (Holstine, 1994). Gold mining was another early resource extraction activity that likely took place in the watershed. The first gold discovered in Washington was in the nearby Naches drainage in 1853, after which gold exploration exploded (Holstine). Although the first mining likely took place within the watershed in the mid-1800s, the first mining claim was filed within the upper Naneum in 1932 (USFS, 1995).

In the mid-1800s, logging began in the foothills around the Kittitas Valley (USFS, 1995). Shortly after the first logging began, in 1870 the first sawmill in the region was opened on the lower reach of Naneum Creek (USFS). Over the years several other small mills opened near or on Naneum Creek (USFS). Large-scale logging first occurred in the Naneum in 1930 and has continued until the present (USFS). Since then, more than 15,353 MBF of timber has been harvested from the upper Naneum watershed (USFS).

Euro-American grazing began in the area in the 1860s (Holstine, 1994), although the Yakama and Wenatchi Indians likely grazed horses and cattle in the area as early as 1730 and 1840, respectively (Hollenbeck & Carter, 1986). From the 1860s to the 1890s, sheep and cattle grazing occurred with no regulation throughout the Wenatchee Range (Holstine). As a result, forest and meadows were reportedly in poor condition due to overgrazing (USFS, 1995). These grazing activities likely altered the hydrology of the meadows in the upper Naneum, as springs were improved to provide water for livestock (USFS). Additionally, soil compaction related to livestock grazing may have altered hydrology within meadows.

Grazing was first regulated in the Wenatchee Range following the creation of the Washington Forest Reserve in 1897, after which a grazing permit system was implemented (Holstine, 1994). Thousands of sheep and cattle continued to graze in the upper Naneum until the 1940s, when grazing allotment boundaries shifted and livestock numbers were reduced significantly (USFS, 1995). Grazing had very negative impacts on the vegetation cover of the meadows within the area. In the 1930s, many of the wet meadows were closed to grazing, and range restoration efforts took place in many of the meadows (USFS). These efforts included spraying herbicides, hand weeding, seeding, irrigating, and fertilizing (USFS). Today, little to no grazing occurs in the upper Naneum watershed, with the exception of recreational pack animals and horses (V. Worthington, personal communication, July 8, 2008).

Traditionally, recreation had been fairly limited within the study area, but today recreation is the main land use within the upper Naneum watershed. With road construction increasing the accessibility of the area and an increased enthusiasm for outdoor recreation, thousands of recreationalists visit the meadows of the upper Naneum annually. The meadows within the study area attract horseback riders, hunters, wildlife viewers, mushroom hunters, hikers, mountain bikers, motorcyclists, off-road vehicle users, snowmobilers, cross country skiers, fishers, and campers.

CHAPTER IV

METHODS

I used a variety of methods to achieve the objectives of this research project. To document the spatial distribution of meadows within the upper Naneum watershed, classify meadows, and select sample sites, geographic information system (GIS) mapping was used. To determine the temporal, spatial, and species patterns of invasion I recorded tree location, cored trees, and recorded tree species. To determine how climate, fire return intervals, and land use changes correlated with the timing of tree invasion these factors were compared with dates of tree establishment. A more detailed account of the methods used in this research follows.

Meadow Mapping

Using digital orthophotographs and U.S. Forest Service (USFS) vegetation maps, I identified and delineated all of the meadows within the study area in a GIS. For the purposes of this study, meadows were defined as grass or forb dominated areas with less than 10% tree cover at least 1,000 m^2 in size (Coop & Givnish, 2007). To minimize misidentifying clear cuts and rock outcrops as meadows, stereoscopic airphotos and forestry maps also were reviewed.

To determine the spatial distribution of meadows within the watershed, ArcGIS 9.2 (ESRI, 2008b) spatial analyst statistics were used to find the predominant aspect, elevation, and slope of the meadows. This was done by creating an aspect layer and a slope layer from a 10-m resolution digital elevation model. I then used the “Extract by Mask” tool to extract the raster cells for each of the aspect, slope, and elevation layers that overlapped the previously delineated meadows. Using ArcCatalog 9.2 (ESRI, 2008a), the spatial statistics for each extracted layer were found to determine the spatial distribution of meadows within the upper Naneum watershed. The spatial statistics examined included the aspect, elevation, and slope of every cell that overlapped a meadow. Using Statistix 8.0 (Analytical Software, 2003), the Kruskal-Wallace test was run to find if the aspect, elevation, and slope were significantly different between meadow types. The landscape position of the meadows was determined to be concave, convex, flat, or part of a continuous slope using topographic maps, a digital elevation model, and stereoscopic airphotos.

Meadow Classification

Meadow type was determined from USFS (1995) vegetation maps. Twenty-one meadows were randomly selected for field truthing to verify the meadow type. In the field, meadow types were determined using indicator species. The presence of larkspur, hellebore, and buttercups accompanied with sedges indicated hydric meadows (USFS). Grass and forb dominated meadows with yarrow, fleabane, and lupine indicated mesic meadow (USFS). Meadows dominated by sagebrush and with low overall cover values were classified as xeric meadows (USFS).

Site Selection

Once all meadows in the study area were delineated and classified, nine meadows were selected for in-depth field sampling: three hydric, three mesic, and three xeric. I selected meadows with comparable area and perimeter lengths similar to other meadows that were to be sampled. Sampled meadows were not adjacent to clear cuts, and when possible, did not have roads in them. Additionally, all sampled meadows were within 3 mi of a road for relatively easy access. When sampled meadows were unnamed, informal names were given to them for record keeping and reporting purposes.

Field Setting and Assessment

Upon first entering a meadow site, basic data about the meadow was described and recorded. This information included the aspect, slope angle, and landscape position of the meadow. Aspect was determined using a Pocket Transit from Brunton (Riverton, Wyoming) and slope was estimated to the nearest 5˚. The landscape position was based on where the meadow was situated in relation to the surrounding slopes and landforms, and generally fell into the categories of continuous slope, concave slope, convex slope, interfluve, and valley bottom (Miller, 1995). Basic field observations, airphotos, and topographic maps were used in these determinations and descriptions.

In addition, slope, aspect, and landscape position, potential landscape disturbance, meadow soils, flora, fauna, and land use was documented. Inferences regarding landscape disturbance, which might have an impact on soil development and the establishment of vegetation, were based on observations of fire scars on trees, evidence of frost heave and bioturbation, presence of charcoal in soil, and presence of material that might indicate rock or landslide activity. Very basic soil descriptions, including basic soil texture, rockiness, and depth when applicable, were made from shallow soil pits dug in each meadow. These soil pits were dug approximately 0.5 m deep, where possible, at the beginning of the first transect, and gave insight into the basic soil type and soil development. Plant species of the meadow and surrounding forest was identified using sight identification and dichotomous botanical keys. Any evidence of fauna was recorded, such as pocket gopher burrows, animal droppings, or antler damage to trees. Finally, potential human land use of the area was recorded based on the presence of trails, fences, fire rings, and discarded items in the meadow and adjacent forest.

Spatial Patterns of Invasion

After a meadow was generally described, five 1-m-wide belt transects were established for detailed sampling in each meadow (Moore & Huffman, 2004; Rochefort & Peterson, 1996; Woodward et al., 1995). These transects were established in the areas of the meadow where the invasion front, the foremost line of invading trees in the meadow, was greatest (i.e., seedlings and saplings establishing farthest from the meadow/forest boundary) (Moore & Huffman). The invasion front was determined in the field based on my observations of tree establishment. Once the transect locations were identified, transects were anchored at the tree farthest meadow-ward while being perpendicular to the forest/meadow boundary (Hadley, 1999; Jakubos & Romme, 1993; Moore & Huffman; Norman & Taylor, 2005). These anchored points were recorded with a Garmin Ltd. (Chicago, Illinois), eTrexH Geographic Positioning System (GPS) and the azimuth of the transect was recorded with a Brunton (Riverton, Wyoming) Pocket Transit. From the anchor tree, the transect ran in a straight line back toward the meadow/forest boundary for 50 m (Moore & Huffman). If it was greater than 50 m to the meadow/forest boundary, the length of the transect was increased to reach the meadow forest/boundary (Moore & Huffman). If it was less than 50 m to the meadow/forest boundary, the transect extended into the forest (Moore & Huffman). The amount of forest sampled varied from transect to transect based on how wide the invasion front was. All trees within each 1-m-wide transect were dated and identified by species. Also, transect location and specific characteristics about the tree, such as damage to tree, and direct understory of tree, were recorded for each tree sampled. Additionally, elevation, slope, aspect, location, percentage of groundcover, and understory vegetation were recorded for each transect (Hessl & Baker, 1997; Jakubos & Romme; Magee & Antos, 1992; Miller & Halpern, 1998). Spearman rank correlation tests were performed to determine if transect location and tree age had any relationship. A weak relationship indicated a leap-and-fill pattern, while a strong relationship indicated a gradual spatial pattern of invasion. Also, a chi-square test was performed to determine if there was a significant difference between tree species invading per meadow type.

Temporal Patterns of Invasion

To determine tree age, I cored all trees that were 6 cm in diameter or greater at breast height (Hessl & Baker, 1997). If trees were not large enough to core, the branch whorls were counted from the base to the top of the tree to find an approximate age (Magee & Antos, 1992). To core trees, a 50-cm-long, 5-mm-diameter Haglof (Avestal, Sweden) increment borer was used. Trees were cored at 30 cm above the ground level (Hessl & Baker), with the intent of counting rings in Central Washington University's Geography Department's biogeography lab. A ground height correction was used to estimate the average age of trees at 30 cm (Wong & Lertzman, 2001). To find the ground height correction factor for each species within each meadow, two trees of each species were cut in each meadow at ground level and at 30 cm. The age of the trees were later found using standard dendrochronology techniques at ground level and at 30 cm, and the differences in these ages were averaged (Wong & Lertzman). This averaged age was added to tree ages determined in the laboratory. These cut trees were also used to determine the accuracy of whorl counting.

All tree cores and cross sections collected in the field were dried and mounted using standard dendrochronology techniques (Stokes & Smiley, 1968). After mounting the cores, I sanded them using a belt sander with 240- and 320- grit sandpaper (Grissino-Mayer, 1996). A final polish of the cores and cross sections was done by hand with 460-grit sand paper (Grissino-Mayer). This sanding enabled me to see intricacies in the wood that might not have otherwise been visible.

After the cores and cross sections were prepared, I examined each specimen under a 40x Uritron dissecting microscope. Each core and cross section was counted under the microscope from bark to pith (Stokes & Smiley, 1968). The list method of crossdating was used while counting to identify any false or missing rings that may have otherwise comprised the accuracy of the ring count (Stokes & Smiley). All rings were measured using the Velmex (Bloomfield, New York) Manual Slide measuring system and j2X 2.0 measuring software. After all the rings were measured, COFECHA (Holmes & Cook, 1988) software was used to statistically crossdate all the ring widths of all samples (Grissino-Mayer, 1996). Any samples that fell below the 90% confidence level of accuracy were recounted and remeasured.

Two correction factors were used, one to correct for taking the cores at 30 cm rather than ground level and another for when the pith was not hit when coring. As described above, to do the ground height correction two trees for each species sampled in each meadow were cut in cross section at ground level and at 30 cm (Wong & Lertzman, 2001). The rings for each specimen were counted at both ground level and at 30 cm, and the differences between the counts were found (Wong & Lertzman). These were then averaged for each species in each separate meadow, and the average was added to the tree ages of the appropriate species taken from the same meadow (Wong & Lertzman). In the rare instance that the pith was missed while coring a tree, a standard pith correction was done. To do this, the total arc length of the last complete ring was measured using the Velmex Manual Slide measuring system and j2x 2.0 (VoorTech Consulting, 1999) measuring software and divided by two (Wong & Lertzman). This number was added to the ring count to find the date of tree establishment (Wong & Lertzman). Once the date of tree establishment was found, the Kolmogorov-Smirnov test was run to determine if the temporal pattern of tree establishment was significantly different between meadow types.

In addition to the dating techniques described in this section, I also used airphotos to determine general temporal patterns of invasion within the sampled meadows. Using 1954 and 2006 airphotos, invasion was noted and qualitatively described for each meadow.

Causes of Invasion

To compare the dates of tree establishment with climate, fire, and land use variability, I needed to collect data on these topics. Based on previous literature, several climatic factors were examined: annual temperature, growing season temperature, maximum temperature, minimum temperature, annual precipitation, growing season precipitation, April 1 snow depths, April snow water equivalent, annual Pacific Decadal Oscillation (PDO) values, annual Palmer Drought Severity Index (PDSI) values (Franklin et al., 1971; Miller, 1995; Miller & Halpern, 1998; Norman & Taylor, 2005; Rochefort & Peterson, 1996; Woodward et al., 1995). PDO is a long-term phenomenon that occurs in the northern Pacific Ocean. PDO significantly impacts climate in the Pacific Northwest, bringing cool, wet climate during its negative phase, and warm, dry climate during its positive phase (Mass, 2008). PDO is measured on a scale of 4 to −4 (Mass). PDSI is an index that uses temperature and precipitation to determine the severity of drought conditions on a scale of 6 to −6, with 0 being normal conditions, 6 being the moistest conditions, and −6 being the most droughty conditions (Woodward et al.).

Temperature and precipitation data were collected from a weather station in Ellensburg, Washington, located approximately 30 mi south of the study area (Western Regional Climate Center, n.d.). I collected snow depth and snow water equivalence data from the National Resource Conservation Service's (NRCS) Blewett Pass SNOTEL site, located approximately 5 mi northwest of the study area. PDO data were collected from University of Washington's Joint Institute for the Study of the Atmosphere and Ocean (2008), and PDSI data were collected from the National Oceanic and Atmospheric Administration (n.d.). Head of cattle allowed under grazing permits was obtained from the USFS Cle Elum Ranger District Office. Finally, the fire return interval for an adjacent watershed, the Teanaway (Figure 3), was used to better understand fire variability within the study area (Wright, 1996).

Once I found the date of establishment for all trees on each of the transects, I organized all the dates of tree establishment by meadow type so the effects of climate, fire, and land use data could be assessed in the different meadow types. Correlation tests were done to determine if any relationship existed between the date of tree establishment in each of the meadow categories and the aforementioned factors. To determine if the parametric or nonparametric correlation test should be used, I built normal probability plots and performed a Shapiro-Wilks test with a 95% alpha level on the data to see if it met the normality standard for the parametric test. Most of the data were not normally distributed, so I used the nonparametric Spearman rank correlation test. All tests were run using the Statistix 8.0 statistical package. I also qualitatively assessed historical information to better understand how land use may have impacted tree establishment.

Management Recommendations

To make management recommendations based on the findings of my research, I reviewed mountain meadow management literature from around the upper Naneum watershed, the Cascade Range, Sierra Mountains, and Rocky Mountains. This provided a depth of knowledge on current practices occurring in meadow restoration, conservation, and management. Unfortunately, little literature exists for the eastern slopes of the Cascades, which is a drier environment with different vegetation communities.

CHAPTER V

RESULTS AND DISCUSSION

Spatial Distribution of Meadows

General Patterns

Within the upper Naneum watershed, 249 meadows were identified and mapped, which covers approximately 6% of the study area (378 ha). Of these 249 meadows, 45 are hydric, 124 are mesic, and 80 are xeric (see Appendix). These meadows inhabit a variety of locations throughout the watershed: from northern aspects to southern aspects; from valley bottoms to high, subalpine zones; and from locations of steep slope gradients to flat slope gradients. This is illustrated in Figure 5 and Table 2, which show the diverse aspect, elevation, and slope of the meadows within the study area. This is very similar to what is already known about the spatial distribution of meadows (Miller, 1995). The mean aspect of the meadows within the upper Naneum is 153.5°, meaning that the average meadow within the study area has a SSW facing aspect. This southern aspect is likely due to the overall aspect of the watershed, which is SE facing, and may explain why there are more xeric and mesic meadows within the watershed compared with hydric. As discussed in the literature review, meadow moisture regime can be vary depended on aspect, as this influences evapotranspiration, snowmelt, and soil surface temperatures (Benedict, 1983).

The minimum elevation of meadows within the study area is 1,316.5 m, with the maximum elevation being 1,909.8 m, indicating that meadows inhabit nearly a 600 m

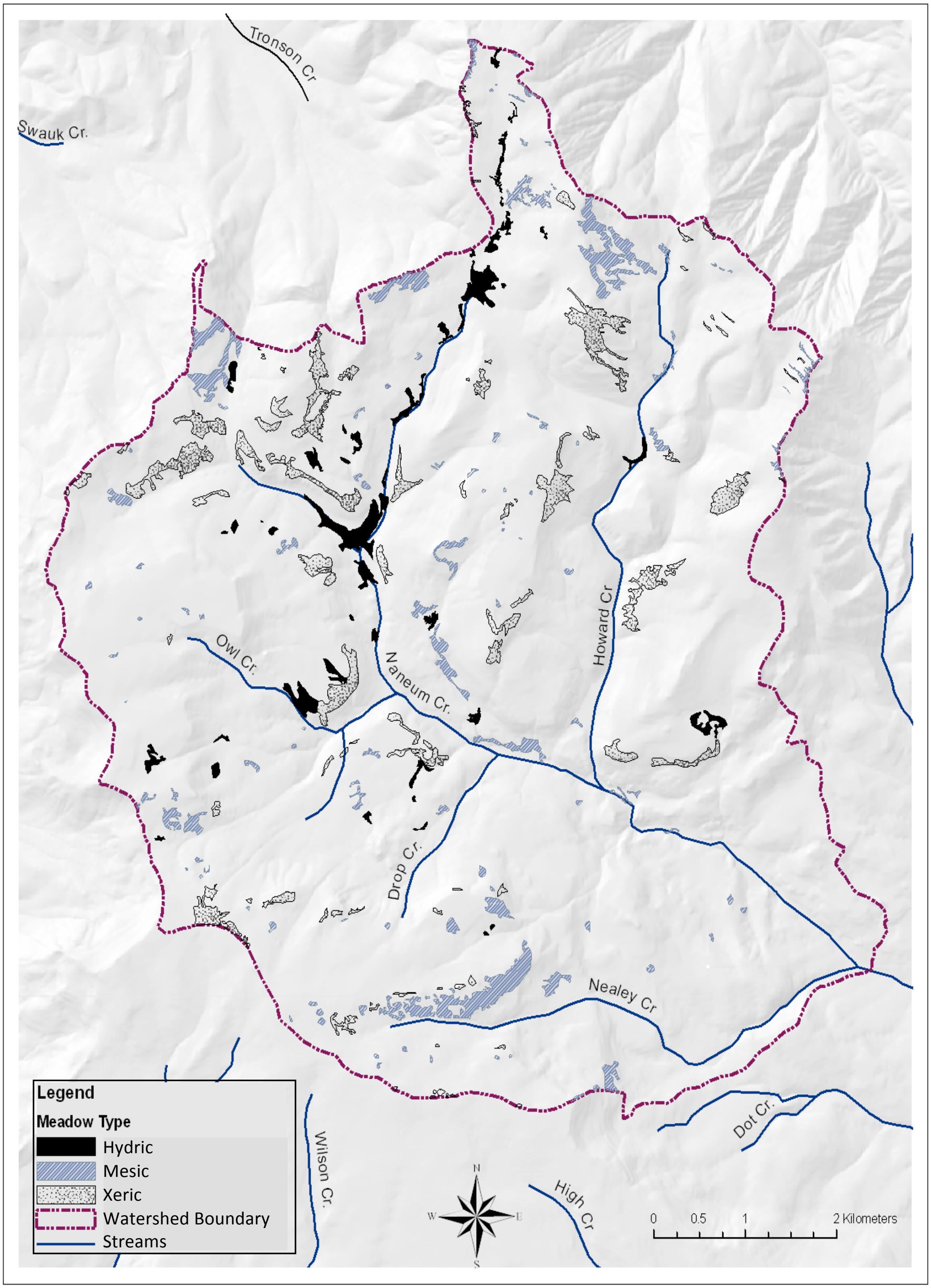

Figure 5. Spatial distribution of meadows within the upper Naneum watershed.

Table 2

Aspect, Elevation, and Slope of All Meadows Within the Upper Naneum Watershed

Parameters	Aspect (°)	Elevation (m)	Slope (°)	Perimeter (m)	Area (m^2)
Minimum	0	1,315.5	0	134.5	1,078.1
Maximum	359.9	1,909.8	43.3	8,293.8	208,930.6
Mean	153.5	1,694.0	13.7	726.9	15,154.0
Median	152.6	1,732.8	10.4	346.9	3,520.3

elevation range within the study area. The mean elevation of meadows within the upper Naneum is 1,694.0 m.

The slope of meadows within the study area, much like the aspect and elevation, is also varied. Some meadows within the study area are nearly horizontal, while others are very steep, with slopes ranging from 0° to 43.3° slopes. The average slope of meadows within the study area is 13.7°.

The landscape positions of the meadows within the study area ranged from convex slopes, concave slopes, flat sites, and continuous slopes, with most meadows (59%) being found on convex slopes This, along with aspect, could help explain why there are more mesic and xeric meadows than hydric meadows (Benedict, 1983).

When comparing the aspect, elevation, slope, perimeter, and area of all the meadows, hydric meadows, mesic meadows, and xeric meadows there appears to be slight differences in these values and means. Despite this, there is no statistically significant difference in these variables between the various meadow types being examined.

Spatial Patterns by Meadow Type

Hydric

As with all meadows within the watershed, hydric meadows have a varied spatial distribution (see Figure 6), but unlike the patterns seen previously with all the meadows within the watershed, hydric meadows tend to be found in valley bottoms and near streams. This is similar to what has previously been found regarding the spatial distribution of meadows (Benedict, 1983; Miller & Halpern, 1998).

The average aspect of hydric meadows within the watershed is 157.1° (see Table 3), with the minimum aspect and the maximum aspect being 0.1° and 359.7°, respectively. The average aspect of hydric meadows within the watershed is SSE. This aspect is somewhat surprising given that many hydric meadows elsewhere are wetter than average because of topographic shading (Benedict, 1983). It is likely that the average aspect of hydric meadows within the upper Naneum is such because of the overall aspect of the study area. The location of hydric meadows is likely related to water table and/or topography.

The minimum elevation of hydric meadows is 1,459.2 m and the maximum elevation of this meadow type is 1,860.8 m. The mean elevation of hydric meadows within the watershed is 1,622.6 m (Table 3). This is slightly below the average for all meadows, likely because these meadows are found in valley bottoms, near streams.

The average hydric meadow within the watershed has a slope angle of 6.8°, with a minimum slope of 0.7° and a maximum of 32.1°. This is logical since one reason a meadow might be hydric is proximity to the water table (Benedict, 1983; Miller & Halpern, 1998).

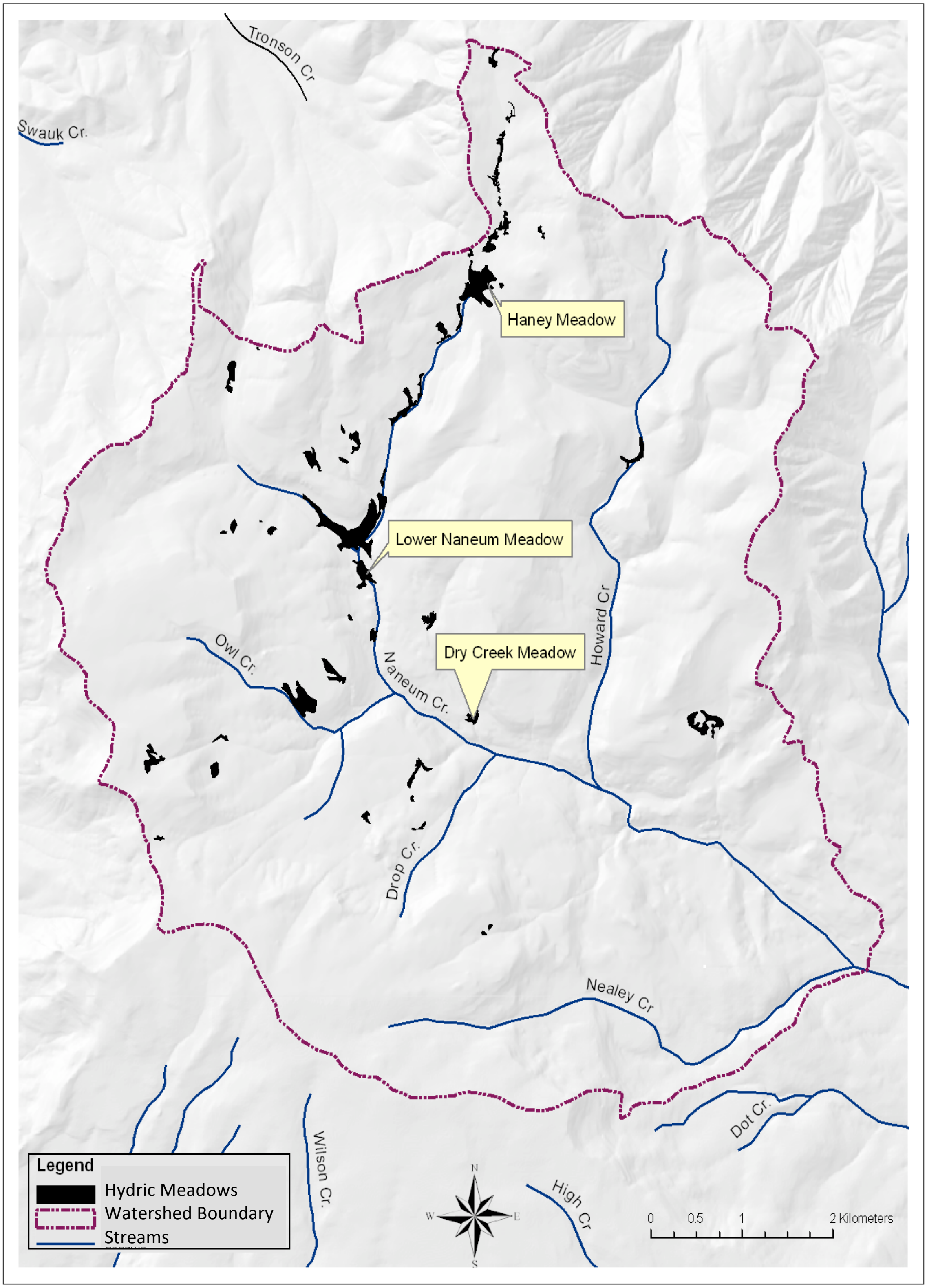

Figure 6. Hydric meadows of the upper Naneum watershed.

Table 3

Aspect, Elevation, and Slope of Hydric Meadows Within the Upper Naneum Watershed

Parameters	Aspect (°)	Elevation (m)	Slope (°)	Perimeter (m)	Area (m$^{2)}$
Minimum	0.1	1,459.2	0.7	147.2	1,275.9
Maximum	359.7	1,860.8	32.1	3,896.3	148,163.3
Mean	157.1	1,622.6	6.8	751.1	15,043.7
Median	147.7	1,666.2	7.3	433.7	5,248.3

Most hydric meadows within the watershed are found on concave surfaces (64%), which is fairly common for all hydric meadows (Benedict, 1983). Some hydric meadows are found on flat sites (2%) and on continuous slopes (16%). These meadows are likely hydric because of the concave, hence water gathering, surfaces they are found on. This is inline with previous findings (Benedict).

Mesic

The distribution of mesic meadows throughout the watershed closely mirrors the overall distribution of meadows, as illustrated in Figure 7. Mesic meadows appear to inhabit high and low location, a variety of aspects, and all types of slopes. This is likely because mesic meadows are the most dynamic of all the meadow types (Debinski et al., 2000).

The aspect of mesic meadows within the study area ranges from 0° to 359.5°, with the mean aspect being 145.7° (see Table 4). It is slightly surprising to find that mesic meadows are more east-facing than hydric meadows, which tend to be SSE

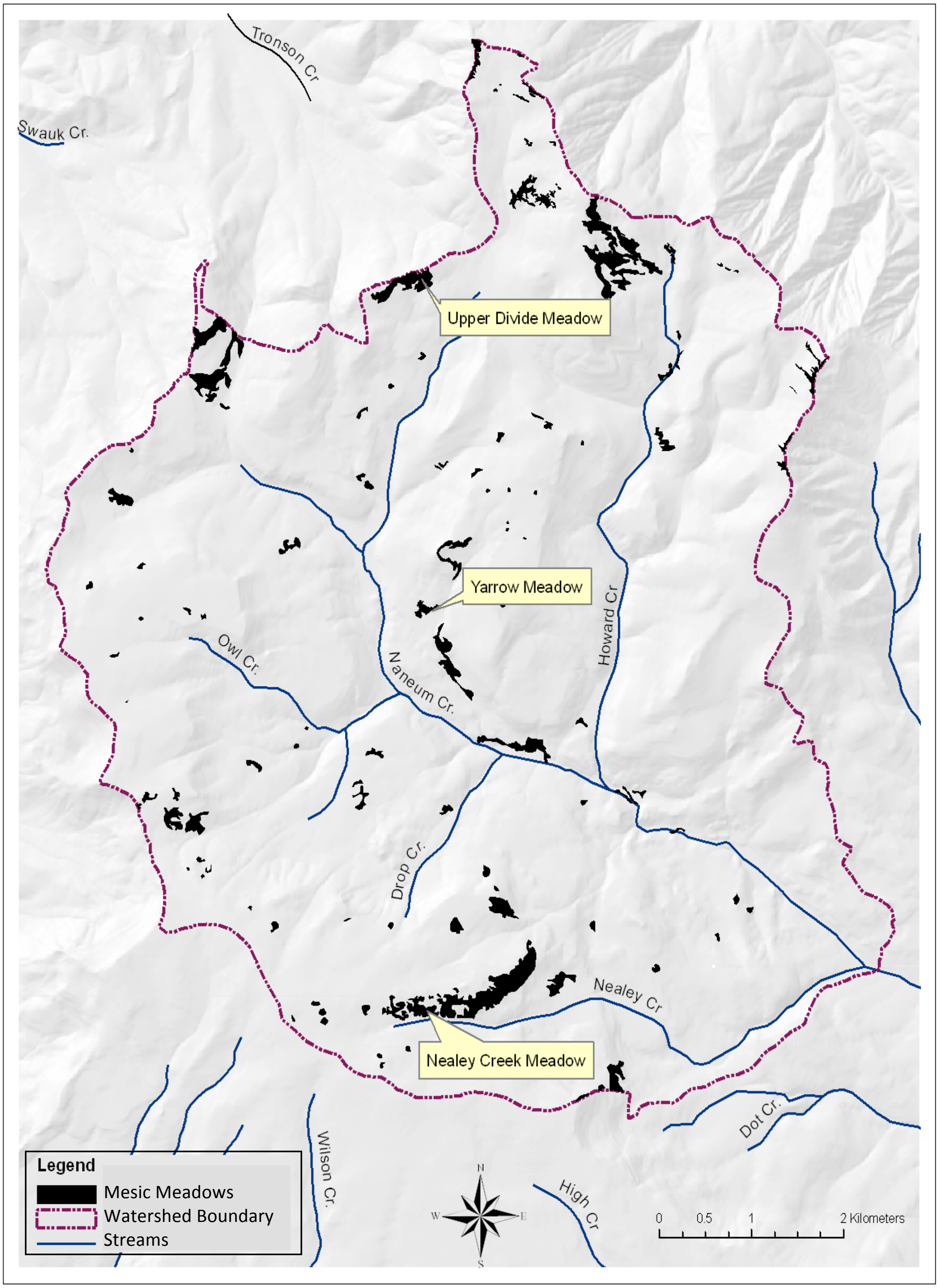

Figure 7. Mesic meadows of the upper Naneum watershed.

Table 4

Aspect, Elevation, and Slope of Mesic Meadows Within the Upper Naneum Watershed

Parameters	Aspect (°)	Elevation (m)	Slope (°)	Perimeter (m)	Area (m^2)
Minimum	0	1,316.5	0	134.5	1,078.1
Maximum	359.5	1,900.0	40.8	8,293.8	208,930.6
Mean	145.7	1,716.4	15.2	582.4	10,947.1
Median	151.5	1,757.9	10.7	275.3	2,617.5

facing within this watershed, given that topographic shading can help determine a meadow’s moisture regime.

The elevation range of this meadow category is 1,316.5 m to 1,900.0 m (Table 4), which is the greatest elevation range of all the meadow types. The average elevation of mesic meadows within the upper Naneum is 1,716.4 m, which is significantly higher than the average elevation of hydric meadows.

The minimum slope angle of mesic meadows within the watershed is 0°, while maximum slope of this meadow type is 40.8°. The mean slope angle is 15.2°. It is logical that mesic meadows would be found on greater slopes than hydric meadows, making them further way from the water table.

Mesic meadows probably have the most diverse landscape position of the all the meadow types. They are found on concave (14%), convex (51%), flat (0.8%), and continuous slopes (34%). This may be because mesic meadows, which are in the middle of the wet/dry gradient, and their vegetation can tolerate more varied site conditions (Benedict, 1983).

Xeric

Xeric meadows, much like all the other meadow types, inhabit a large variety of locations (see Figure 8). Like mesic meadows, they too appear to occupy high and low elevational zones, a variety of aspects, and a many different slopes.

The average aspect of xeric meadows within the watershed is 157.3° (see Table 5). As was the case in hydric and xeric meadows, this mean aspect is likely because of the overall aspect of the watershed, although it should be noted that, generally, xeric meadows tend to be more abundant on south-facing slopes (Benedict, 1983).

The elevation range of xeric meadows is 1,461.0 m to 1,909.8 m (Table 5). The mean elevation of this meadow type is 1,704.6 m, which is slightly higher than the other two meadow types. Xeric meadows may occur at higher locations because slower weathering processes have led to more poorly developed, and thus rockier soils. The phenomenon might also be the result of steeper slopes or more concave slopes occurring at higher locations.

Most xeric meadows are found on slope angles of 16.3°, with a minimum slope of 0° and a maximum slope of 43.3° (Table 5). These are steeper slope gradients than those of hydric or mesic meadows are found on. It is not surprising to find xeric meadows on steeper slopes, where soil is shallower and water is less likely to percolate into the soil (Benedict, 1983).

Xeric meadows tend to occur on convex slopes (90%), although some are found on continuous slopes (10%). This also could be contributed to the fact that water will not percolate into the soils of a convex slope as well as it might on other slope types.

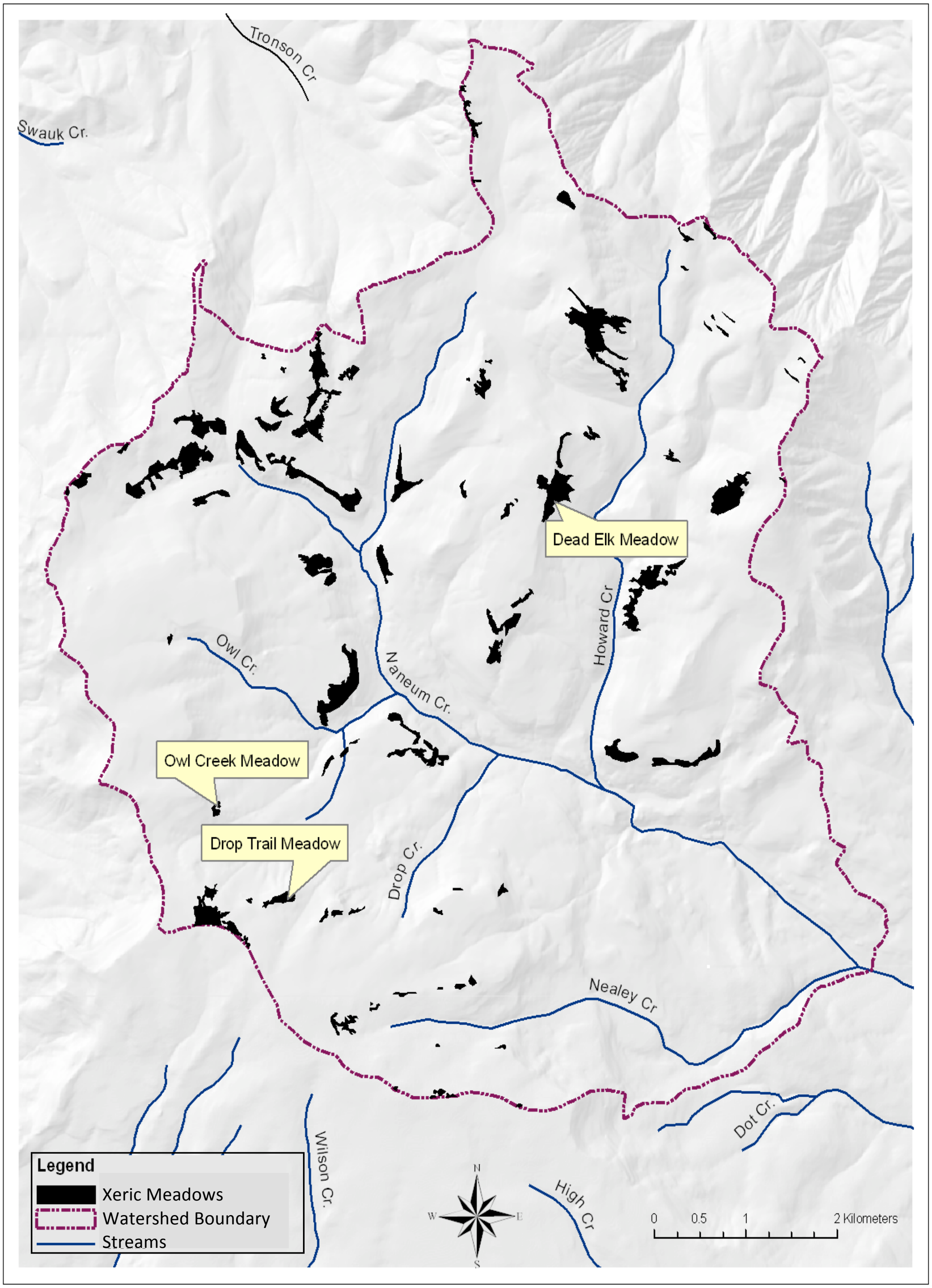

Figure 8. Xeric meadows of the upper Naneum watershed.

Table 5

Aspect, Elevation, and Slope of Xeric Meadows Within the Upper Naneum Watershed

Parameters	Aspect (°)	Elevation (m)	Slope (°)	Perimeter (m)	Area (m^2)
Minimum	0	1,461.0	0	192.8	1,465.5
Maximum	359.9	1,909.8	43.3	5,862.6	173,290.8
Mean	157.3	1,704.6	16.3	946.7	21,924.9
Median	168.1	1,750.0	15.9	507.7	5,568.3

Meadow Descriptions

Hydric Meadows

Three hydric meadows were sampled for this study: Dry Creek Meadow, Lower Naneum Meadow, and Haney Meadow. The location of these meadows can be viewed in Figure 6.

Dry Creek Meadow

Dry Creek Meadow is a relatively flat meadow, with a very slight southwestern exposure. This meadow is located in the valley bottom, near a creek that appears to run dry late in the summer, and was determined to be on a concave surface. The soils of this meadow are fairly deep, rocky, and appear to be rich in organics. This meadow is dominated by grasses and sedges, although some forbs, such as western false hellebore, buttercup, fleabane, and larkspur are present. There is evidence of antler rubbing on some of the saplings located on the meadow edge, indicating the presence of deer and elk. Additionally, there is evidence of pocket gopher burrowing on the north edge of the meadow. There is a road near the southwest edge of the meadow, but there is little evidence of land use within the meadow. Fire scares on trees and soil charcoal indicate that there may have been a fire at this site within recent history.

Lower Naneum Meadow

Lower Naneum Meadow, is also a relatively flat meadow located in a valley bottom. This meadow has a very slight southern aspect and was determined to be on a concave surface. The soils of this meadow are very deep, with a large amount of organics. The texture of the soil almost felt histic. The main vegetation of this meadow consists of sedges. Grasses and forbs, such as western false hellebore, fleabane, and larkspur, are also present. Elk were spotted near this meadow when I was conducting my fieldwork. There were also many pocket gopher casts near the western edge of the meadow. There is a road just to the west of this meadow. Additionally nearby trails and primitive campsites indicate that is meadow is a popular recreation site.

Haney Meadow

Haney meadow is located on a fairly flat site with a slight southwestern aspect. This meadow was determined to be on a concave surface, which is common for hydric meadows within the upper Naneum watershed. The soils of this meadow are deep and rich in organics, with a slightly histic texture in areas of especially poor drainage. The main vegetation of the meadow consists of sedges and grasses, with some fleabane, western false hellebore, larkspur, buttercup, and Canada thistle present. Elk and deer droppings were found throughout the meadow, indicating their presence. There is a road on the southwestern edge of the meadow. A trail and a nearby horse camp indicate that the area is popular for recreation. There is livestock fence near the margins of the meadow, but it appears as though this fencing had fallen into disrepair several decades ago.

Mesic Meadows

Three mesic meadows were sampled for this study: Yarrow Meadow, Nealy Creek Meadow, and Upper Divide Meadow. The location of these meadows can be viewed in Figure 7.

Yarrow Meadow

Yarrow Meadow is located on a southwest slope of approximately 10º. This meadow is located on a convex surface. The soils of this meadow are shallow, rocky, and loamy. The main vegetation of the meadow consists of grasses and forbs, with yarrow, lupine, and strawberry being abundant. There is evidence of antler rubbing, demonstrating the presence of deer and elk. Additionally, there is evidence of pocket gopher burrowing. This meadow likely has hikers, horseback ridings, and off road vehicle enthusiasts traveling through given the trail that runs through the southwestern portion of the meadow.

Nealy Creek Meadow

Nealy Creek Meadow is located on a continuous, south-facing slope of approximately 5º. The soils of this meadow are shallow and loamy. Grass is the dominant vegetation type, although many forbs, such as fleabane, yarrow, Indian paintbrush, and lupine, can be found in the meadow. Deer and elk apparently use this meadow, with dung and trees damaged from alter rubbing providing evidence for their presents. Additionally, pocket gopher casts were found throughout the meadow. A trail is located in the southern portion of the meadow.

Upper Divide Meadow

Upper Divide Meadow is located on a fairly steep (approximately 15º), south-facing slope. This meadow was determined to be part of a continuous slope. The soils of this meadow are shallow, rocky, and loamy. Grass is the dominant vegetation type, although several forbs, such as yarrow, lupine, and strawberry, were are also present. This meadow is located near a trail, making it a likely destination for recreationalists.

Xeric Meadows

Three xeric meadows were sampled for this study: Owl Creek Meadow, Drop Trail Meadow, and Dead Elk Meadow. These meadows can be viewed in Figure 8.

Owl Creek Meadow

Owl Creek Meadow is located on a steep (approximately 15º) slope. The aspect of this meadow is southeast-facing. This meadow was determined to be located on a convex slope. The soils of this meadow are very shallow, rocky, and loamy. Sage and rabbit brush are the main vegetation types, although the meadow does support a few grass and forb species. There is evidence of antler rubbing on some young trees in the southern portion of the meadow. A trail is located near the southern edge of this meadow, making it accessible to recreationalists.

Drop Trail Meadow

Drop Trail Meadow is located on a steep (approximately 10º convex slope. This meadow is south-facing. The soils of this meadow are very shallow, rocky, and loamy. Sage and rabbit brush are the dominant species found in this meadow. In addition to sage and rabbit brush, strawberry, buckwheat, and Indian paintbrush occur in this meadow. This meadow is located near a trail and several primitive campsites. I also found spent ammunition in the meadow, indicating that it is a popular site for shooting and/or hunting.

Dead Elk Meadow

Dead Elk Meadow is located on a very steep (> 15º), southwest-facing slope. This meadow was determined to be part of a continuous slope. The soils of this meadow are shallow and rocky. There are two springs located in this meadow. Sage and rabbit brush are the dominant vegetation type, although sedges, grasses, and forbs were found near the springs. The presence of deer and elk droppings, in addition to a dead elk found in the meadow, indicate that this meadow is used by these species. There is a trail located at the eastern edge of the meadow, and a clear cut located near the northern edge of the meadow. The presence of a hunter also indicates that this meadow is used for recreation.

Spatial, Temporal, and Species Patterns of Invasion per Meadow Type

Hydric Meadows

Spatial Patterns of Invasion

The invasion pattern for the three sampled hydric meadows within the upper Naneum watershed is difficult to discern. It appears as though leap-and-fill invasion is occurring in all three meadows, as pioneer trees establish well out in the meadows, and younger trees subsequently fill in the gap between these pioneer trees and the meadow-forest boundary. These patterns can be viewed in Figures 9, 10, 11, and 12. Here, one can see a few older trees near the beginning of the transects (0 m), which is in the meadow, followed by a somewhat dense grouping of younger trees, before tree age

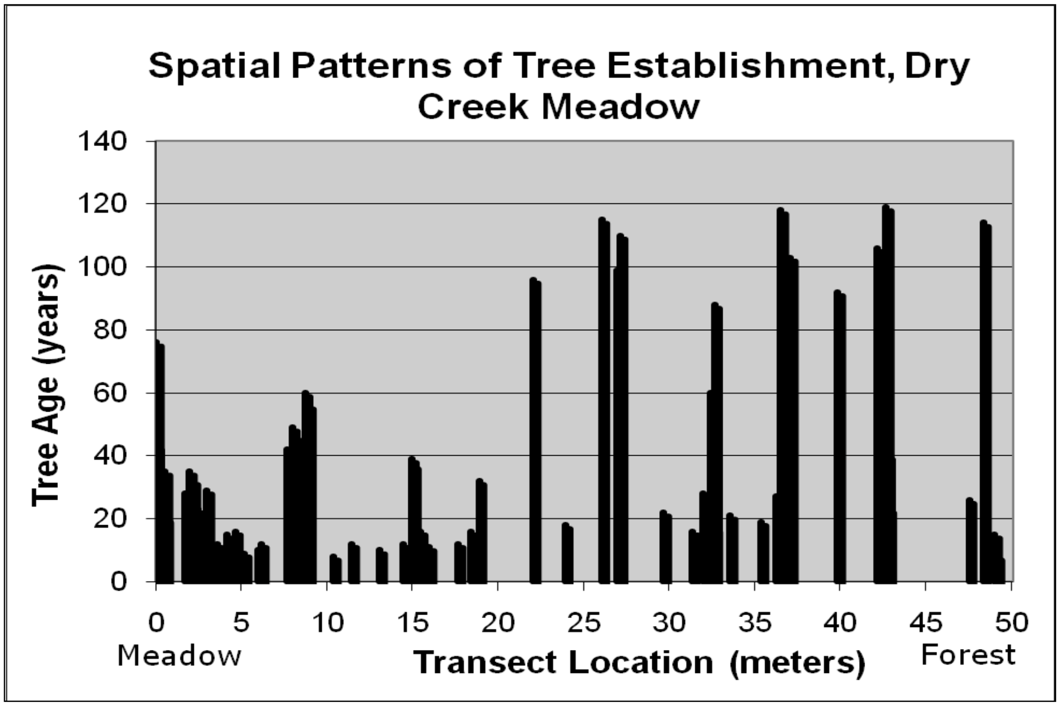

Figure 9. Graph illustrating spatial patterns of tree invasion for all transects at Dry Creek Meadow, a hydric meadow.

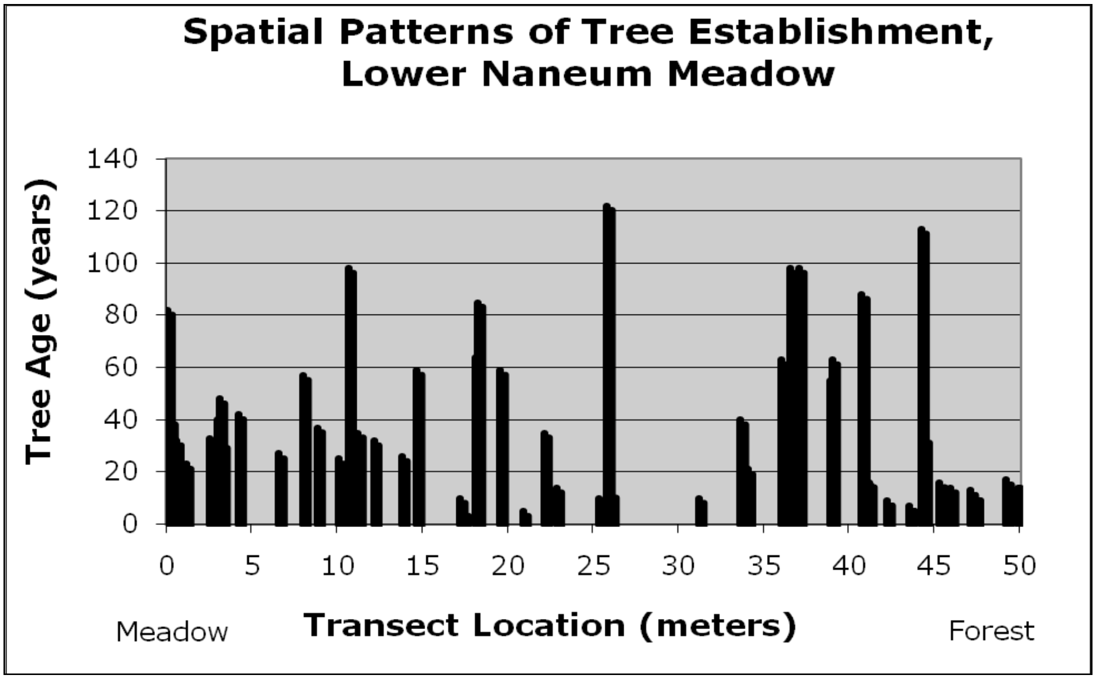

Figure 10. Graph illustrating spatial patterns of tree invasion for all transects at Lower Naneum Meadow, a hydric meadow.

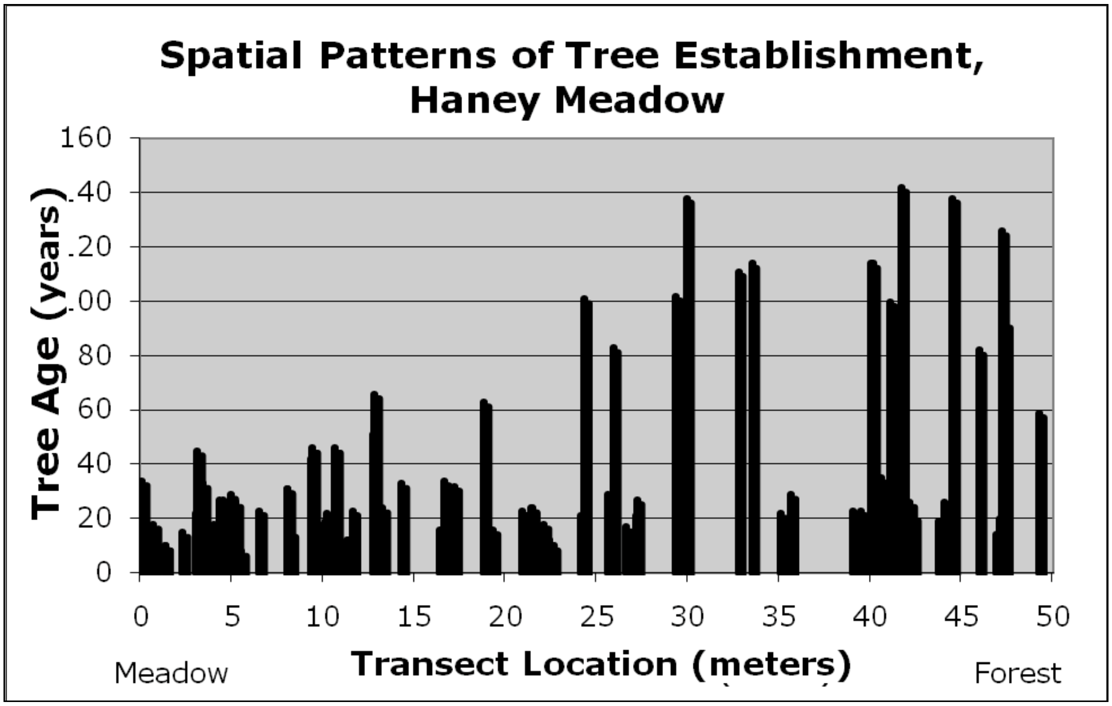

Figure 11. Graph illustrating spatial patterns of tree invasion for all transects at Haney Meadow, a hydric meadow.

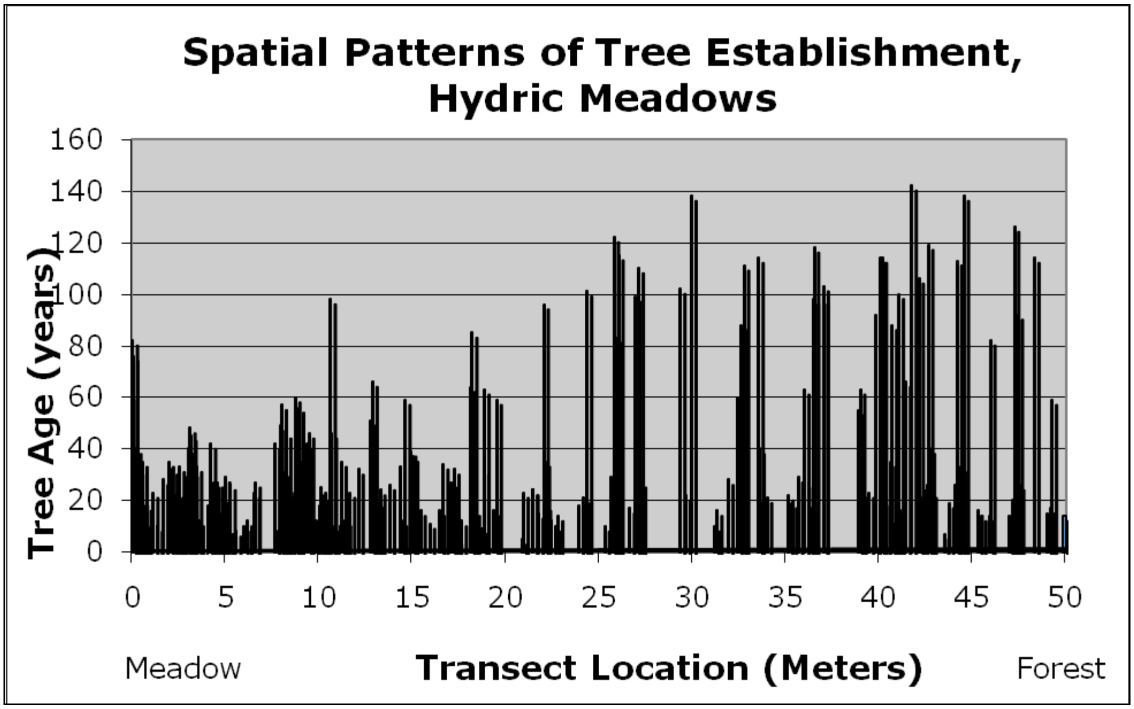

Figure 12. Graph illustrating spatial patterns of tree invasion aggregated for all hydric meadow sites.

increases and density decreases after reaching the meadow/forest boundary. This assessment is corroborated by statistical analysis, which shows a weak correlation between transect location and tree age in Dry Creek Meadow ($r = 0.22$, $p = 0.04$), Lower Naneum Meadow ($r = 0.29$, $p = 0.02$), and Haney Meadow ($r = 0.26$, $p = 0.00$).

The spatial patterns of invasion can also be viewed in Figures 13, 14, and 15. These photos show each hydric meadow sampled in 1954 and 2006. Comparing these two aerial photographs, one can see both the amount of invasion and the pattern. In these wet meadows, it appears as though tree establishment has been somewhat limited, although the resolution of the airphotos makes it difficult to see young, small trees. It appears as though invasion has been the greatest on the drier margins of hydric meadows. Invasion is indicated on these figures by circles, and wet areas appear darker than dry areas in these photos.

It is difficult to determine, based solely on airphotos, whether invasion in hydric meadows follows a leap-and-fill pattern or a gradual pattern. The pattern that emerges in Figure 12 indicates that invasion in hydric settings most closely follows the leap-and-fill pattern documented by Franklin et al. (1971), and Norman and Taylor (2005). This could be linked to high soil moisture in the intervening settings. Invading trees might first establish a ways out from the meadow/forest boundary, in areas of more moderate soil moisture conditions, such as on convex surfaces, as occurred in the moist subalpine meadows of Mt. Rainier (Rochefort & Peterson, 1996). Once trees establish on these more moderate sites, they may ameliorate negative site conditions, such as wet soils, by changing soil attributes or microtopography making conditions more tolerable for other trees (Norman & Taylor; Rochefort & Peterson). This would allow trees to establish

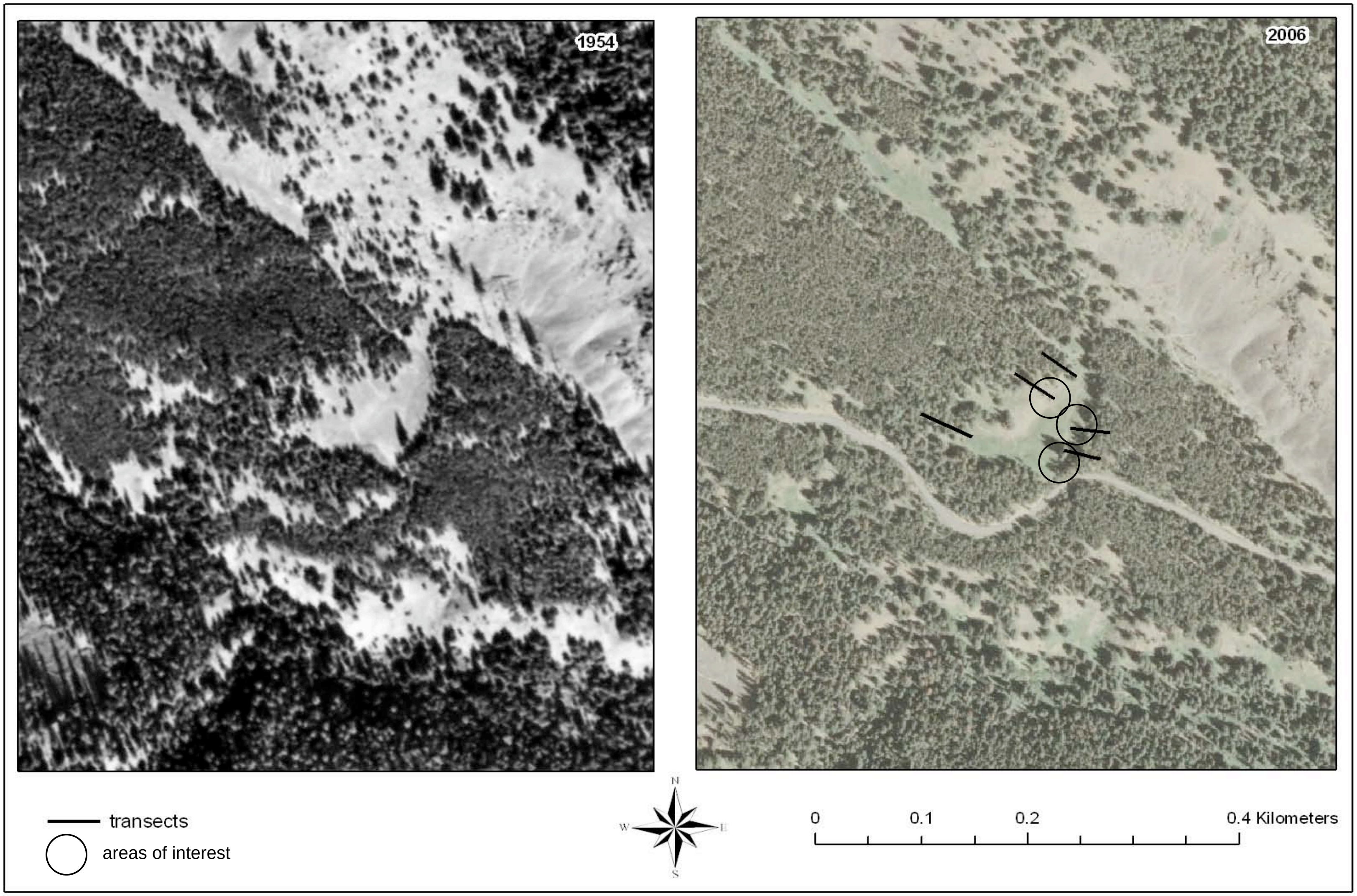

Figure 13. Airphotos of Dry Creek Meadow, 1954 and 2006.

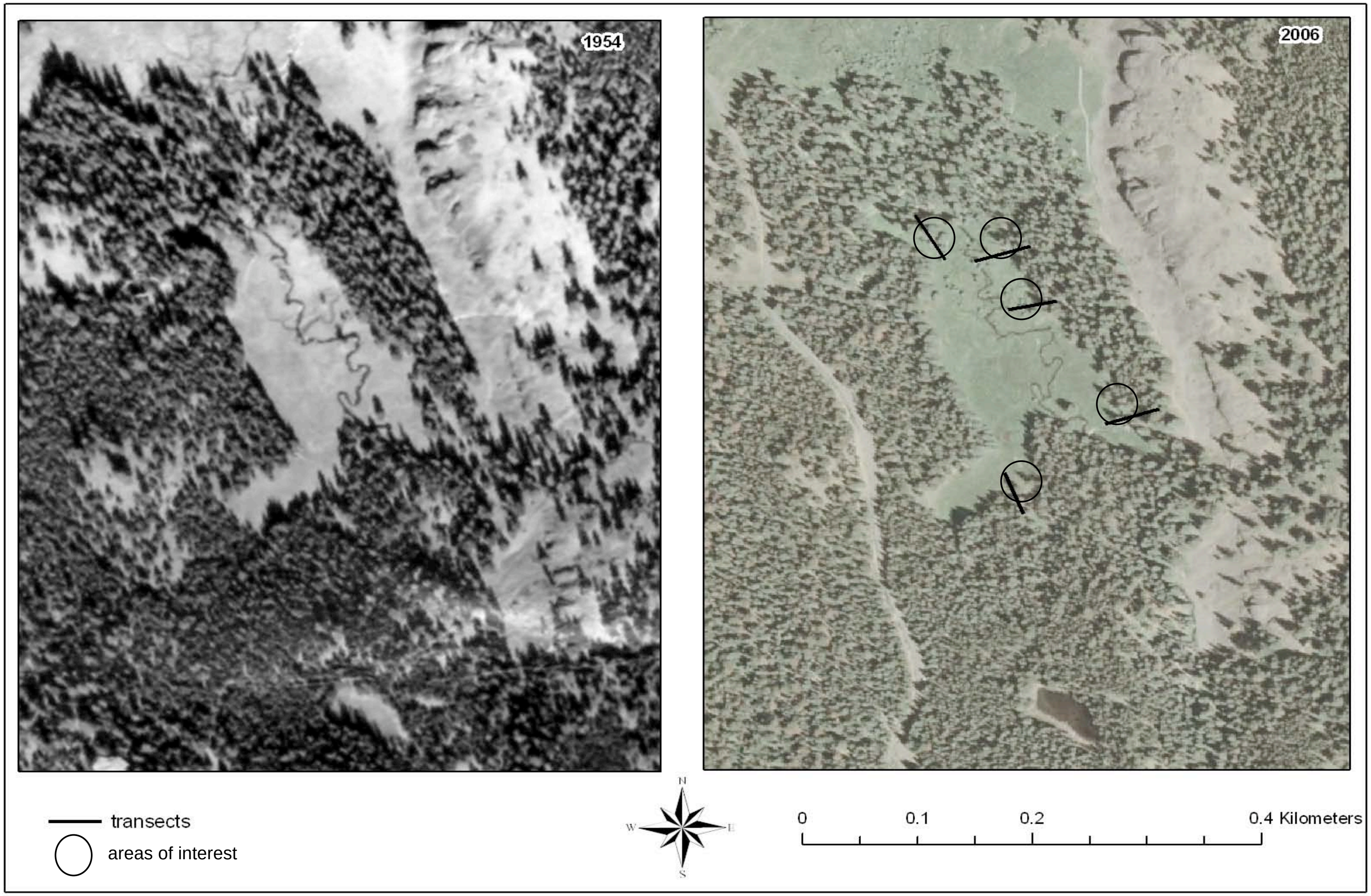

Figure 14. Airphotos of Lower Naneum Meadow, 1954 and 2006.

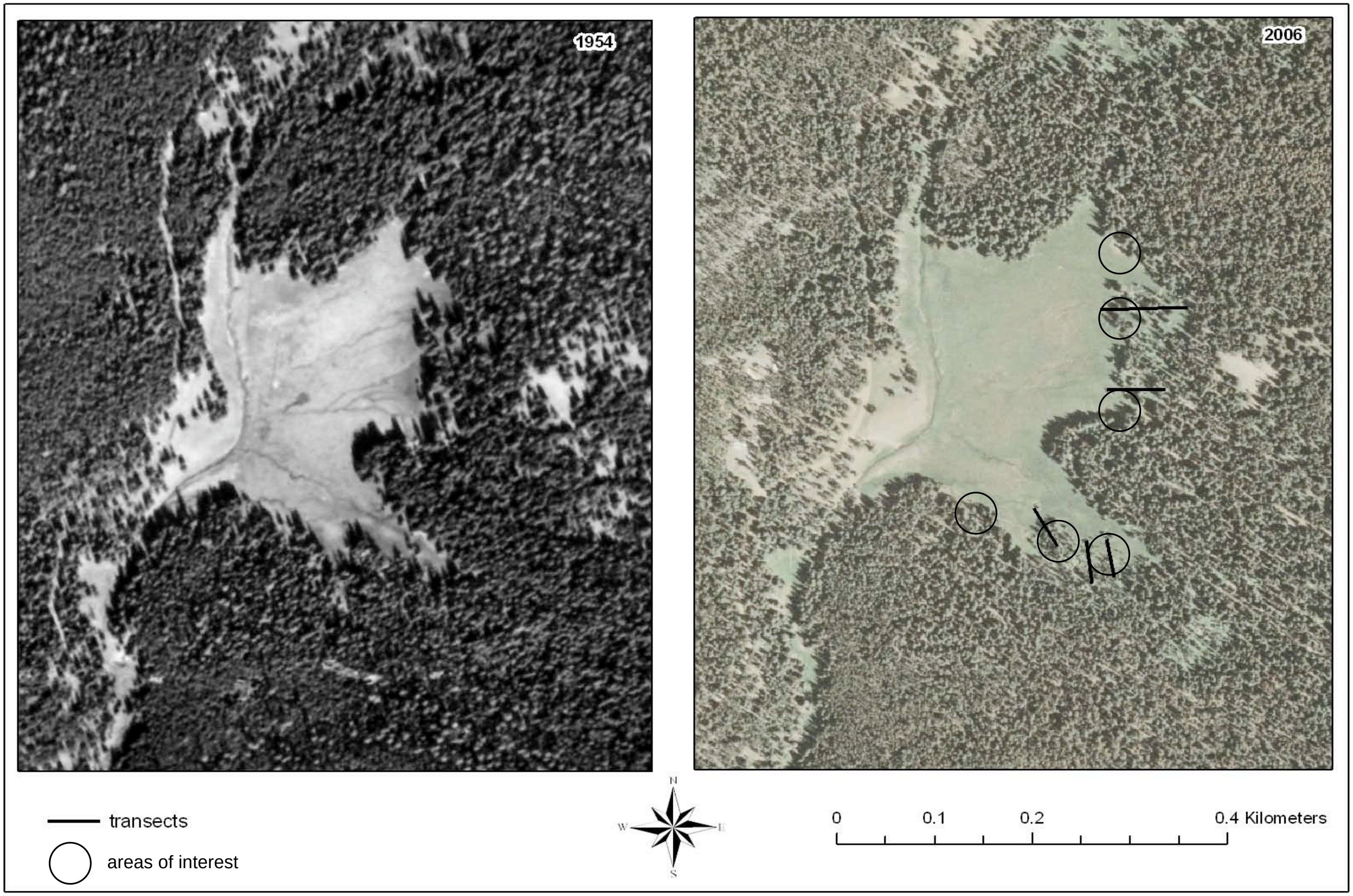

Figure 15. Airphotos of Haney Meadow, 1954 and 2006.

between the meadow/forest boundary and the pioneer trees. Although it appears as though a leap-and-fill pattern exists in hydric meadows when examining Figure 12, there is not a statistically significant relationship between transect location and tree age ($r = 0.10$, $p = 0.09$).

Temporal Patterns of Invasion

The age range of trees within the hydric meadows, and the closely surrounding forest, of the upper Naneum are 6 to 336 years, with the earliest date of establishment being 1673 and the latest date of establishment at 2003. The temporal pattern of tree invasion in hydric meadows is easier to distinguish than the spatial patterns (see Figures 16, 17, 18 and 19). In all three of the hydric meadows sampled, tree invasion varied somewhat throughout the time frame examined. In Dry Creek Meadow, there has been a

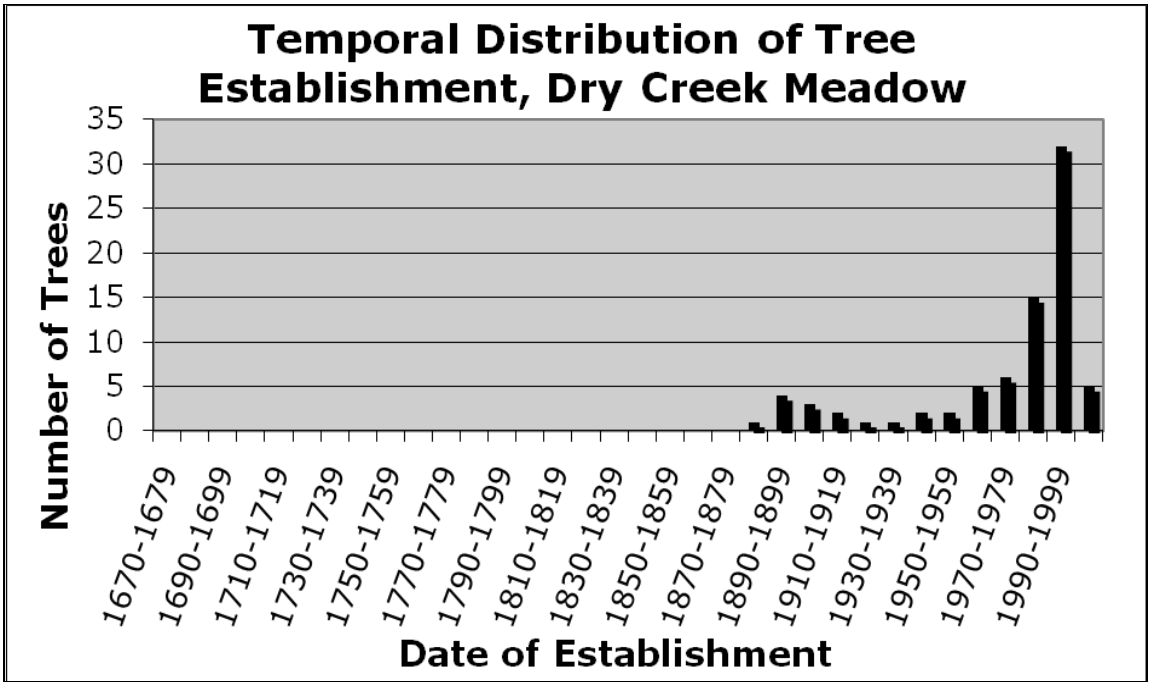

Figure 16. Temporal pattern of tree invasion for Dry Creek Meadow, a hydric meadow.

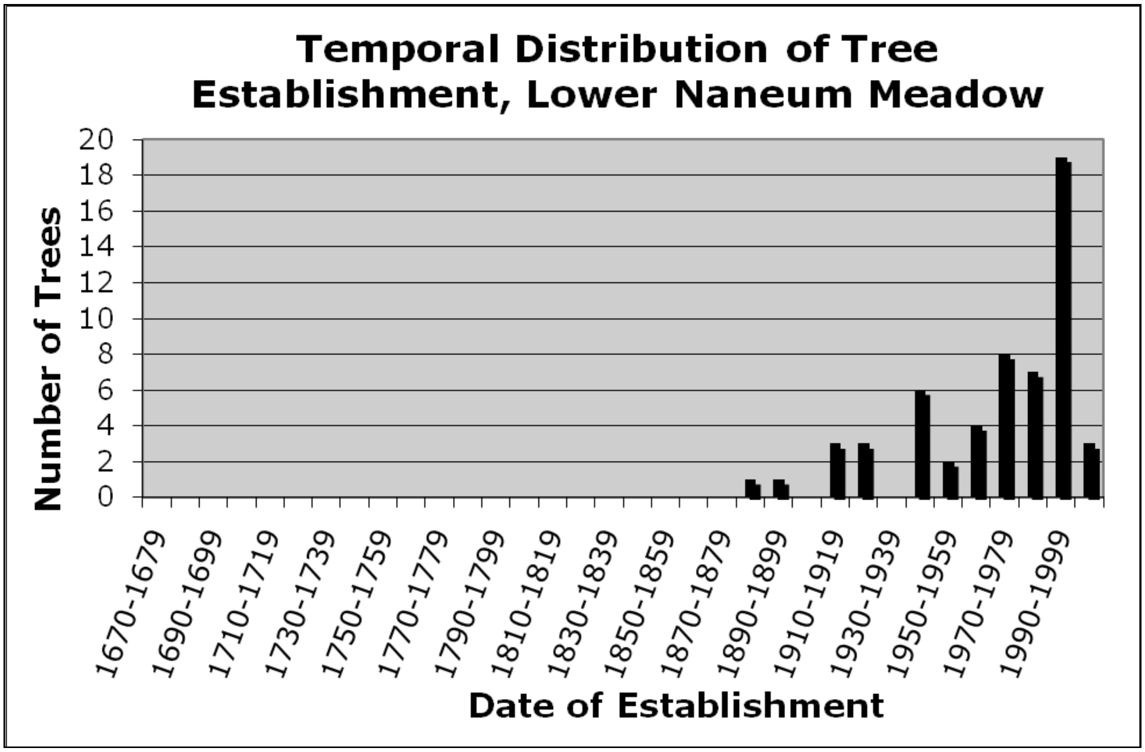

Figure 17. Temporal pattern of tree invasion for Lower Naneum Meadow, a hydric meadow.

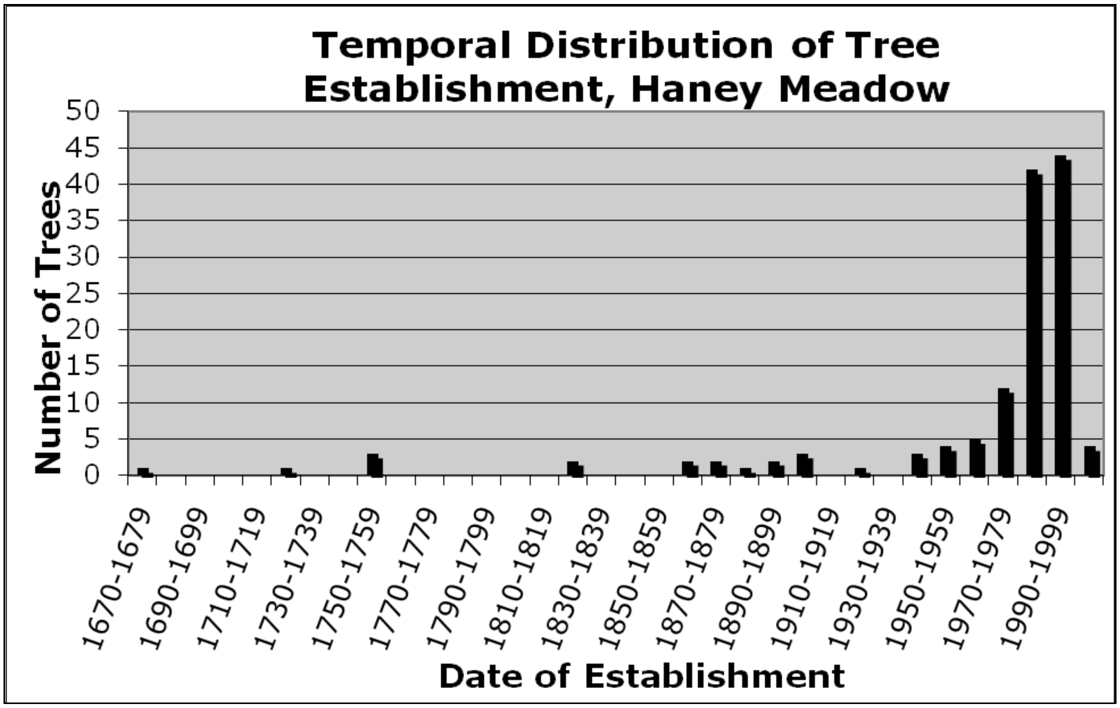

Figure 18. Temporal pattern of tree invasion for Haney Meadow, a hydric meadow.

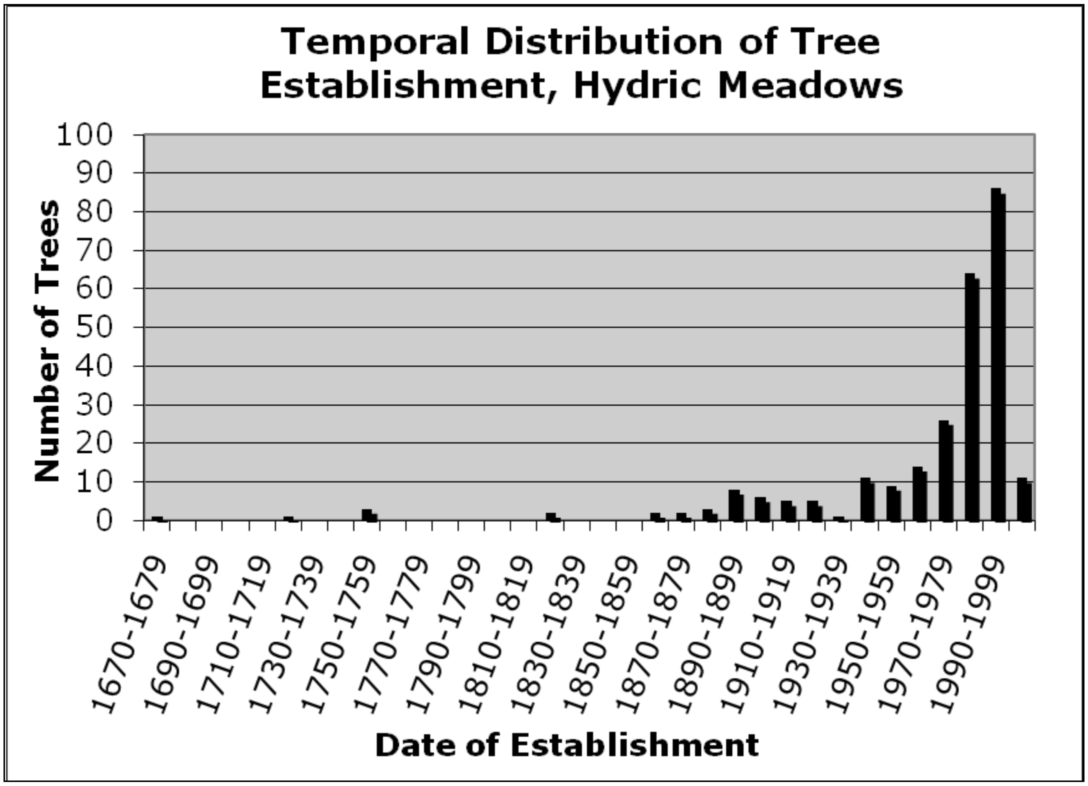

Figure 19. Temporal pattern of tree invasion aggregated for all hydric meadow sites.

steady increase in invasion beginning in 1940 and continuing through the 1990s. This pattern was also seen in Lower Naneum Meadow and in Haney Meadow.

When examining the data for all hydric meadows sampled (Figure 19), it appears that a small peak in invasion occurred around 1890 through 1910, with tree establishment remaining high, but gradually declining through 1930. The lowest period of invasion during the 20th century occurred from 1930 to 1939. In the 1940s, invasion began to increase again, and reached its peak from 1990 to 1999. There has been a sharp decline in invasion since 2000, but this can likely be attributed to missing very small, young trees while sampling. These trees were often difficult to recognize in the field. This general pattern of invasion and noninvasion is similar throughout the three hydric meadows sampled, with the 1930s being a distinct period of low or noninvasion and the 1990s being the peak of invasion. It is difficult to determine a temporal pattern of invasion from the Figures 13, 14, and 15, given the coarse temporal resolution of the comparisons, but it is clear that invasion has been occurring since 1954.

Given these peaks and lulls in invasion over the years, invasion in the hydric meadows of the upper Naneum most closely resemble episodic invasion, as documented by Coop and Givnish (2007), Haugo and Halpern (2007), Miller and Halpern (1998), and Woodward et al. (1995). It is likely that these episodic peaks in invasion are linked to specific climatic, fire, or land use disturbance, which will be examined in greater depth later. It is also possible that the temporal pattern of invasion in hydric meadows is somehow related to masting, yearly cycles of considerable seed production. There does not appear to be a statistically significant difference in the temporal pattern of invasion between hydric meadows and mesic meadows ($r = 0.12$, $p = 0.07$), and hydric meadows and xeric meadows ($r = 0.10$, $p = 0.15$).

Species Patterns of Invasion

Grand fir, subalpine fir, Pacific silver fir, lodgepole pine, Englemann spruce, and Douglas fir were all found within hydric meadows of the upper Naneum watershed (see Figures 20, 21, 22, and 23). The greatest number of invaders belonged to two species, subalpine fir and Englemann spruce. These are also among the first species to establish (see Figure 24). These species are likely the most invasive in these settings because they can tolerate moist soil conditions (Miller, 1995), making them more capable of establishing in the moderate moisture of these wet meadows. The most invasive species did vary between meadows. In Dry Creek Meadow, very few Englemann spruce were

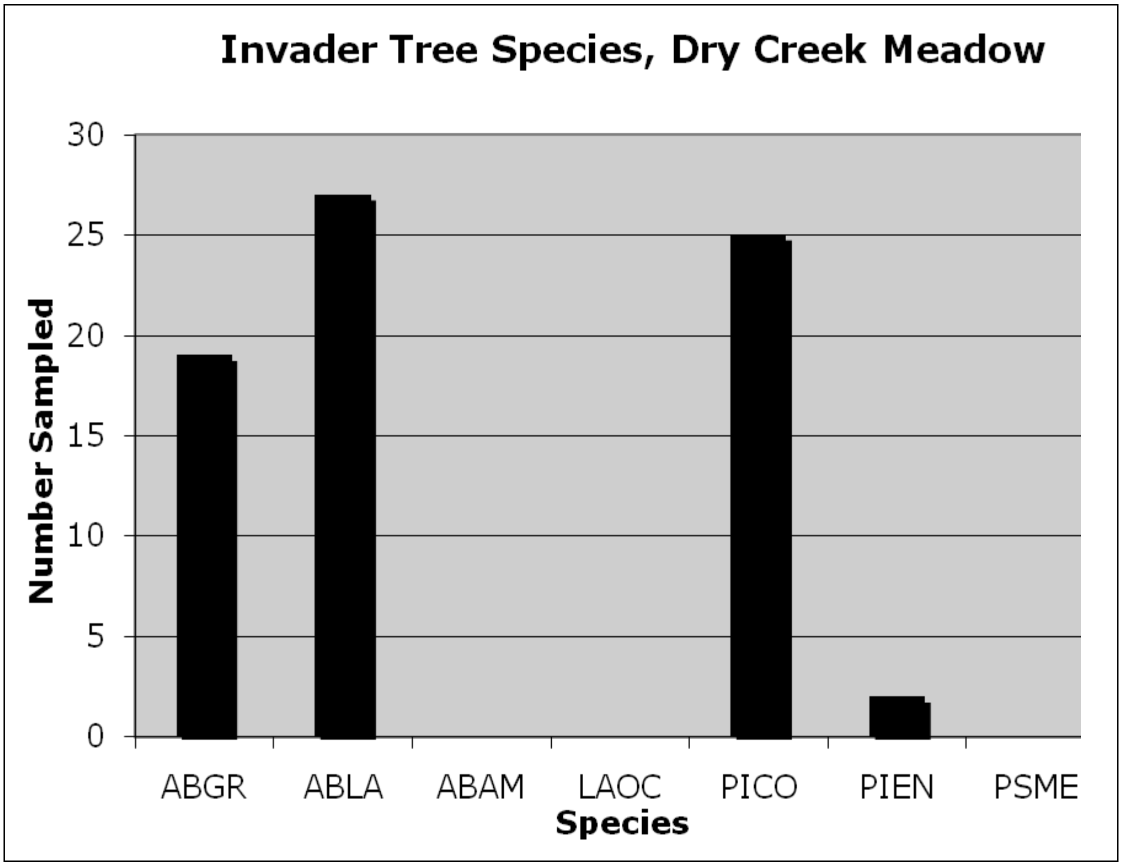

Figure 20. Invading tree species of Dry Creek Meadow, a hydric meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

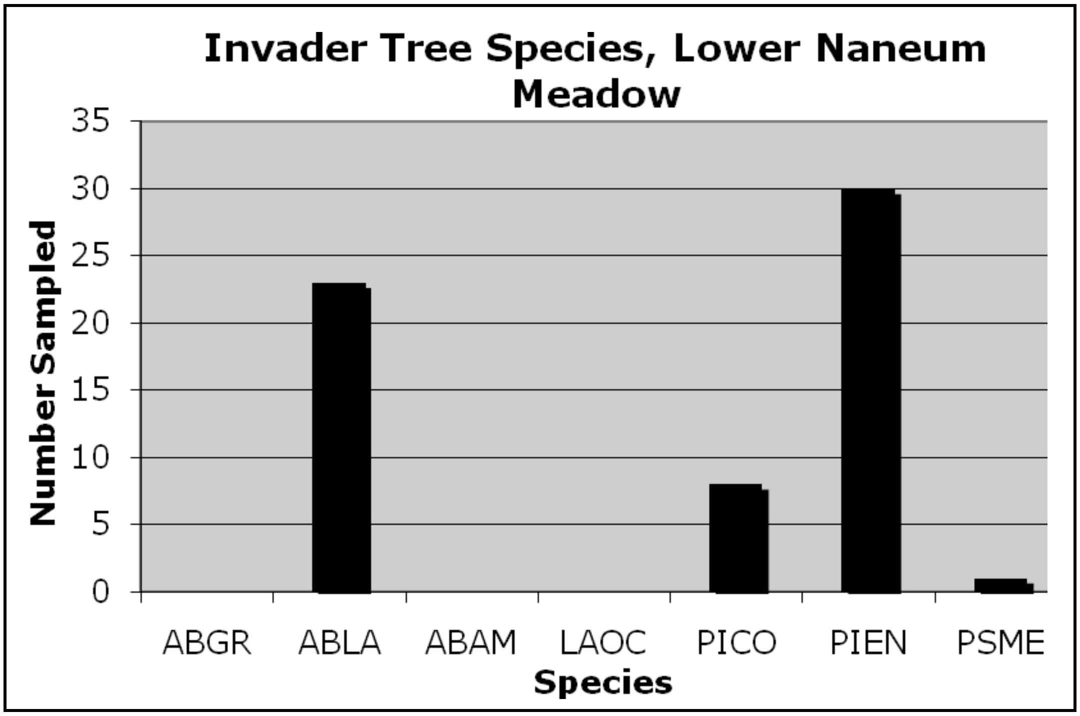

Figure 21. Invading tree species of Lower Naneum Meadow, a hydric meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

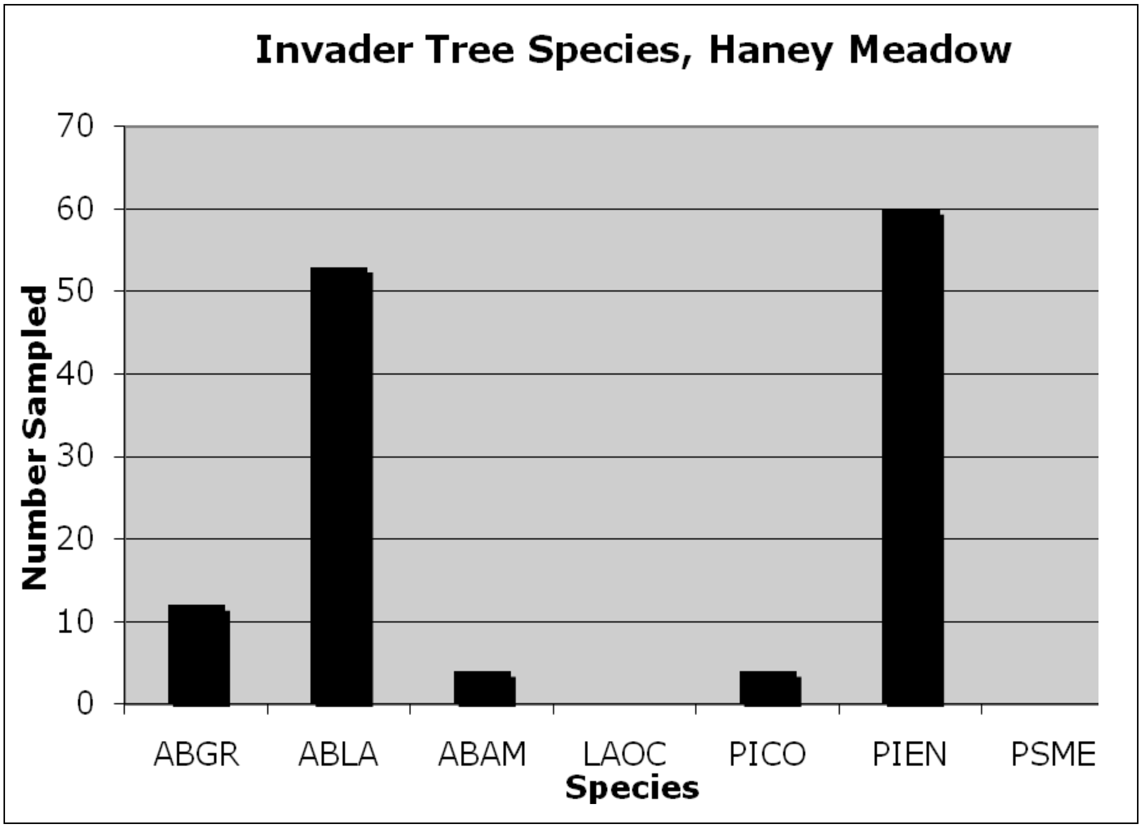

Figure 22. Invading tree species of Haney Meadow, a hydric meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

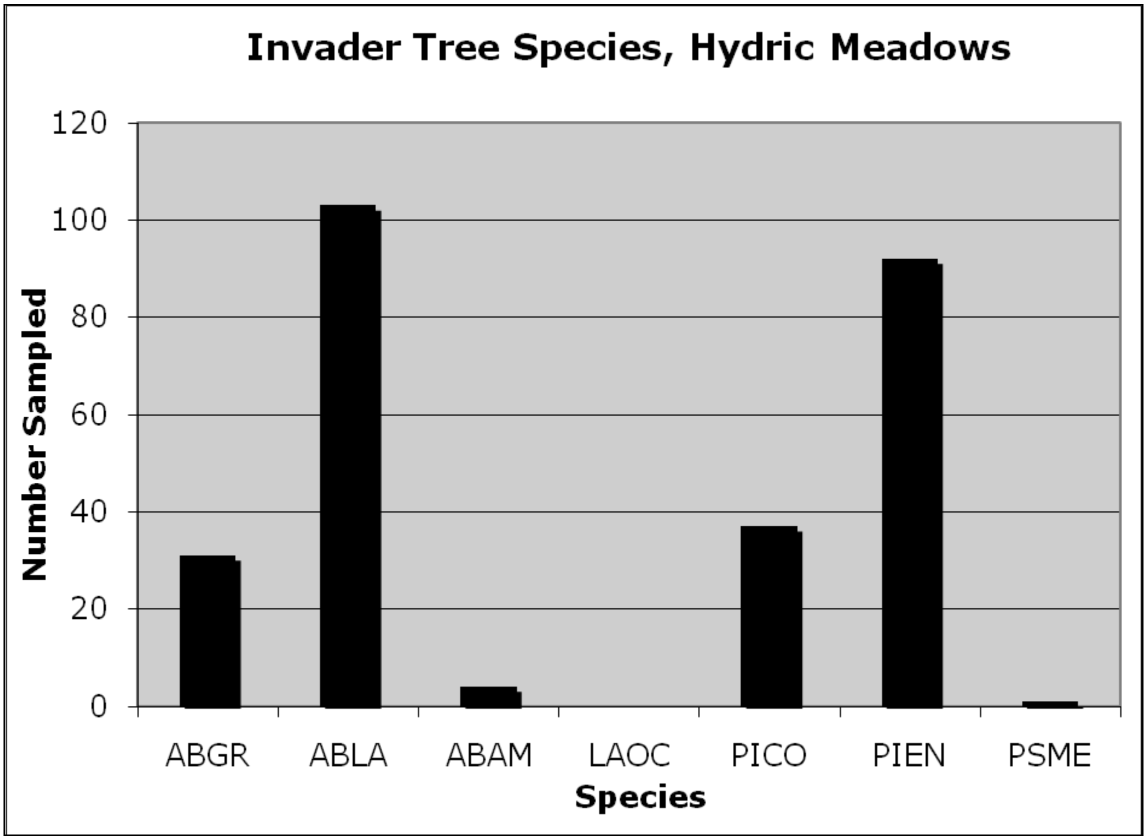

Figure 23. Invading tree species data aggregated for all hydric meadows. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

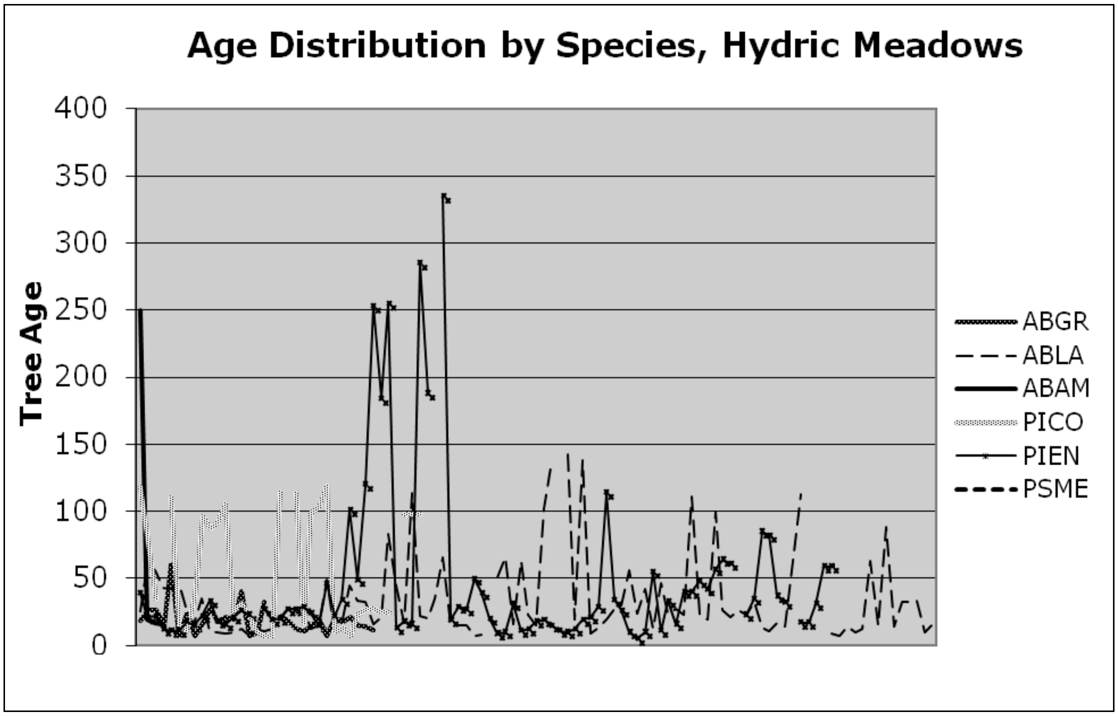

Figure 24. Age distribution of invading trees by species of all hydric meadow sites. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

present, and lodgepole pine was the second most invasive species after subalpine fir. There does not appear to be a statistically significant difference in invading species between hydric meadows and other meadow types.

Mesic Meadows

Spatial Patterns of Invasion

The spatial pattern of tree establishment in the three sampled mesic meadows of the upper Naneum is somewhat different from the patterns seen in hydric meadows. Rather than having a leap-and-fill pattern, with older pioneer trees at the beginning of the transects (toward meadow center), followed by a decrease in tree age and a steady increase in tree age there after to the meadow/forest boundary (Norman & Taylor, 2005), we see a much different pattern. As illustrated in Figures 25, 26, 27 and 28, pioneer trees in these mesic meadows are followed by a decrease in tree age, then an increase in tree age as one moves from meadow to forest edge. This occurs several times along the transects before tree age increases and density decreases in the forest (see Figure 29). This spatial pattern emerges in all of the meadows sampled as well as the aggregated data, although this pattern is weakest in Nealy Creek Meadow. Statistical analysis corroborates that the common leap-and-fill pattern is not occurring in most of these mesic meadows, with Upper Divide Meadow (r = 0.02, p = 0.08), Yarrow Meadow (r = 0.03, p = 0.08), and aggregated data for mesic meadows (r = 0.08, p = 0.20) showing no strong

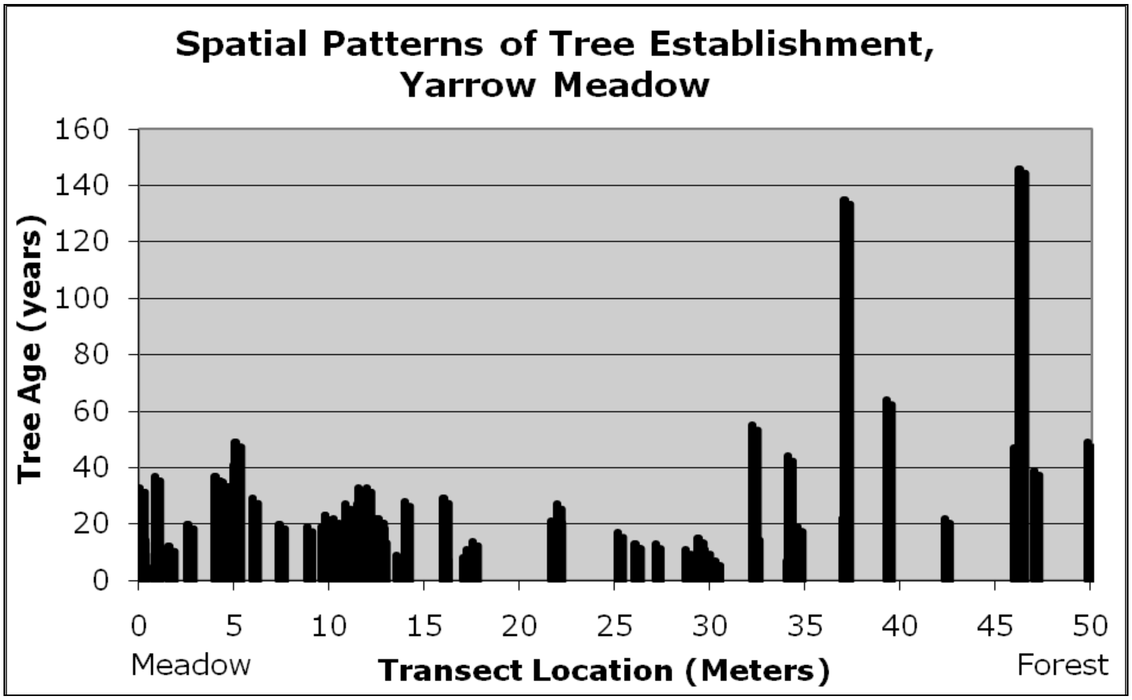

Figure 25. Graph illustrating spatial patterns of tree invasion for all transects at Yarrow Meadow, a mesic meadow.

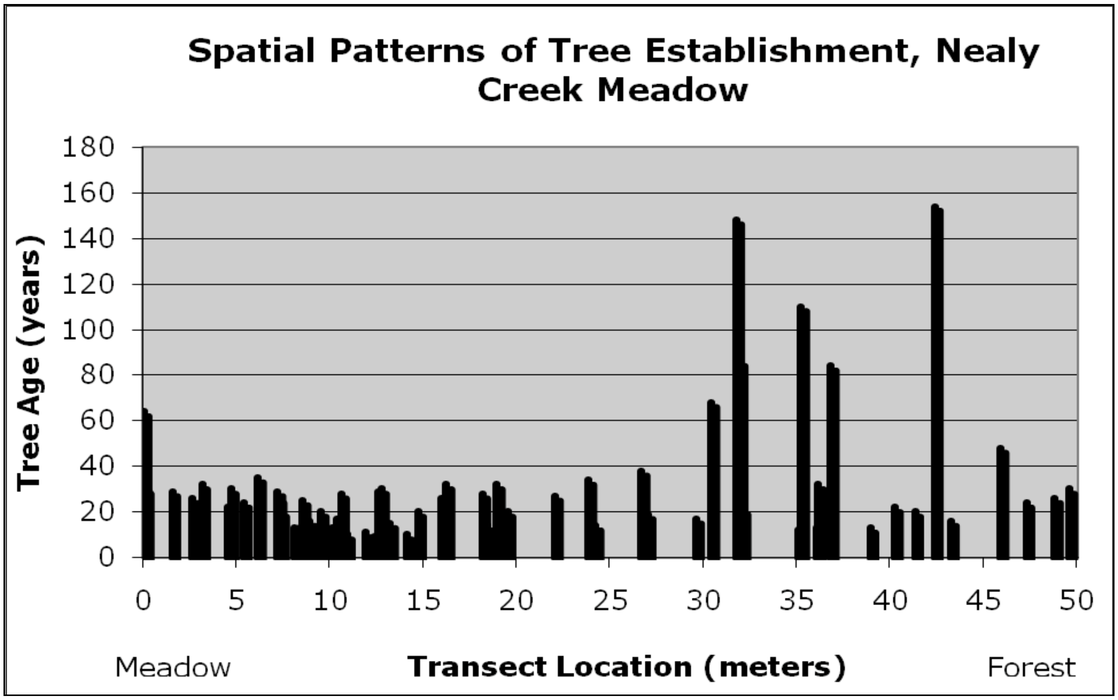

Figure 26. Graph illustrating spatial patterns of tree invasion for all transects at Nealy Creek Meadow, a mesic meadow.

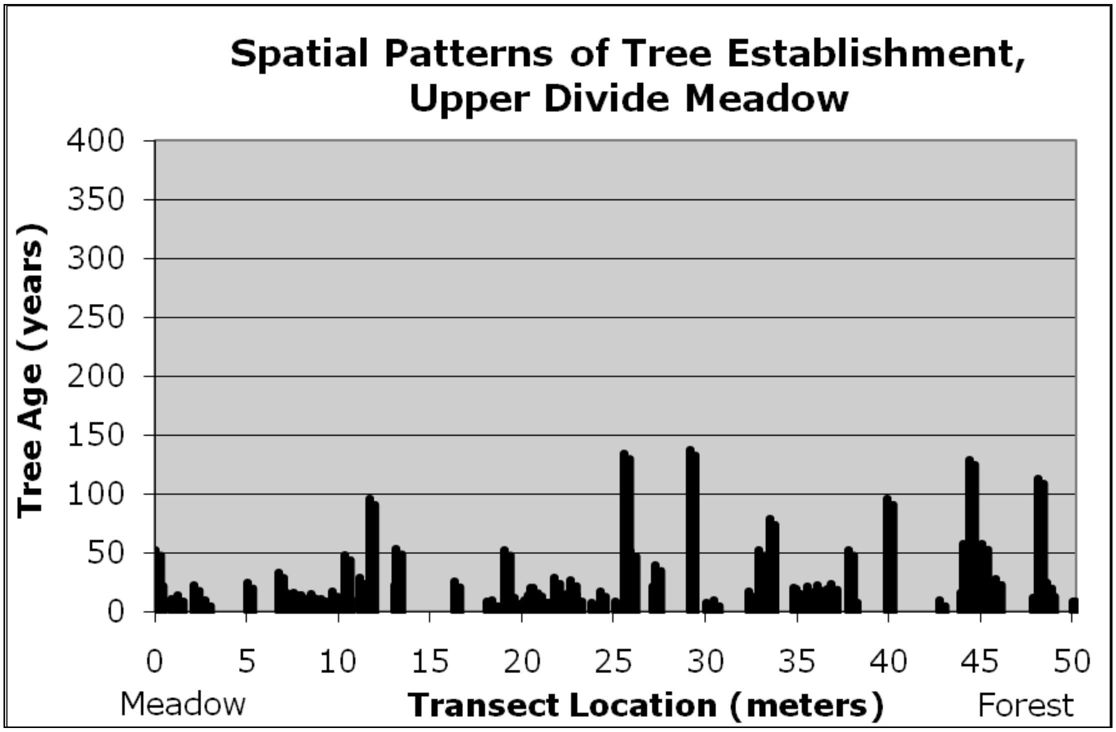

Figure 27. Graph illustrating spatial patterns of tree invasion for all transects at Upper Divide Meadow, a mesic meadow.

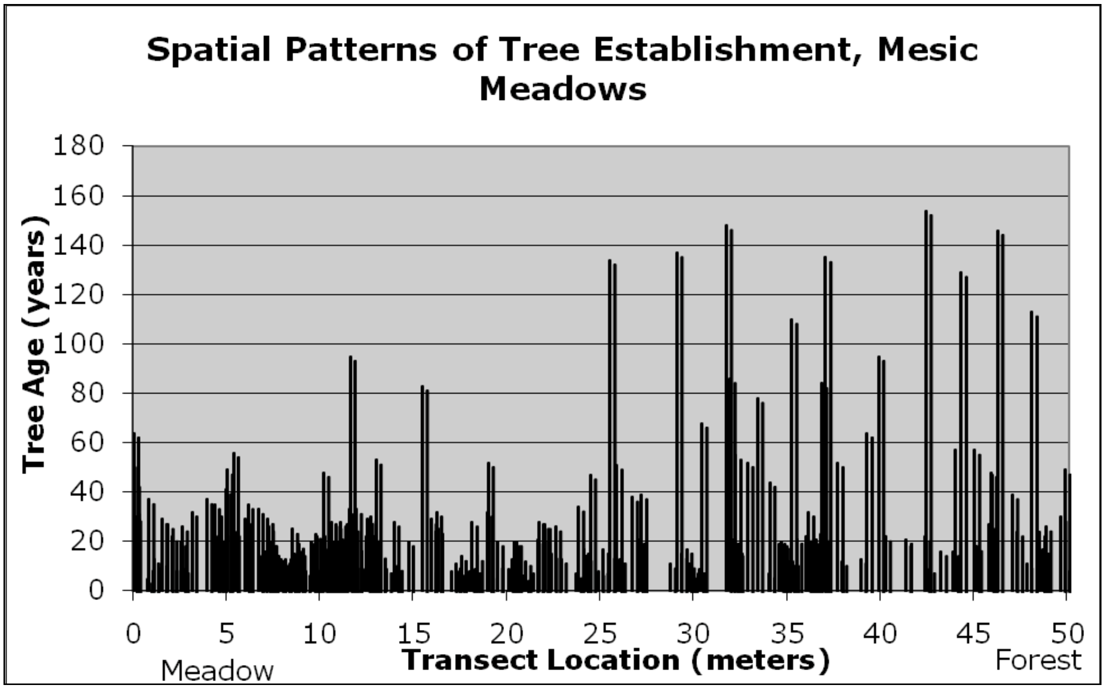

Figure 28. Graph illustrating spatial patterns of tree invasion aggregated for all mesic meadow sites.

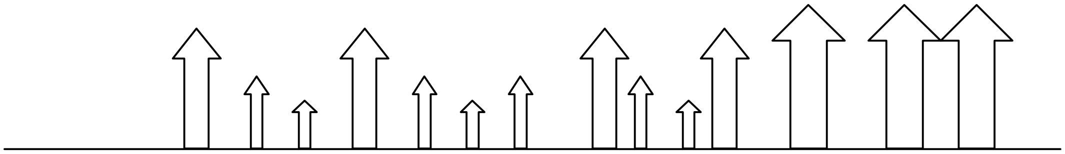

Figure 29. Conceptual illustration of cyclic leap-and-fill patterns as found in the mesic meadows of the upper Naneum watershed.

relationship. The standard leap-and-fill pattern we've seen elsewhere appears to be occurring in Nearly Creek Meadow (*r* = 0.20, *p* = 0.04).

The pattern seen here is very different from what others have reported for meadow invasion elsewhere (Franklin et al., 1971; Norman & Taylor, 2005). In these mesic meadows, trees may first establish in areas where the seedbed has been disturbed (Magee & Antos, 1992; Norman & Taylor). After pioneer trees establish in disturbed areas, other seedlings may establish near these pioneers, giving way to the pattern we see in Figure 28 (Magee & Antos; Norman & Taylor). This leads to cycles or series of leap-and-fills, as illustrated in Figure 29.

The spatial patterns of invasion can also be viewed in Figures 30, 31, and 32. These figures show each mesic meadow that was sampled for this study in 1954 and 2006. Comparing these areal photographs, one can see both the amount of invasion and the pattern. In the mesic meadows of the upper Naneum watershed, it appears as though there has been a greater amount of tree establishment than in the hydric meadows of the watershed. In two of the three figures below (Figures 31 and 32), the meadows appear to have closed in and/or decreased in size.

Temporal Patterns of Invasion

The temporal pattern of tree invasion in each mesic meadow sampled can be viewed in Figures 33, 34, and 35. In Yarrow, Nealy, and Upper Divide Meadow, one can see a general increase in the rate of invasion throughout the later half of the 20th century. For the aggregated mesic meadow data (see Figure 36), it appears that invasion peaks occurred in the late 19th century as well as the mid to late 20th century. The largest peak in tree invasion began in 1950 and continued until 1999, with the highest period of tree establishment being from 1980 to 1999. This peak in invasion can be views in Figures 30, 31, and 32. In these aerial photos, it is apparent that tree invasion occurred from the 1950s through 2006. Much like the temporal pattern of invasion in hydric meadows, this pattern appears to be episodic, and is likely related to environmental, or land use/ management changes, as changes in these factors may facilitate tree invasion (Coop & Givnish, 2007; Miller & Halpern, 1998; Woodward et al., 1995). As was the case with hydric meadows, masting may impact the temporal pattern of tree establishment. There

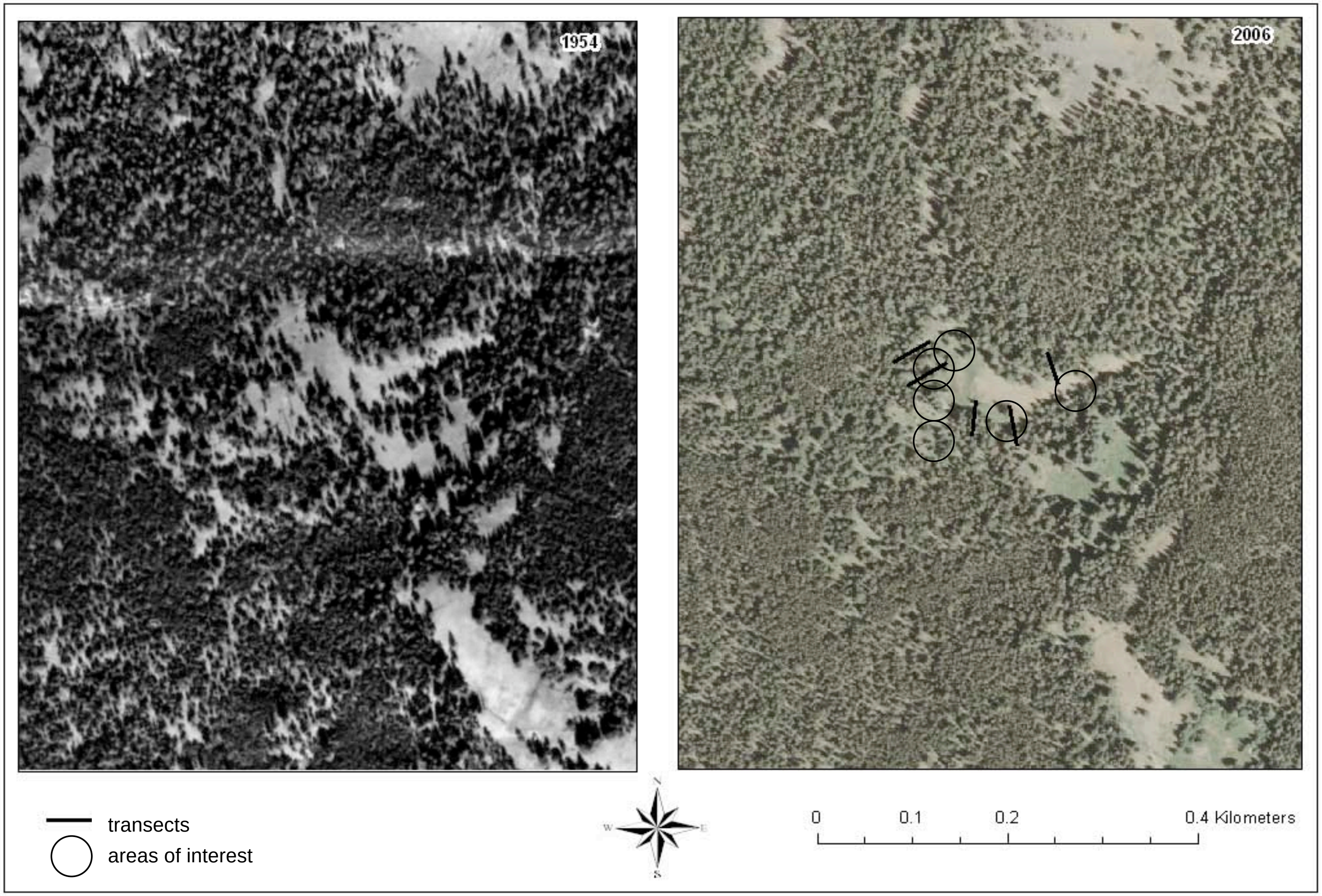

Figure 30. Airphotos of Yarrow Meadow, 1954 and 2006.

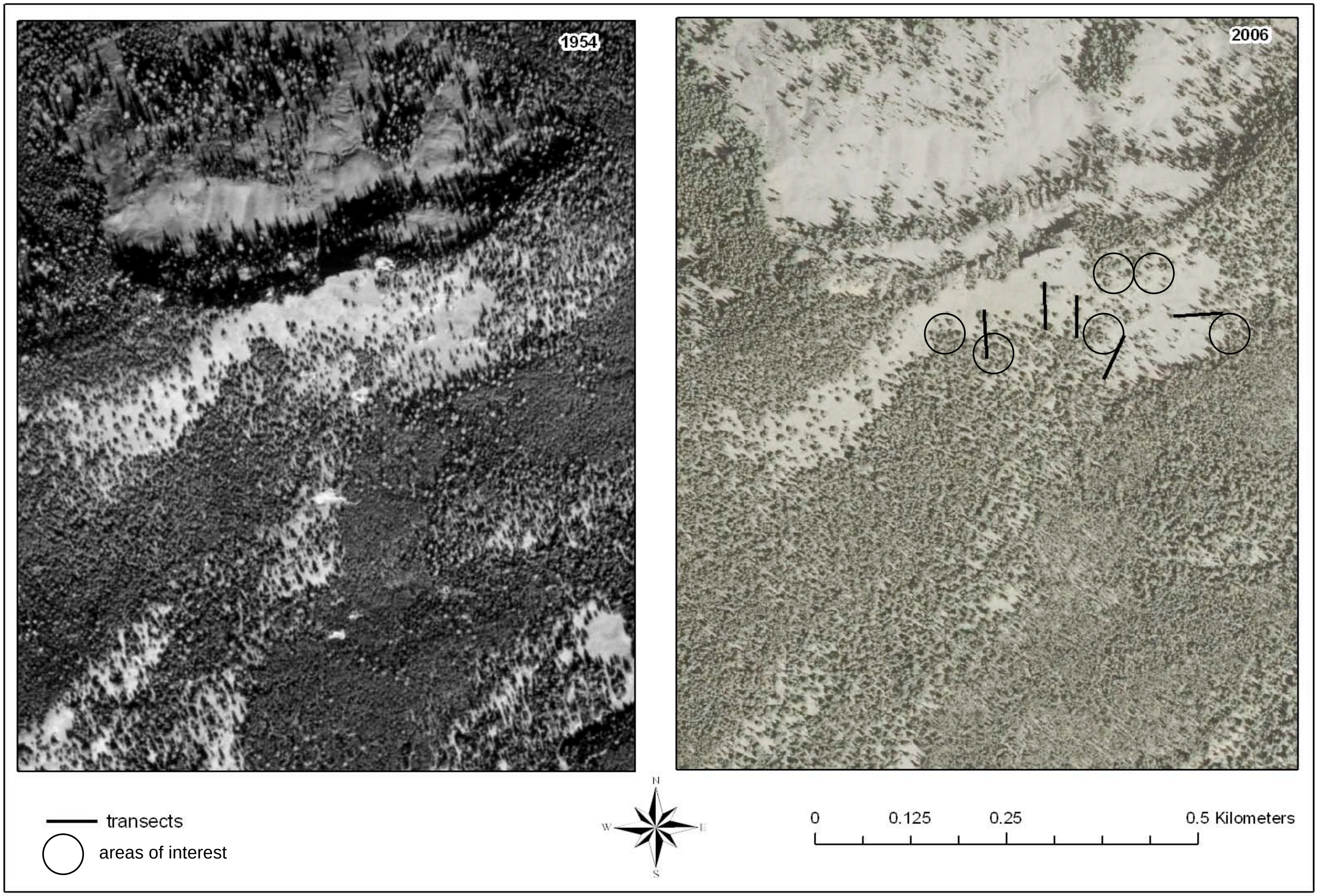

Figure 32. Airphotos of Upper Divide Meadow, 1954 and 2006.

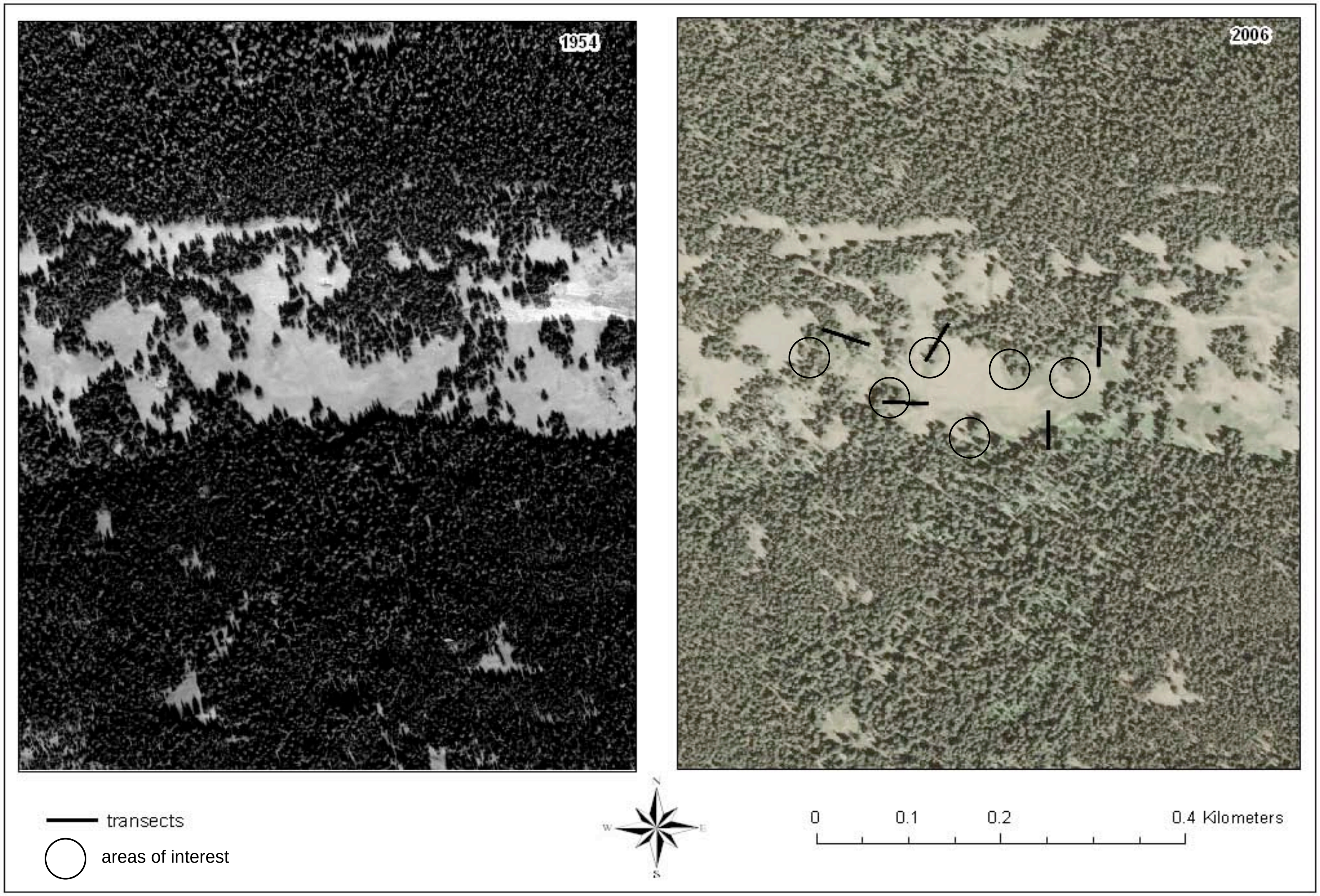

Figure 31. Airphotos of Nealy Creek Meadow, 1954 and 2006.

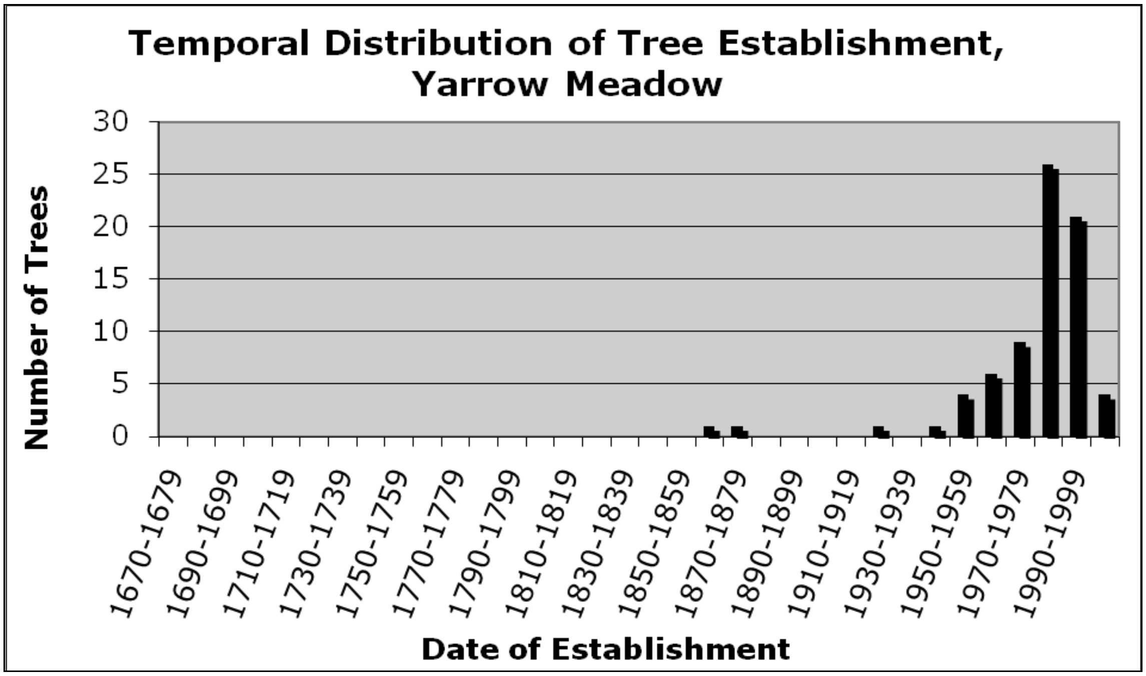

Figure 33. Temporal pattern of tree invasion for Yarrow Meadow, a mesic meadow.

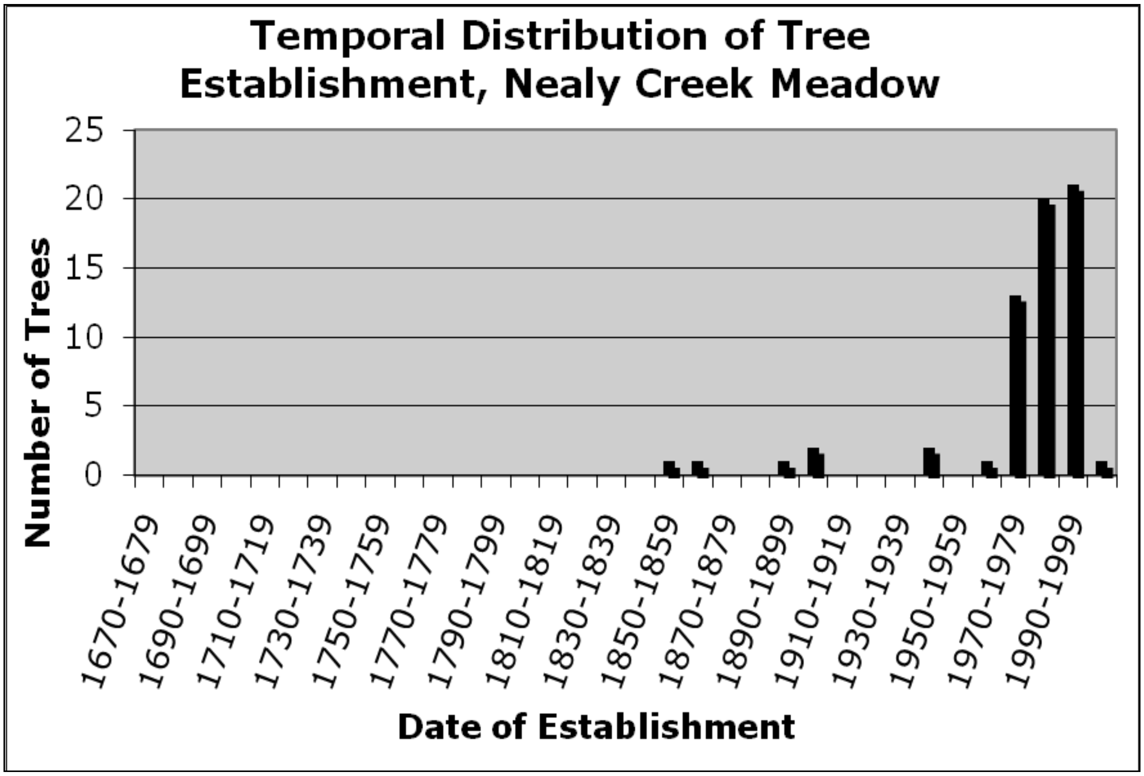

Figure 34. Temporal pattern of tree invasion for Nealy Creek Meadow, a mesic meadow.

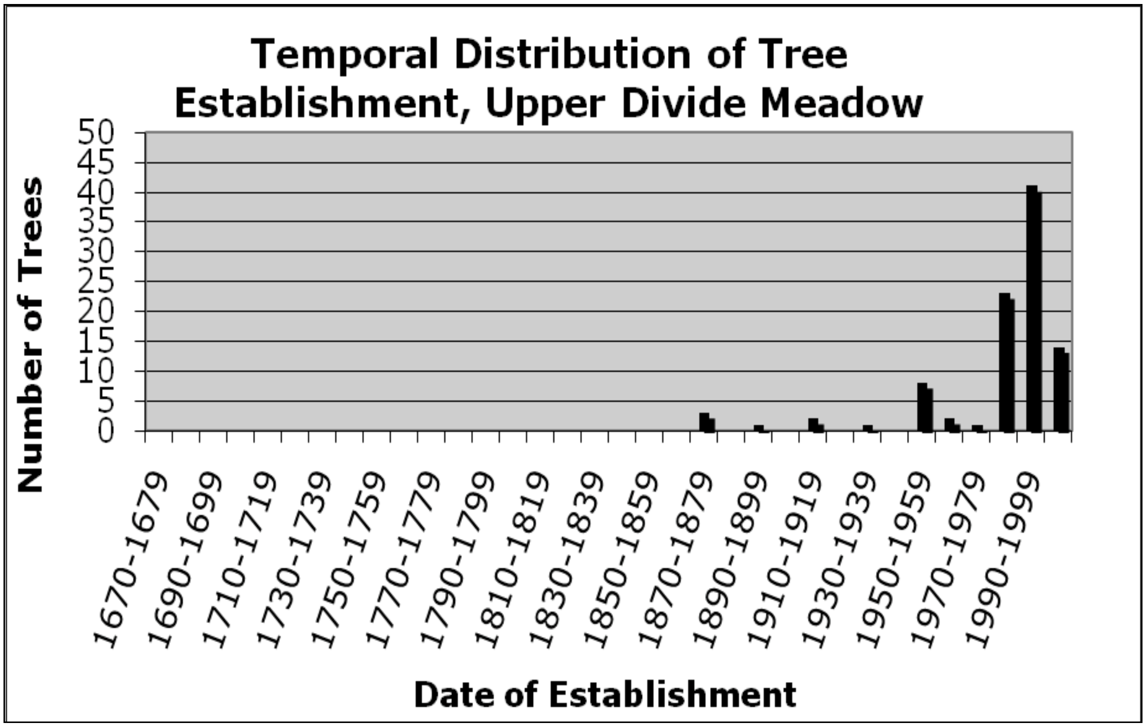

Figure 35. Temporal pattern of tree invasion for Upper Divide Meadow, a mesic meadow.

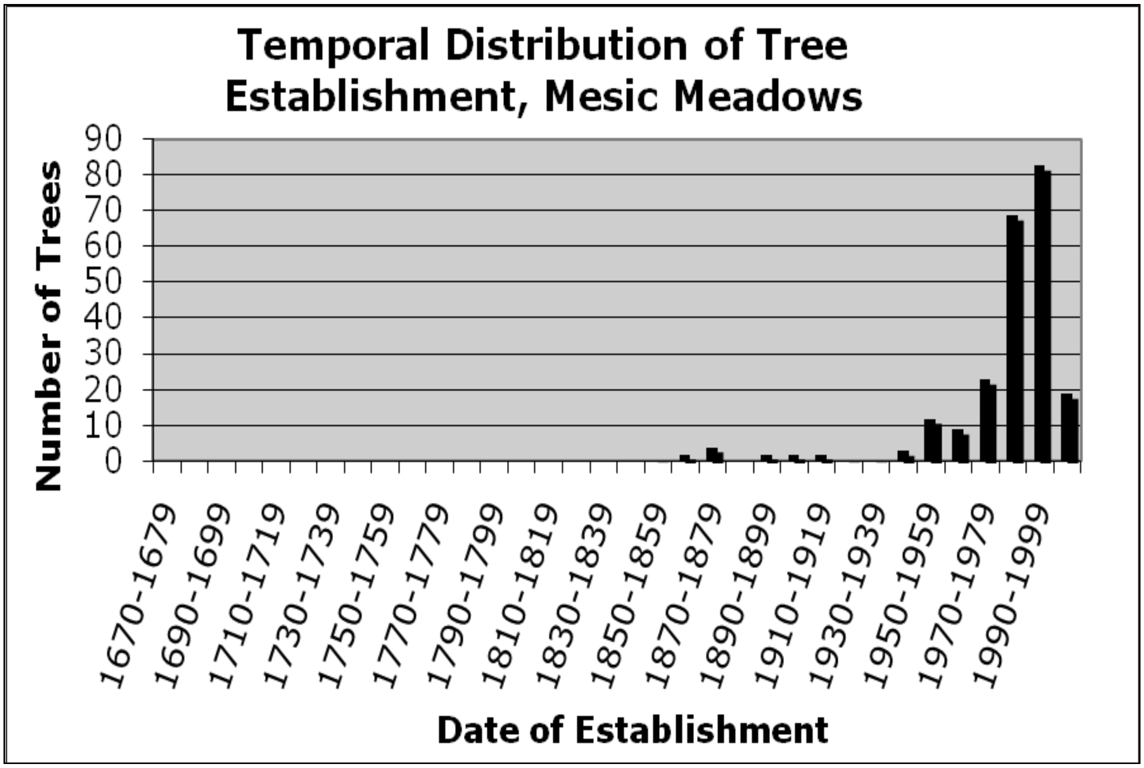

Figure 36. Temporal pattern of tree invasion aggregated for all mesic meadow sites.

is no significant difference in the temporal pattern of invasion between mesic meadows and hydric meadows (r = 0.12, p = 0 .07), and mesic meadows and xeric meadows (r = 0.21, p = 0.10). This pattern could also be related to tree mortality (Coop & Givnish). With most trees establishing within the last 30 years, it is possible that most invading trees tend to survive only about 30 or 40 years, and then die off, which would create the pattern seen below (Coop & Givnish). Although this is a possibility, I saw no evidence of this in the field.

Species Patterns of Invasion

Subalpine fir, grand fir, lodgepole pine, Englemann spruce, Douglas fir, and larch were all found invading the sampled mesic meadows of the upper Naneum watershed (see Figures 37, 38, 39, and 40). The species that occurred in the greatest frequency was by far subalpine fir. Subalpine fir was also among the oldest species found in mesic meadows (see Figure 41). This is likely because subalpine fir is well adapted to sites that are moderately moist and high in elevation, although they can tolerate dry and moist conditions as well (Woodward et al., 1995). Grand fir, lodgepole pine, and Englemann spruce were found in low to moderate frequencies. It was surprising to find Englemann spruce in these settings, considering their preference for moist sites, but they are also high elevation species and all of the mesic sites sampled were high in elevation. In addition to these species, a few Douglas fir and larch were present. There was in significant difference in invading species between meadow types.

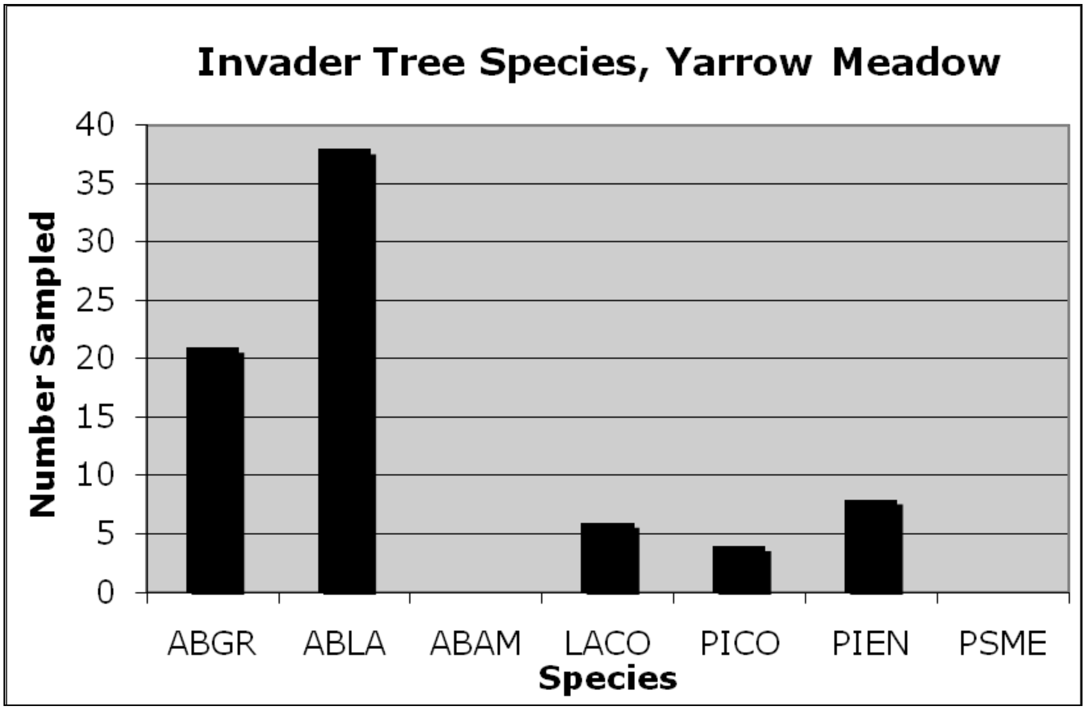

Figure 37. Invading tree species of Yarrow Meadow, a mesic meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

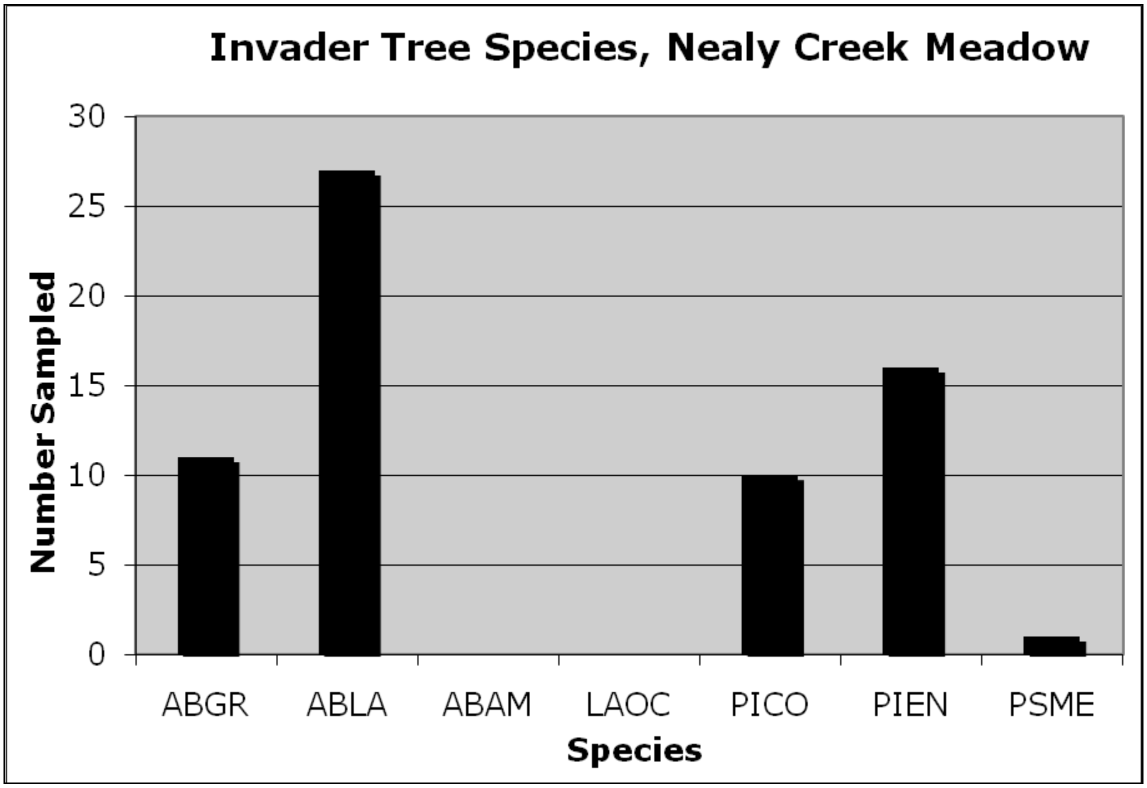

Figure 38. Invading tree species of Nealy Creek Meadow, a mesic meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

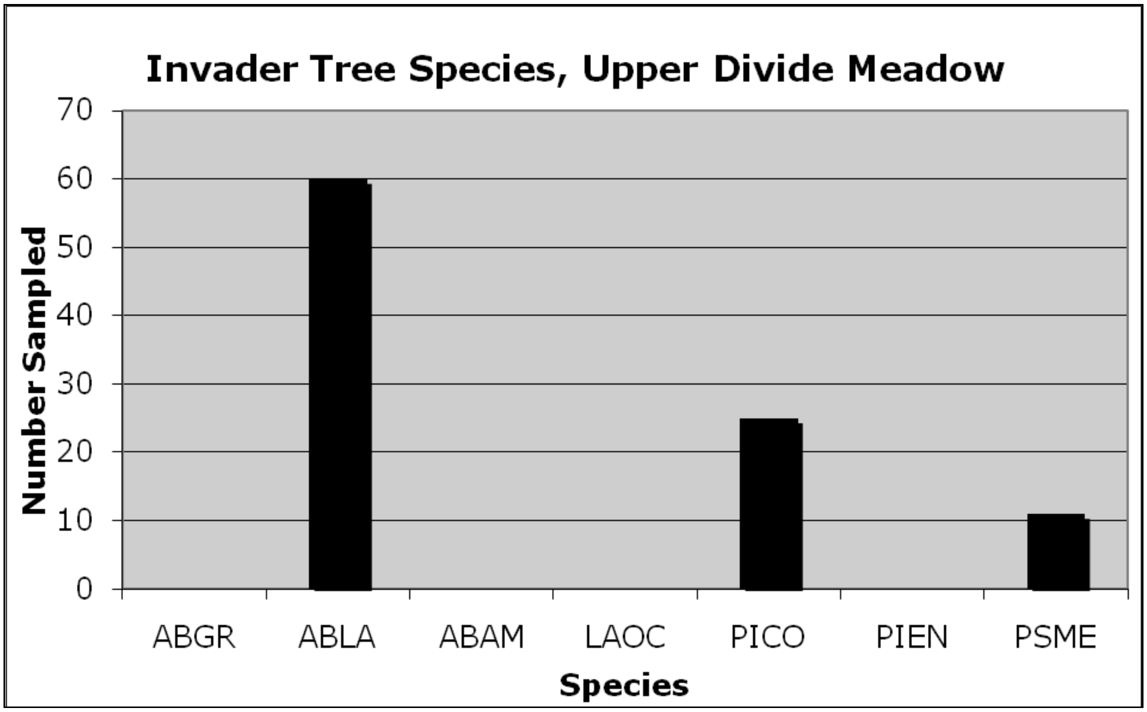

Figure 39. Invading tree species of Upper Divide Meadow, a mesic meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

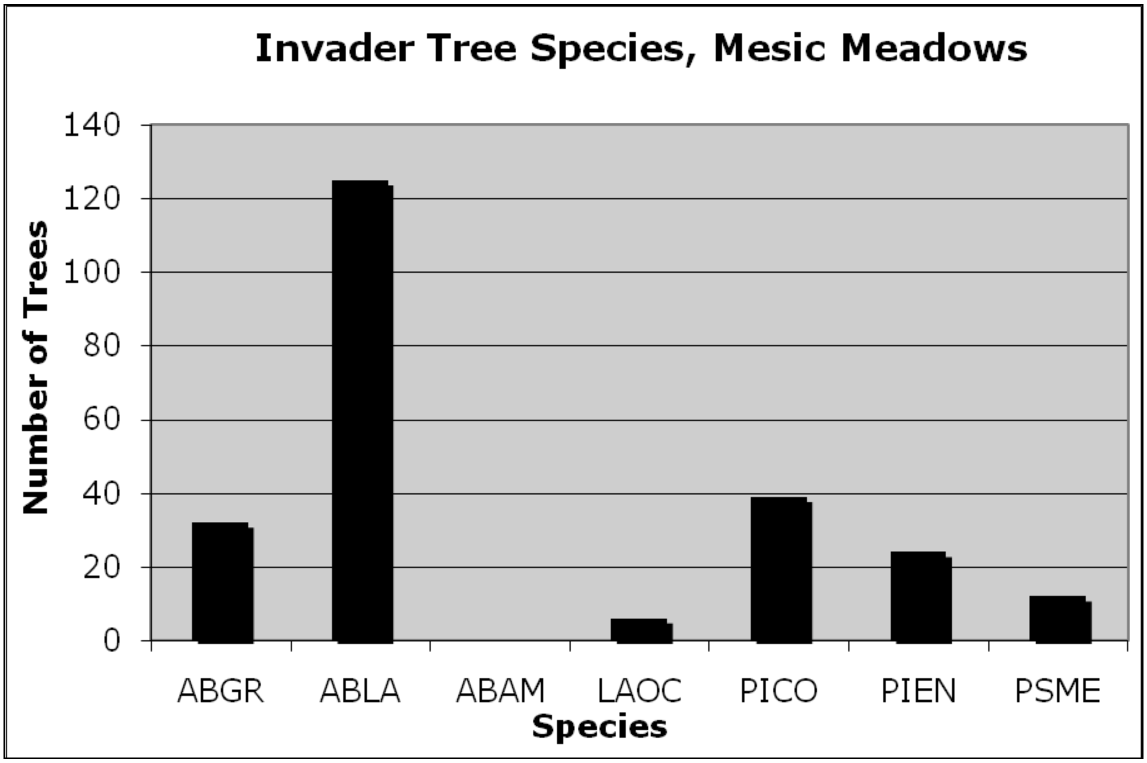

Figure 40. Invading tree species data aggregated for all mesic meadows. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

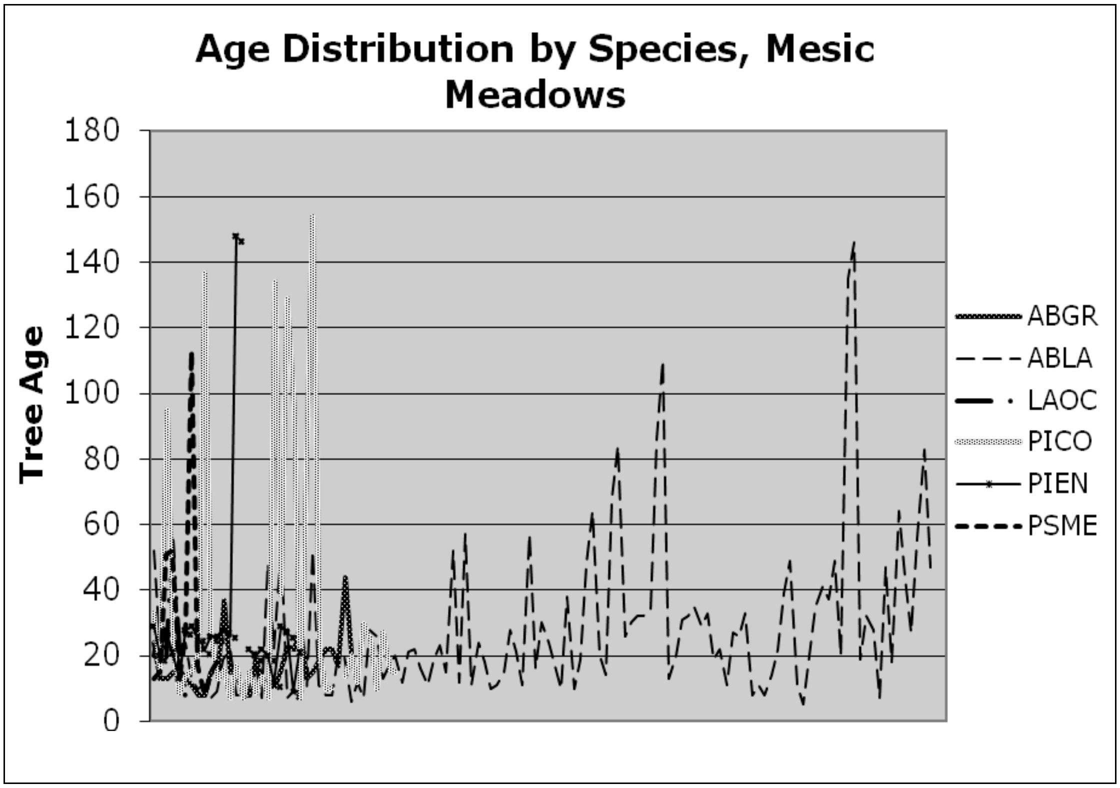

Figure 41. Age distribution of invading trees by species for all mesic meadow sites. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

Xeric Meadows

Spatial Patterns of Invasion

Figures 42, 43, 44, and 45 show that invasion has occurred in the three sampled xeric meadows in a much different fashion than in hydric and mesic meadows. No distinct spatial pattern, such as leap-and-fill or gradual invasion, is discernable from the aggregated histogram. This is supported by statistical analysis ($r = 0.01$, $p = 0.82$). There appears to be a slight increase in tree ages from the beginning of the transects (0 m) to the forest boundary, and then a slight decrease in age. When one looks at the

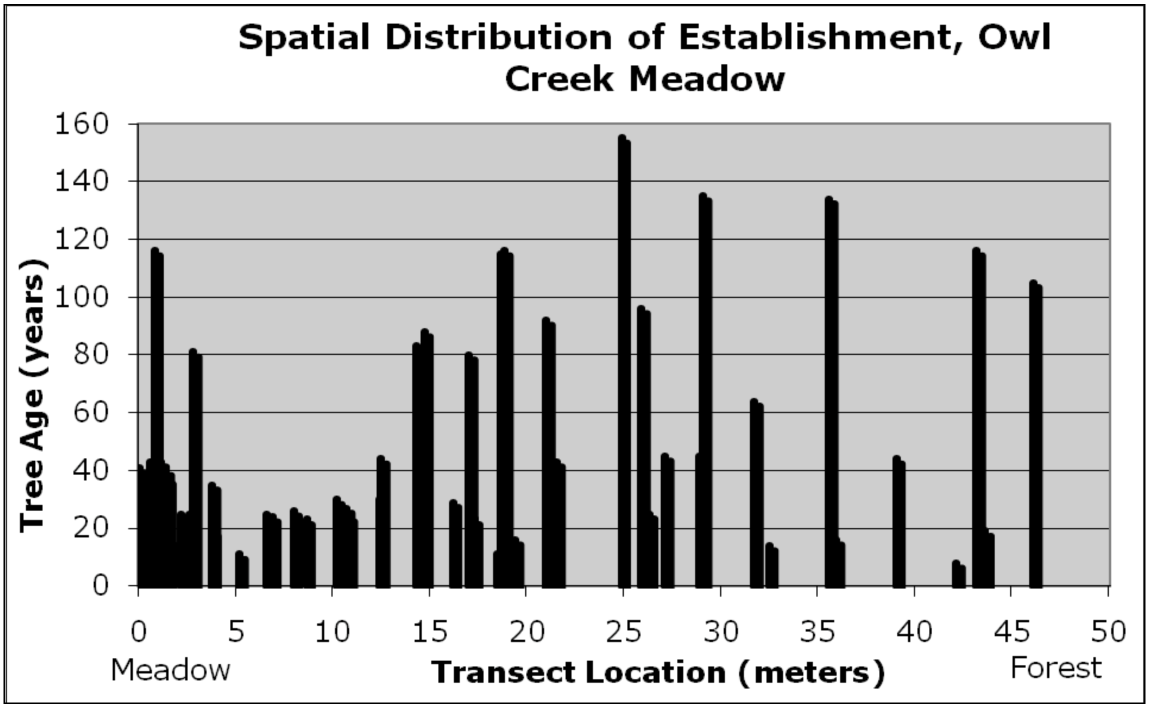

Figure 42. Graph illustrating spatial pattern of tree invasion for all transects at Owl Creek Meadow, a xeric meadow.

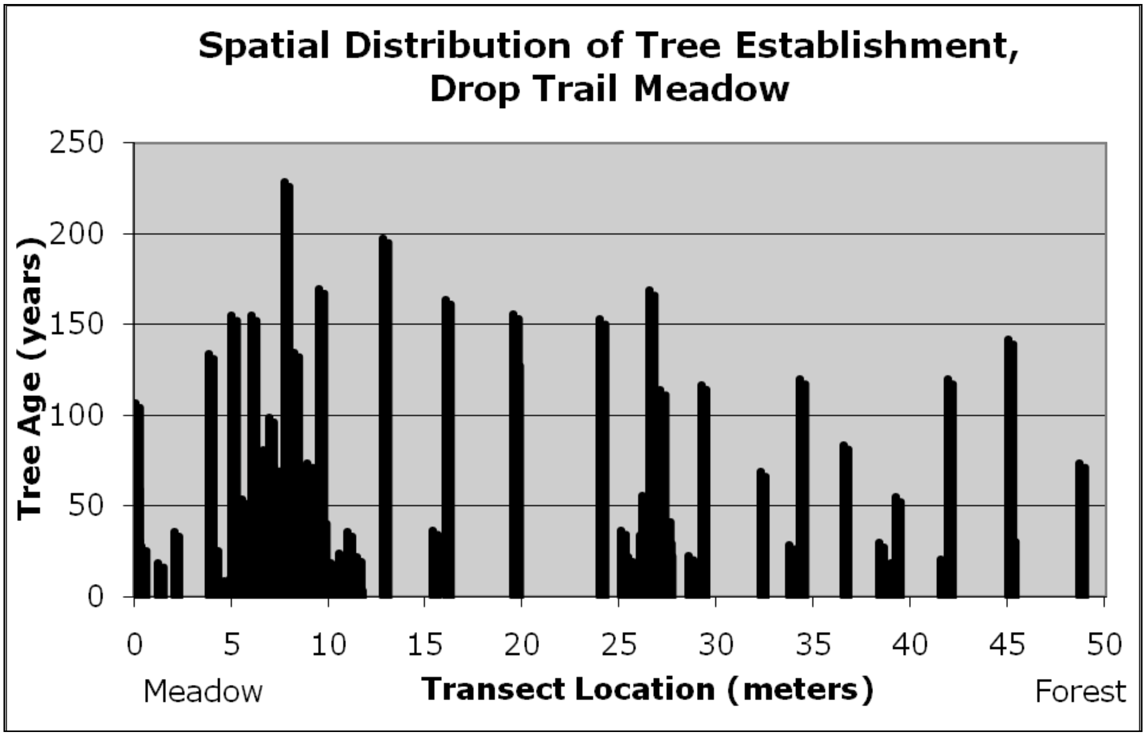

Figure 43. Graph illustrating spatial pattern of tree invasion for all transects at Drop Trail Meadow, a xeric meadow.

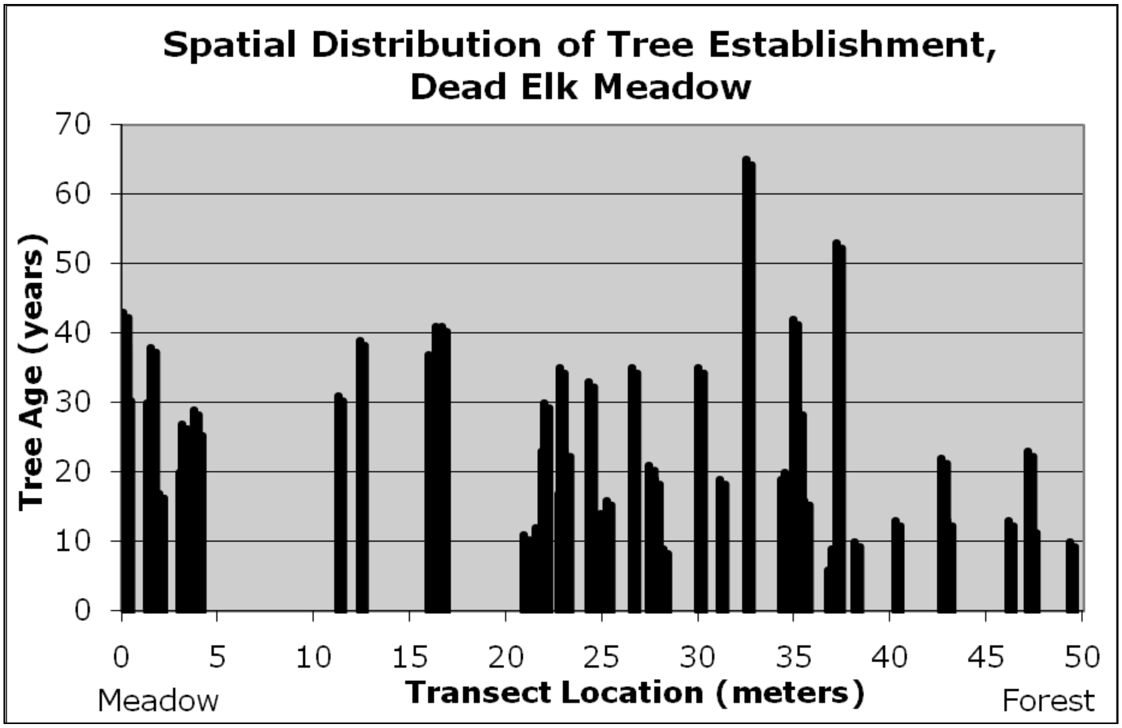

Figure 44. Graph illustrating spatial pattern of tree invasion for all transects at Dead Elk Meadow, a xeric meadow.

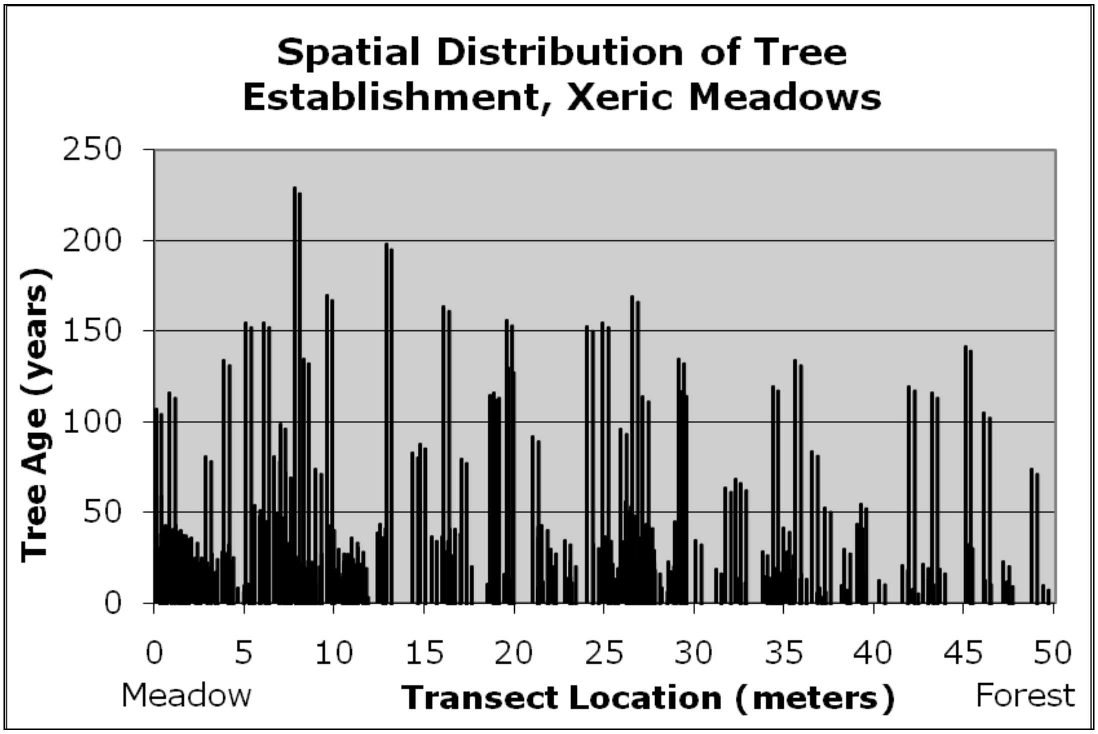

Figure 45. Graph illustrating spatial pattern of tree invasion aggregated for all xeric meadow sites.

histograms for each individual xeric meadow a more familiar and discernable pattern emerges. In Owl Creek Meadow and Drop Trail Meadow, tree age is high at the beginning of the transects, decreases, than increases again, as occurs in the leap-and-fill pattern discussed in the hydric and mesic meadows (Normal & Taylor, 2005). Despite this appearance, there is not a statistically significant relationship between tree age and location in Owl Creek ($r = 0.13$, $p = 0.19$) or Drop Trail Meadow ($r = 0.21$, $p = 0.10$). Looking at the histogram, a leap-and-fill pattern does not appear to exist in Dead Elk Meadow. This is supported by statistical analysis ($r = 0.43$, $p = 0.00$). These r and p values indicate a gradual pattern of invasion occurring. In xeric meadows, we do not see soil disturbance or microtopography facilitating invasion, as we do in the other meadow types, but rather forest edge effects being more important to invasion.

Despite the fact that a spatial pattern of invasion may be difficult to detect from Figure 45, it does appear as though some level of invasion is occurring in these meadows when one reviews Figures 46, 47, and 48. Although it is difficult to see small trees in the airphotos, more trees are visible in the meadows in the 2006 airphotos than in the 1954 airphotos, especially in Figure 46.

Temporal Patterns of Invasion

The temporal pattern of tree invasion in xeric meadows can be observed in Figures 49, 50, 51, and 52. As was the case in previous meadows, invasion rates in Owl Creek, Drop Trail, and Dead Elk meadows tended to increase in the late 20th century. When viewing the aggregated data for xeric meadows, we see a pattern similar to what was found in hydric and mesic meadows. After 1959, we see a pattern that closely resembles the temporal pattern of invasion in hydric and mesic meadows: an increase in

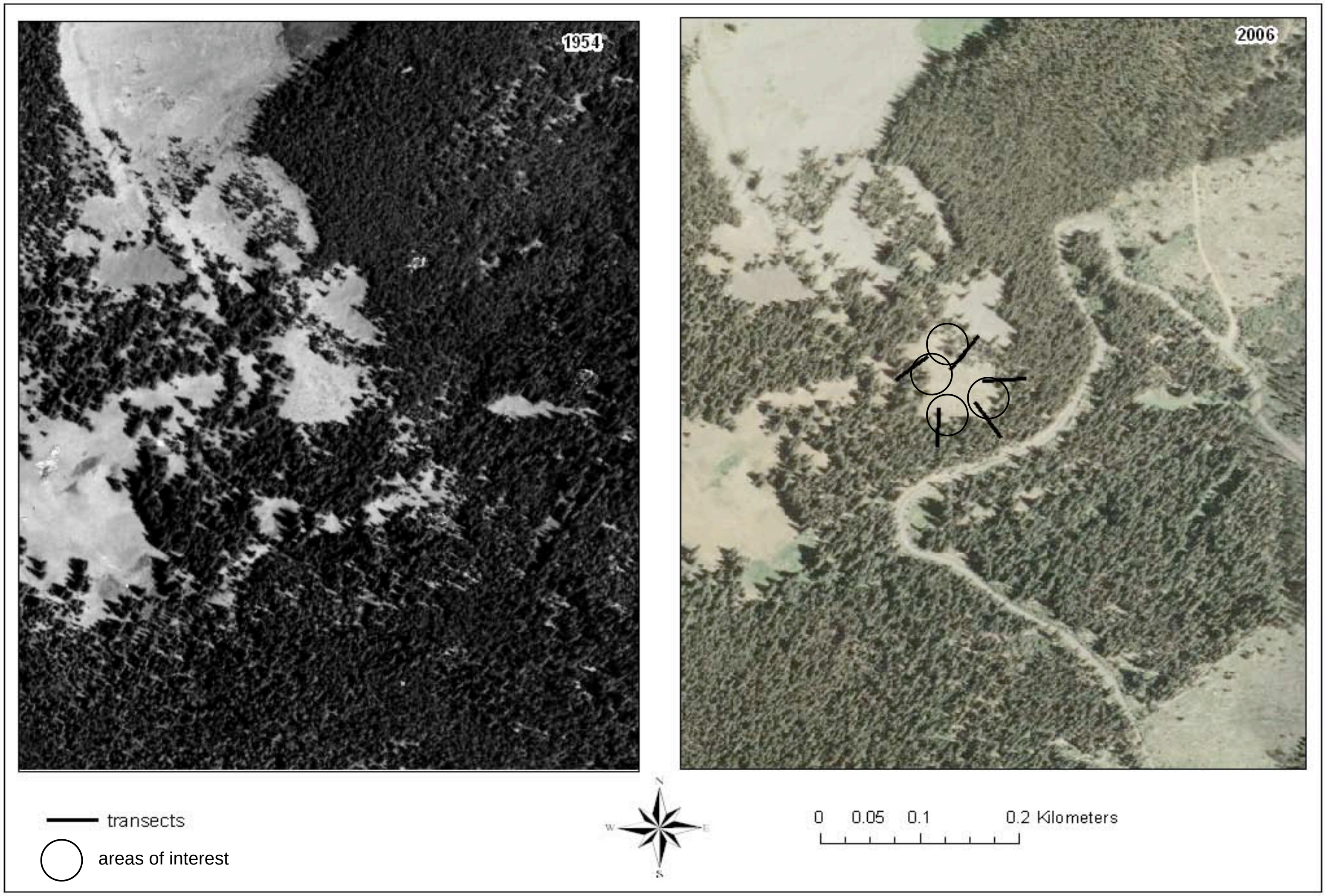

Figure 46. Airphotos of Owl Creek Meadow, 1954 and 2006.

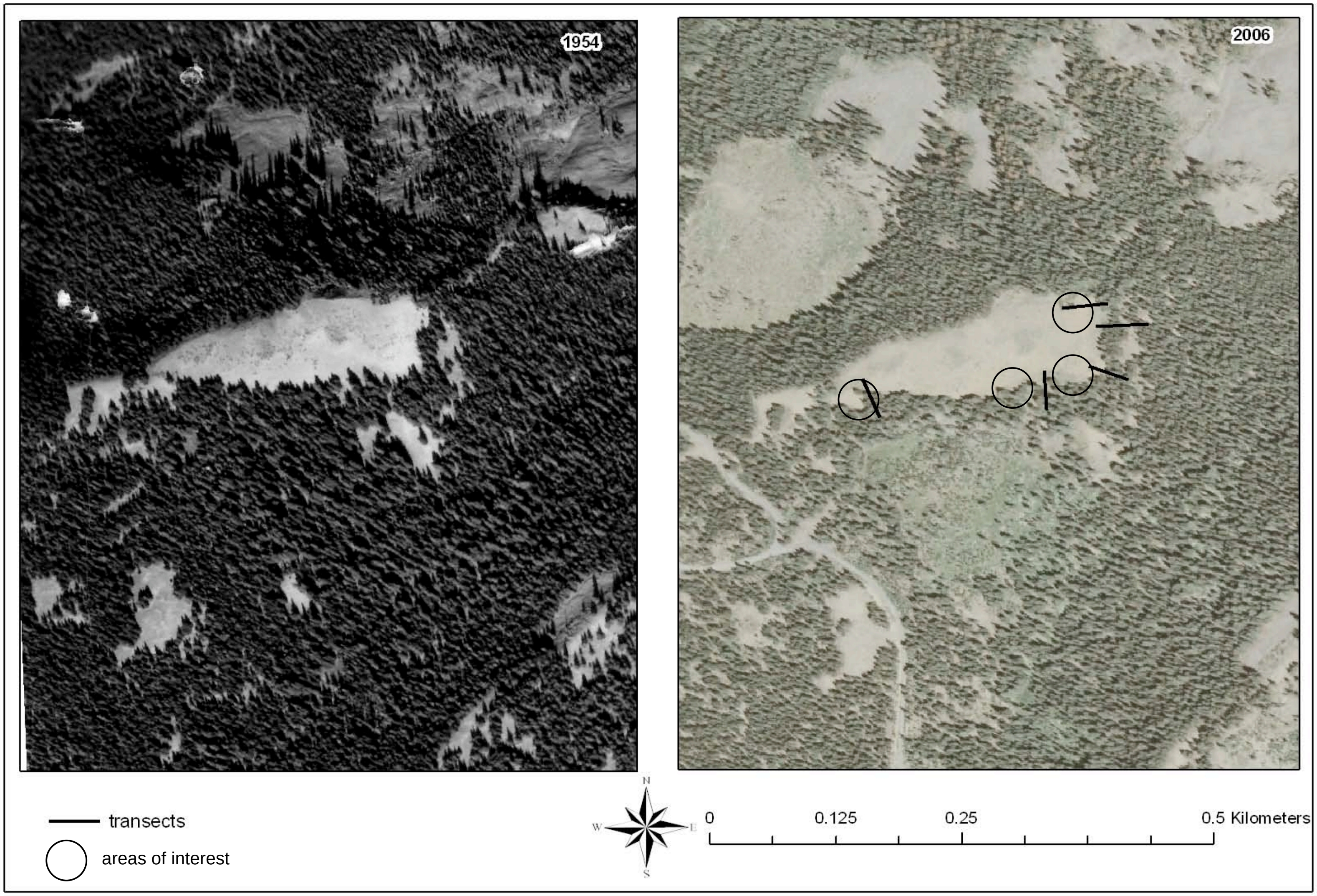

Figure 47. Airphotos of Drop Trail Meadow, 1954 and 2006.

Figure 48. Airphotos of Dead Elk Meadow, 1954 and 2006.

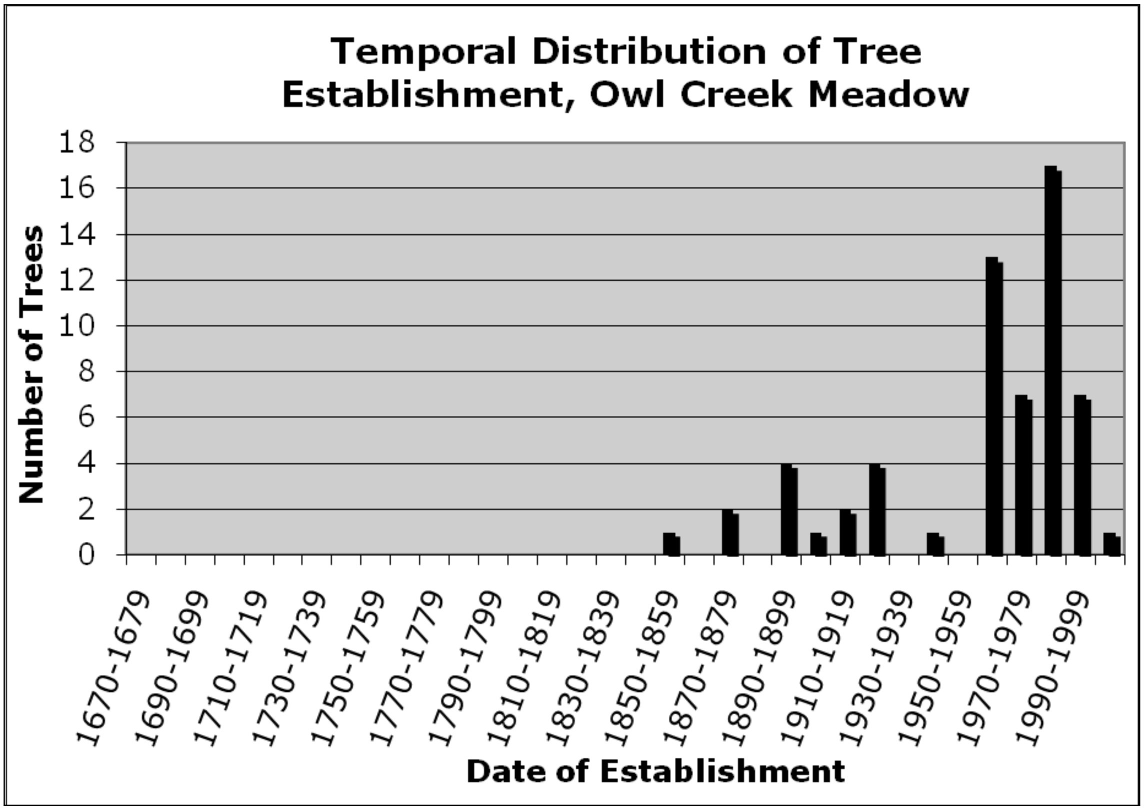

Figure 49. Temporal pattern of tree invasion for Owl Creek Meadow, a xeric meadow.

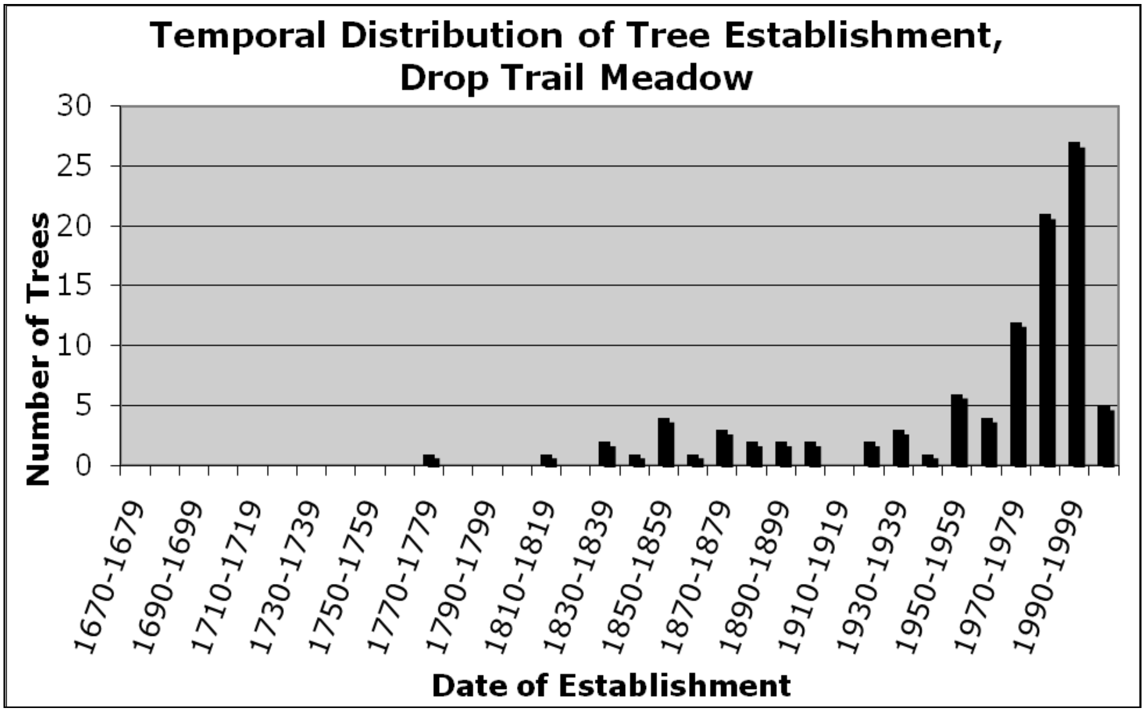

Figure 50. Temporal pattern of tree invasion for Drop Trail Meadow, a xeric meadow.

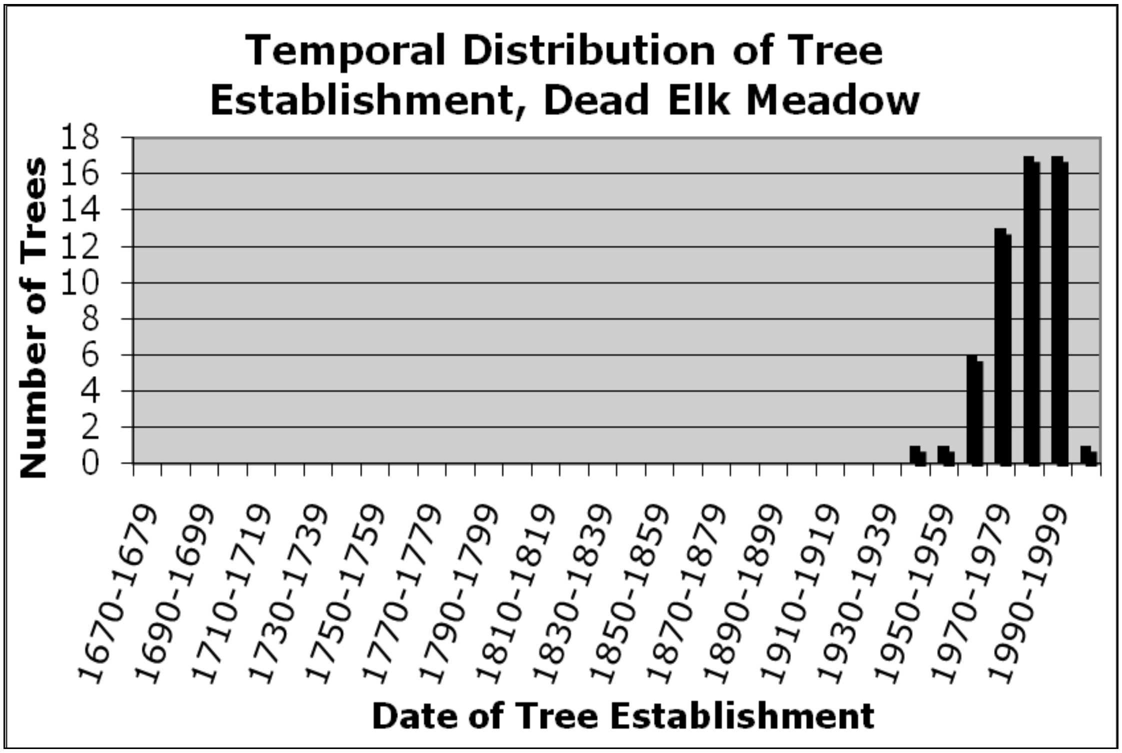

Figure 51. Temporal pattern of tree invasion for Dead Elk Meadow, a xeric meadow.

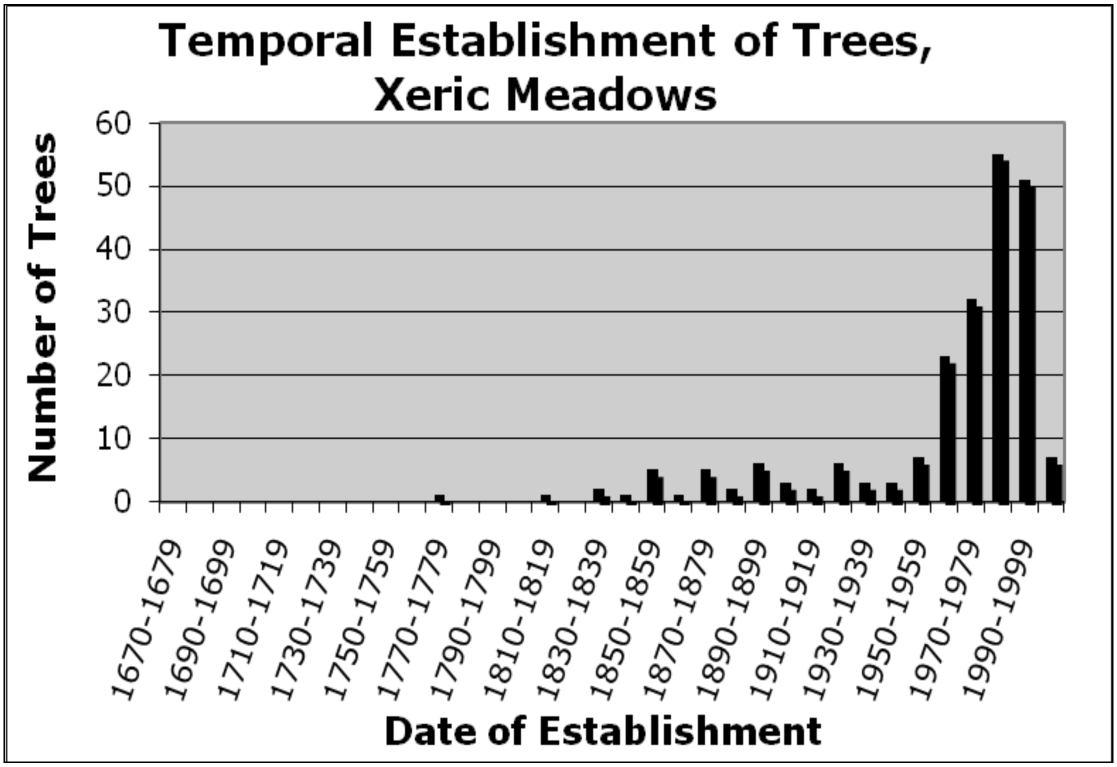

Figure 52. Temporal pattern of tree invasion aggregated for all xeric meadow sites.

tree invasion after this period, with the highest peaks occurring from 1970 to 1999. No significant difference in the temporal pattern of invasion exists between xeric meadows and hydric meadows ($r = 0.10$, $p = 0.15$), and xeric meadows and mesic meadows ($r = 0.21$, $p = 0.10$). This pattern is present in all the xeric meadows sampled, in addition to the aggregated xeric meadow data. As is the case with hydric and mesic meadows, this pattern is likely the result of changes in climate, fire regime, and/or land use altering environmental conditions of the meadow, making these sites more suitable for invasion (Coop & Giivnish, 2007; Miller & Halpern, 1998; Woodward et al., 1995). This idea will be explored in more detail in the following section of this chapter. Additionally, masting patterns may have an impact on the temporal pattern of invasion seen in these meadows.

Species Patterns of Invasion

Subalpine fir, grand fir, lodgepole pine, Douglas fir, and Pacific silver fir were all found within the xeric meadows of the upper Naneum watershed. As can be seen in Figures 53, 54, 55, and 56, most of the trees sampled in the xeric meadows were subalpine fir. Subalpine fir was also the oldest trees found within xeric meadows (see Figure 57). Subalpine fir is likely the oldest and most abundant trees within these meadow systems because of the elevation range these trees prefer, and their ability to tolerate drought (Miller, 1995). A very few grand fir, lodgepole pine, and Douglas fir were also present. Surprisingly, one Pacific silver fir was found growing near a spring in one of the meadows. The silver fir probably would not have been able to tolerate the conditions of a xeric meadow had it not been for the spring. No larches or Engelmann spruce were found in any of the xeric meadows sampled for this study. There is no significant difference in invading species between meadow types.

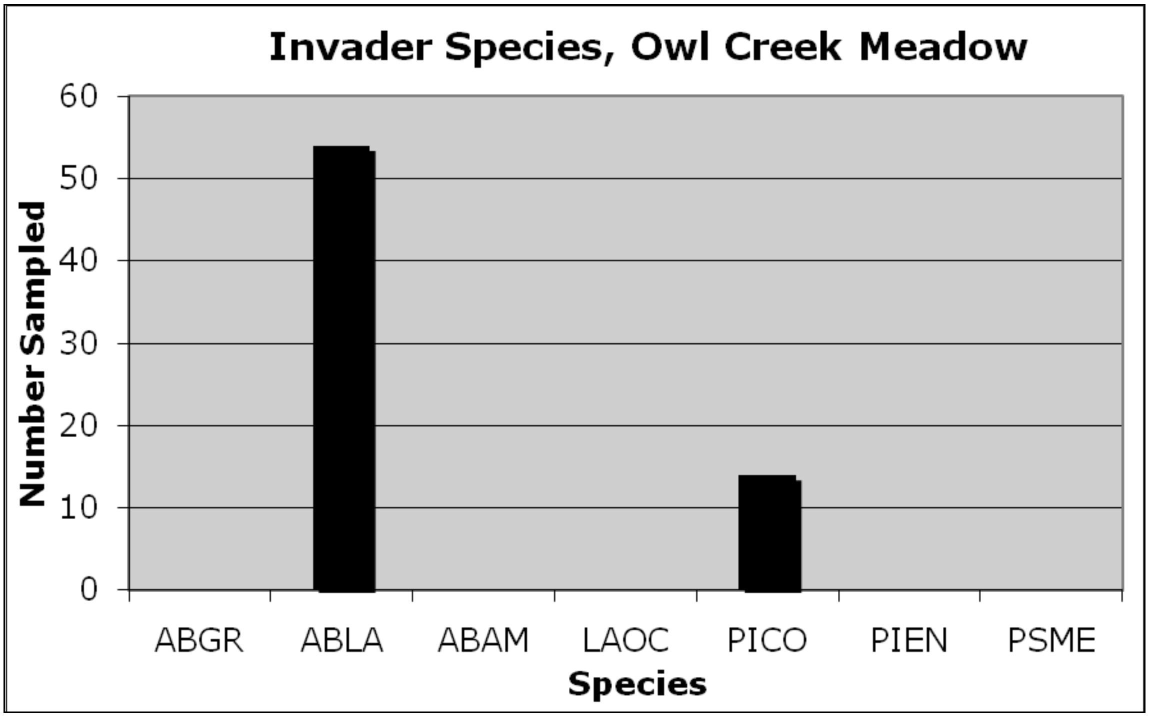

Figure 53. Invading tree species of Owl Creek Meadow, a xeric meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

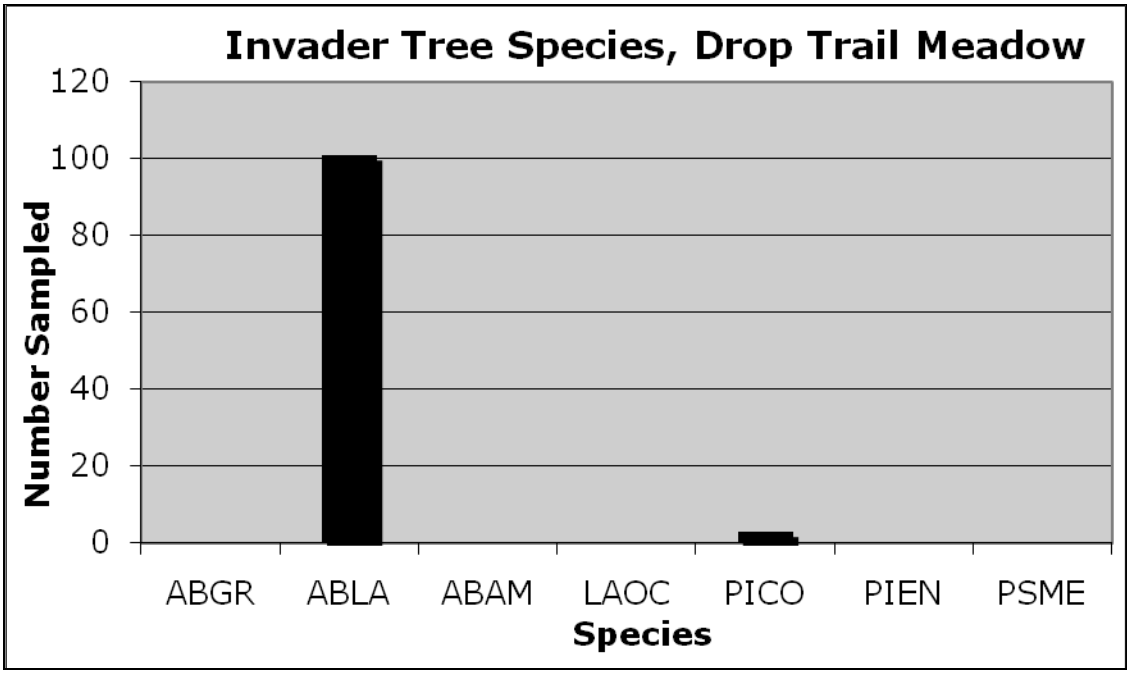

Figure 54. Invading tree species of Drop Trail Meadow, a xeric meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

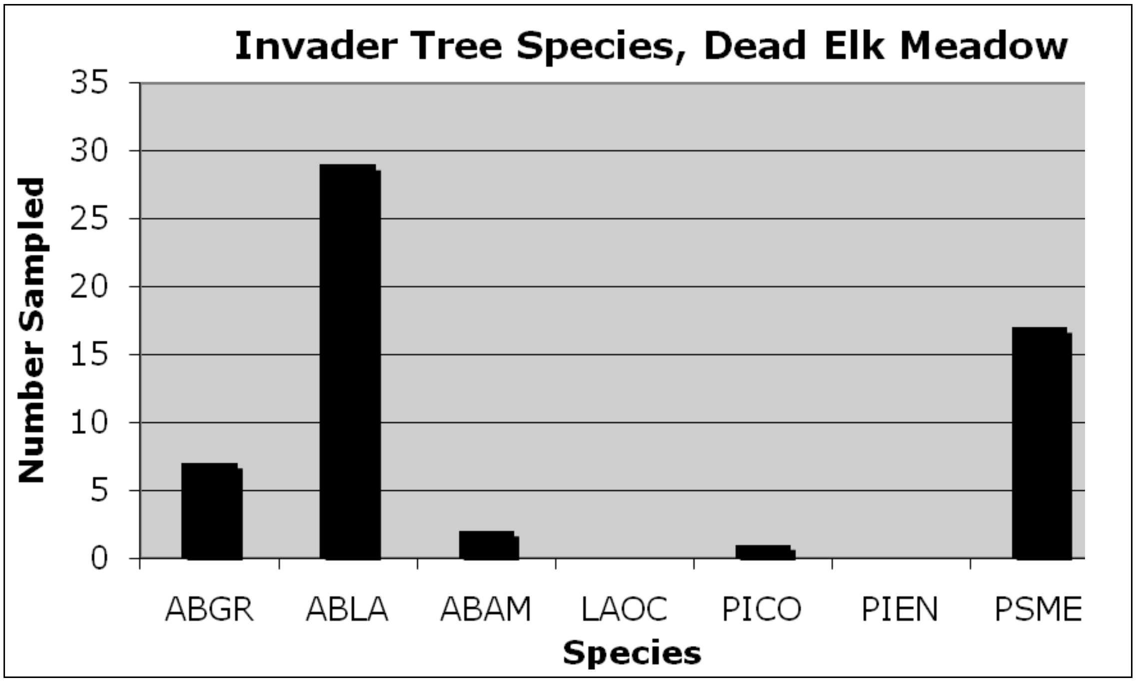

Figure 55. Invading tree species of Dead Elk Meadow, a xeric meadow. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

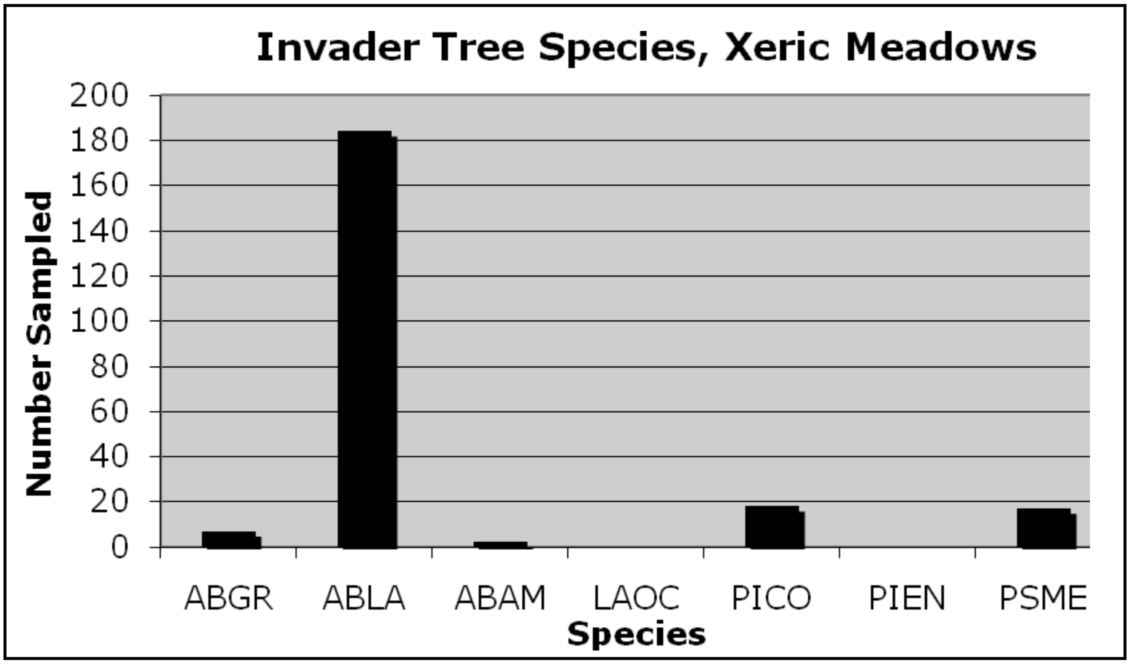

Figure 56. Invading tree species data aggregated for all xeric meadow sites. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

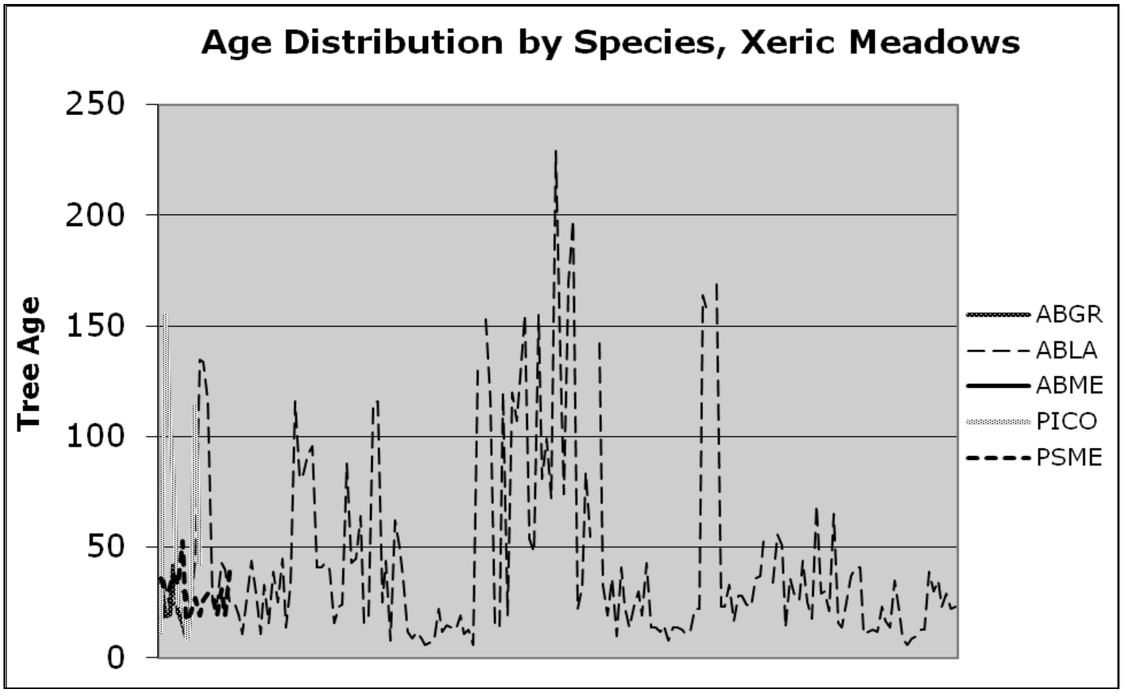

Figure 57. Age distribution of invading trees by species for all xeric meadow sites. ABGR = *Abies grandis* or grand fir; ABLA = *Abies lasiocarpa* or subalpine fir; ABAM = *Abies amabilis* or Pacific silver fir; LAOC = *Larix occidentalis* or larch; PICO = *Pinus contorta* or lodgepole pine; PIEN = *Picea engelmannii* or Engelmann spruce; PSME = *Pseudotsuga menziesii* or Douglas fir.

Possible Causes of Invasion

Hydric Meadows

To examine the possible causes of invasion, many climate and land use variables were compared with frequency of tree establishment per year. The results indicate that there may be a moderately strong relationship between various climate, land use, and fire conditions and tree invasion.

Several climatic factors have a positive relationship with the timing of tree invasion in the hydric meadows of the study area, although there appeared to be no relationship between tree establishment in hydric meadows and annual precipitation, growing season precipitation, annual average temperature, growing season temperature, maximum annual temperature and minimum annual temperature. PDO patterns have a somewhat strong positive correlation with the timing of tree establishment (see Table 6). This means that when the PDO is in its positive cycle, creating warmer, drier climatic conditions in the Pacific Northwest, tree establishment tended to increase. PDSI values also appear to have a relationship with tree invasion in hydric meadows (Table 6). PDSI has a moderate correlation with tree establishment dates, meaning the higher the PDSI value, the higher tree invasion tends to be. This is similar to what Woodward et al. (1995) found in the eastern Olympic Mountains of Washington State. This research found that tree establishment increased in years of above average, dry, PDSI, indicating soil moisture and snow depth likely are determinants for tree invasion (Woodward et al., 1995). April 1 snow depth and snow water equivalence correlate with tree establishment in hydric meadows, but negatively rather than positively. This means that in lower snow years, tree establishment was higher. This is similar to what Rochefort and Peterson (1996) found at Mt. Rainer and what Woodward et al. found in the eastern Olympics. Apparently, trees are better able to establish in these wet settings, where ample water is available throughout most of the growing season, when the growing season is longer, and not hampered by lingering snow. The relationships found with PDSI and PDO might exist because snow pack is often low in years of high PDO values and high PDSI values. The lack of a relationship between tree establishment in hydric meadows and annual precipitation, growing season precipitation, annual average temperature, growing season temperature, maximum annual temperature and minimum annual temperature indicates that temperature and precipitation play a less important role in tree establishment than snow pack.

Table 6

Spearman Rank Correlation Test Values for Climate, Land Use, and Fire Variables and Establishment in Hydric Meadows

SV	Annual precip	GS precip	Average annual temp	GS temp	Average maximum temp	Average minimum temp	PDO	PDSI	Average annual snow depth	Average annual SWE	Cattle permits	Fire return interval
r	0.02	0.13	0.03	0.03	0.06	0.00	0.50	0.33	−0.47	−0.37	−0.51	0.50
p	0.88	0.35	0.83	0.84	0.64	0.99	0.00	0.02	0.00	0.01	0.00	0.00
n	110	110	110	101	110	110	104	109	58	58	82	98

Note. SV = statistical values; precip = precipitation; GS = growing season; temp = temperature; PDO = Pacific Decadal Oscillation; PDSI = Palmer Drought Severity Index; SWE = snow water equivalent.

The land use factor of grazing appears to have a significant impact on tree invasion in hydric meadows. The Spearman rank test showed a moderately strong negative relationship between head of cattle allotted for grazing and the timing of tree invasion (Table 6). Apparently, with decreased levels of grazing, tree invasion tended to increase. This aligns with the findings of Coop and Givnish (2007), Hadley (1999), Miller and Halpern (1998), and Norman and Taylor (2005). Invasion likely increases with decreased grazing because trampling and browsing may prevent trees from establishing within meadows (Coop & Givnish; Hadley; Miller & Halpern; Norman & Taylor).

Several other land use changes appear to coincide with peaks in tree invasion (see Figure 58). There appears to be a general increase in the level of tree invasion that occurred around the time of European American settlement in the area. This increase in tree establishment could be related to an increase in fire suppression, or greater resource extraction activities occurring because of the influx of a new population (Hadley, 1999). It may also be related to changes in Native American use of meadows. Also, a small peak in establishment coincides and follows the establishment of the Forest Reserve, and thus the regulation of grazing, which occurred in the 1890s. This likely is because tree establishment tends to increase when grazing decreases. Additionally, in other parts of the Cascades ranchers often burned meadows to enhance vegetation before the grazing was regulated (Taylor, 1990). This practice ceased after the creation of the Forest Reserves (Taylor). Finally, we see a peak in tree establishment in hydric meadows from 1970 onward, as recreation became a more pronounced land use. This could be the result

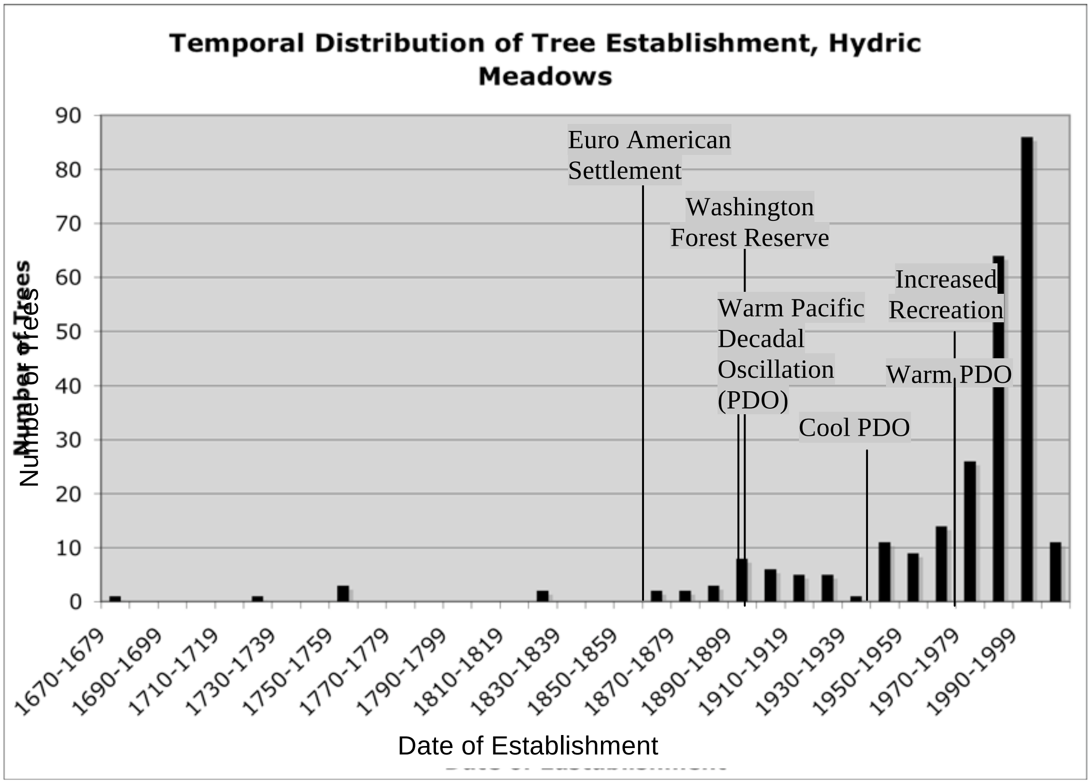

Figure 58. Temporal distribution of tree establishment in hydric meadows compared to significant climate and land use changes.

of changes in grazing and other resource extraction practices that occurred as a result of increased recreation, and thus changes in forest values.

The Spearman rank test reveals that fire return interval, as determined by Wright (1996), has a moderately strong relationship with the timing of tree establishment in hydric meadow systems (Table 6). This means that as fires became less frequent on the landscape, tree establishment in hydric meadows increased. This is similar to what has been found elsewhere in the Cascades (Hadley, 1999; Miller & Halpern 1998; Norman & Taylor, 2005). Fire has been recognized as a meadow maintenance factor because fires enhance meadow vegetation, while destroying tree seedlings and saplings that move into these areas (Coop & Givnish, 2007; Hadley).

Mesic Meadows

The results of the correlation tests, comparing the number of trees establishing per year with various climate, fire, and land use variables, indicate that there may be a moderately strong relationship between these variables and tree invasion in mesic meadows. Several climatic factors appear to be important for invasion in mesic meadows, although no relationship was found between tree establishment in hydric meadows and annual precipitation, growing season precipitation, annual average temperature, growing season temperature, maximum annual temperature and minimum annual temperature. There appears to be a strong positive correlation between tree establishment in mesic meadows and PDO values (see Table 7). Thus, when the PDO is creating warm and dry conditions, invasion increases, much like in hydric meadows. Snow depth and snow water equivalence on April 1 also correlate with the timing of tree invasion. These correlations are moderate, negative correlations. This means that when snow pack is lower, tree invasion tends to increase. As is the case in hydric meadows, this is likely related to growing season. During high snow years, when meadow margins are generally snow covered until early summer, trees are less likely to establish in the mesic meadows. There may be weaker correlation values between snow and invasion than what was found in hydric meadows because water is less available in these mesic systems, so in extremely low snow years there may be less tree establishment. This might also explain why no relationship was found between timing of invasion in mesic meadows and PSDI values. An alternate explanation for the lower snow/invasion values might be that mesic meadows tend to inhabit steeper slopes, where snow accumulation may not be as deep and/or snow may melt off faster because of sun angle.

Table 7

Spearman Rank Correlation Test Values for Climate, Land Use, and Fire Variables and Establishment in Mesic Meadows

SV	Annual precip	GS precip	Average annual temp	GS temp	Average maximum temp	Average minimum temp	PDO	PDSI	Average annual snow depth	Average annual SWE	Cattle permits	Fire return interval
r	0.04	0.05	−0.11	0.03	−0.11	−0.08	0.44	0.19	−0.34	−0.25	−0.54	0.31
p	0.75	0.72	0.43	0.83	0.43	0.57	0.00	0.16	0.01	0.06	0.00	0.00
n	110	110	110	101	110	110	104	109	58	58	82	98

Note. SV = statistical values; precip = precipitation; GS = growing season; temp = temperature; PDO = Pacific Decadal Oscillation; PDSI = Palmer Drought Severity Index; SWE = snow water equivalent.

Cattle grazing appears to have an impact on the timing of tree invasion in mesic meadows, as well as hydric meadows. A moderately strong negative correlation between heads of cattle grazing and the timing of tree invasion (Table 7): as grazing decreased tree establishment increased. The reasons for this increase are likely the same as in hydric meadows. Cattle likely prevent trees from establishing in mesic meadows because they trample and browse seedlings and saplings (Coop & Givnish, 2007; Hadley, 1999; Miller & Halpern, 1998; Norman & Taylor, 2005). Other land use changes that might have also impacted the timing of tree establishment include the establishment of the Forest Reserve, which altered the grazing management regime, and the increase in recreational uses of the forest. Both of these land use changes corresponded with peaks in tree establishment (see Figure 59).

In addition to climate and land use having an impact on the timing of tree establishment in mesic meadows, it appears as though fire return interval influences tree establishment in these systems. A moderate correlation was found between the timing of tree establishment and fire return intervals (Table 7). As fires have decreased in frequency because of fire suppression activities, tree invasion has increased. As hypothesized by many other scholars, this can be attributed to fire enhancing meadow vegetation, thus increasing competition between meadow and forest vegetation, in addition to killing seedlings and saplings in that have established in meadows (Hadley, 1999; Miller & Halpern 1998; Norman & Taylor, 2005).

Xeric Meadows

The results of the correlation tests are somewhat different for the xeric meadows than for the hydric and mesic meadows of the upper Naneum watershed. A moderately

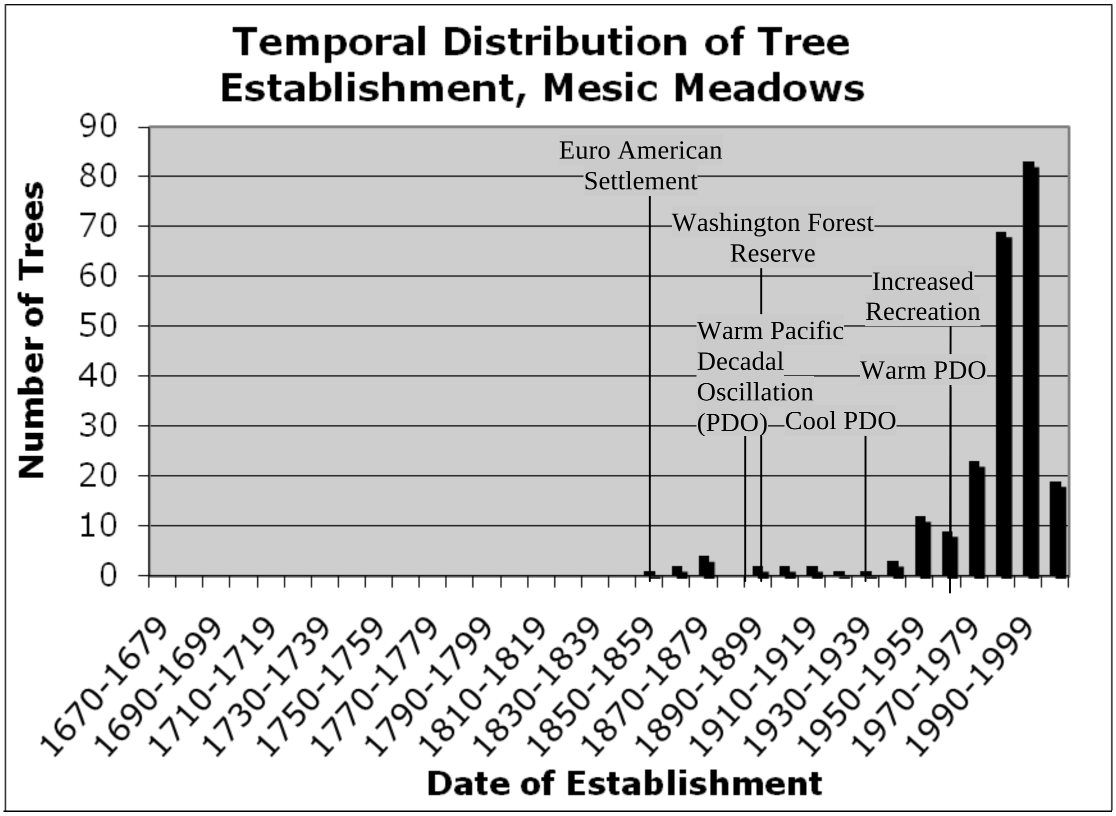

Figure 59. Temporal distribution of tree establishment in mesic meadows compared to significant climate and land use changes.

strong positive correlation between PDO and timing of tree establishment was found (see Table 8). Additionally, a positive correlation between PDSI and tree establishment was found. Both of these correlations indicate that tree establishment was higher during warm, dry years. It was a bit surprising to find this correlation with PDSI being that there was no significant relationship between PDSI and tree establishment in mesic meadows. My assumption was that trees were less likely to establish in mesic meadows in drought years because water is a limiting factor during the growing seasons, despite the lower snow pack and longer growing season. Given this, I was expecting to see the same pattern in xeric meadows.

Table 8

Spearman Rank Correlation Test Values for Climate, Land Use, and Fire Variables and Establishment in Xeric Meadows

SV	Annual precip	GS precip	Average annual temp	GS temp	Average maximum temp	Average minimum temp	PDO	PDSI	Average annual snow depth	Average annual SWE	Cattle permits	Fire return interval
r	−0.01	0.01	0.01	−0.08	0.04	−0.04	0.44	0.34	−0.26	−0.19	−0.54	0.18
p	0.97	0.92	0.97	0.56	0.75	0.75	0.00	0.01	0.06	0.18	0.00	0.00
n	110	110	110	101	110	110	104	109	58	58	82	98

Note. SV = statistical values; precip = precipitation; GS = growing season; temp = temperature; PDO = Pacific Decadal Oscillation; PDSI = Palmer Drought Severity Index; SWE = snow water equivalent.

A negative correlation was found between snow depth and timing of tree establishment. This again shows the importance of snow pack for meadow maintenance by limiting the growing season on meadow margins (Rochefort & Peterson, 1996). One striking difference between xeric meadows and hydric and mesic meadows is that, unlike the other meadow types, there was no correlation between snow water equivalence on April 1 and the timing of tree establishment. This was likely because of the close relationship between PDO, snow water equivalence, and snow depth. I am unsure why this pattern does not hold in xeric meadows. As was the case in hydric and mesic meadows, no relationship was found between tree establishment and annual precipitation, growing season precipitation, annual average temperature, growing season temperature, maximum annual temperature and minimum annual temperature in mesic meadows.

As was the case with hydric and mesic meadows, grazing practices impact the timing of tree establishment in xeric meadows. The results of the Spearman rank test show a moderately strong negative correlation between the numbers of cattle permitted to graze within the study area and the timing of tree establishment (Table 8). This is similar to what has been found in other studies in the Cascades and American Rocky Mountains, and has been attributed to trampling and browsing actives by livestock (Coop & Givnish, 2007; Hadley, 1999; Miller & Halpern, 1998; Norman & Taylor, 2005). There have been other land use changes that might also have impacted tree invasion. There appears to be a slight increase in tree establishment after the arrival of European Americans to the area in the mid-19th century (see Figure 60). This likely occurred because of changes in resource extraction patterns and changes in the fire interval (Hadley; Taylor, 1990). Additionally, a peak in tree establishment was found that corresponded with the creation

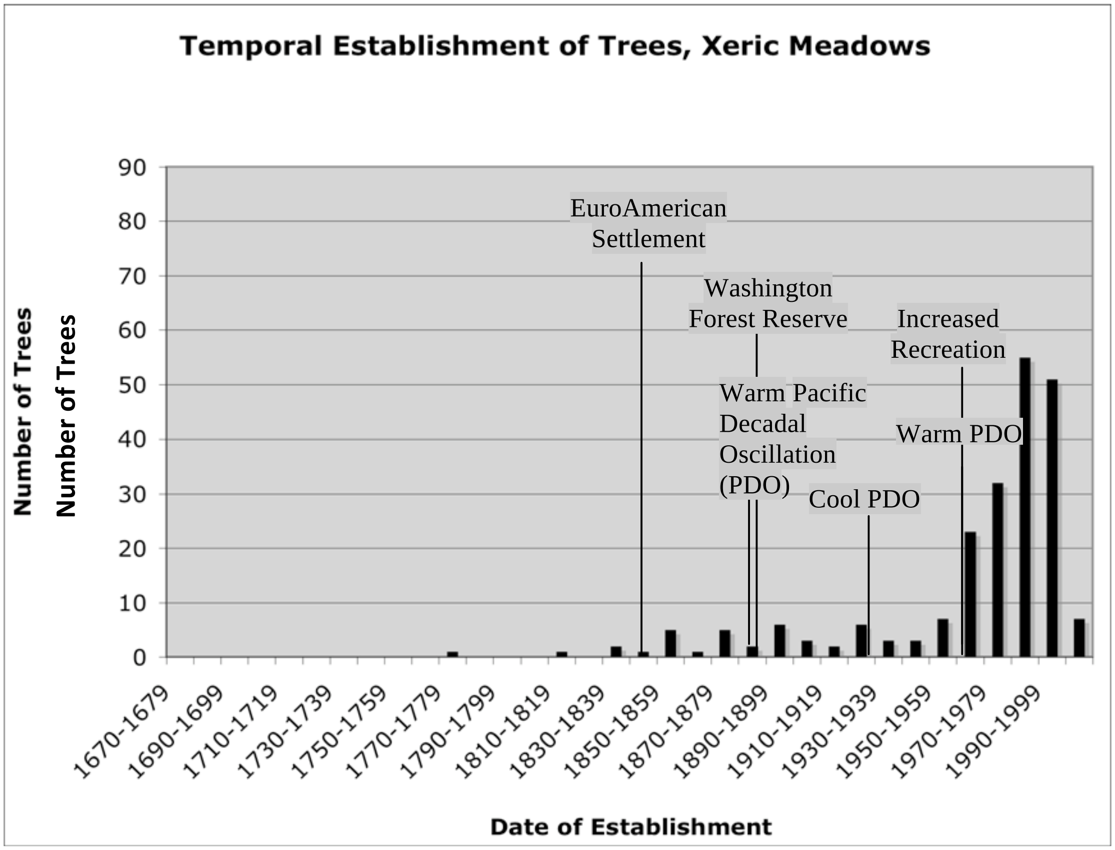

Figure 60. Temporal distribution of tree establishment in xeric meadows compared to significant climate and land use changes.

of the Forest Reserve and the regulation of grazing. Finally, the large peak in tree establishment appears to coincide with the increase in recreation in the National Forest, which occurred with increased road access (USFS, 1995). This could be the result of changes in grazing and resource extraction that occurred as more people began to visit these areas.

Although a positive correlation was found between tree establishment in xeric meadows and fire return intervals, this correlation was much weaker than the ones found in mesic and hydric meadow systems (Table 8). There could be several factors behind this phenomenon. In more dry settings, meadow vegetation may take longer to re-establish following a fire because of fire intensity. This could weaken the competition that usually exists between meadow/forest vegetation after a fire, which is often credited for decreasing invasion levels. Additionally, lower fuel in these systems could contribute to this. Regardless, the increased fire intervals that have resulted from fire suppression do coincide with an increase in tree establishment in xeric meadows.

CHAPTER VI

CONCLUSION, MANAGEMENT RECOMMENDATIONS, AND FUTURE RESEARCH

Conclusion

Meadows are dynamic features of mountain landscapes that have been utilized and valued by people for thousands of years. Because of this, the recent decline of meadows throughout the western United States is somewhat alarming. The upper Naneum watershed of Kittitas County, Washington is no exception. Here tree invasion has been reported by the USFS (1995) and confirmed by this research.

The purpose of this research was to examine the particulars of tree invasion within the upper Naneum. The objectives were to, first, document the spatial distribution of meadows. By doing this, I found the meadows inhabit a wide range of areas within the study area. I also discovered that the aspect and elevation of meadows did not vary considerably based on meadow moisture regime, although slope and landscape positions did. The second objective was to examine the temporal, spatial, and species patterns of invasion for hydric, mesic, and xeric meadows systems. By doing this, I found that leap-and-fill was the general pattern by which trees invaded meadows. Additionally, tree invasion in all meadow types tended to increase considerably since 1970, and subalpine fir was the greatest invader species, although some variation in this occurred between meadow types. The third objective was to determine how climate, land use, and fire return interval impacted the timing of tree invasion in hydric, mesic, and xeric meadows. Low snow pack, decreased grazing, and increased fire return intervals all led to increased invasion in all meadow types. As discussed in chapter V, this is likely because high snow pack, livestock grazing, and fire are meadow maintenance factors. Variables that did not seem to correlate with tree invasion were annual precipitation, growing season precipitation, and temperature.

In the course of this research, I was hoping to find striking differences in when and how invasion occurred in different meadow types. I had hypothesized that moisture was the limiting factor in these meadow types, therefore, changes in climate would impact invasion differently by meadow type. For example, I was expecting that in years with high PDSI values, invasion might increase in hydric meadows and decrease in xeric meadows. I did not find such patterns. This means that there are likely more factors limiting tree establishment in meadows then I had originally speculated. Rather than soil moisture being the sole factor of meadow existence, it is likely a combination of factors relating to disturbance regimes, such as fire and grazing, climate, and growing season length at high altitudes, which is why high snow pack likely decreases invasion. Also, the complex interplay between factors that influence snow accumulations, such as vegetation patterns, slope, aspect, and wind patterns, likely plays a role in meadow formation and maintenance.

One important finding of this research is how tree invasion occurs in the eastern slopes of the Cascade Mountains. Beforehand, little to no research had been done in the eastern Cascades. Since vegetation and climate is very different in the eastern Cascades as compared with the western Cascades, it was important to understand how invasion differed, if at all, in this setting. The findings of this study tend to corroborate findings from the western Cascades, as well as findings from the Rocky Mountains. In all areas, snow pack, grazing, and fire return interval seems to be primary factors influencing invasion patterns.

Given the importance of snow pack in meadow maintenance, tree invasion into mountain meadows will probably continue to increase in the coming decades, as global climate change brings lower snow packs to the mountains of the Pacific Northwest (Climate Impacts Group, 2009). Unfortunately, there is little that can be done in meadow management to prevent this decline in snow pack, and thus in meadows. Considering the current rate of invasion, if no action is taken, the mountain landscape could look very different in the future.

Meadow Management Recommendations for the Upper Naneum Watershed

Given the findings of this study, tree invasion in all meadow types of the upper Naneum watershed will likely continue. Over the past 30 years, tree establishment has increased considerably. Additionally, with the importance of high snow packs, decreased grazing, and low fire return intervals for meadow maintenance in all meadow types, this trend is not likely to change. Without changes in grazing and fire management policy, we will continue to see all types of mountain meadows, which are culturally and biologically important areas within mountain systems, decline in area on the landscape.

A variety of meadow management techniques are currently being employed throughout the Cascades. These techniques obviously vary based on specifics of degradation and different management goals. Management techniques include restoration plantings, prescribed burns, mechanically removing or cutting invading trees, and letting nature take its course (Griffiths et al., 2005; Rochefort & Gibbons, 1992; Taylor, 1990). The Wenatchee National Forest is managing meadows in the upper Naneum watershed with the goal of “improving range and ecological conditions of meadows” (USFS, 1995, p. 149). To achieve this goal, grazing exclosures have continued as well as noxious weed control and decreased grazing (USFS). In addition to current management practices, I would recommend prescribed burns of these meadow systems. If the fire regime was returned to the one that occurred before European American arrival, tree invasion into these systems may slow (Taylor). Although tree invasion would still likely occur with changing climatic conditions, increasing the number of low intensity fires in these systems may help preserve the meadows of the upper Naneum watershed.

Future Research

Other research that could be done to enhance the research conducted for this study include looking at the relationship between meadows and landforms, examining aerial photos of the same meadows over small time intervals, and studying how different management techniques might impact different meadow types.

Better understanding of how the spatial distribution of meadows relates to landforms would be a good addition to the analysis of the overall spatial distribution of meadows conducted in this study. It would be interesting to know if meadows are found more often on specific landforms. One could also find if different types of meadow are associated with different types of landforms; for example, if xeric meadows are more likely to be found on basalt benches as opposed to ridge tops.

In addition to enhancing the spatial distribution aspect of this study, work could be done to strengthen the portion of this research that examines the specific patterns of invasion. Research that examined the same meadows with aerial photos over shorter time intervals would also be interesting. This would help us better understand spatial patterns of invasion over time. Additionally, we could find how much meadows have changed over specific time periods. This might also shed some light on what areas of meadows are more susceptible to invasion, and why some areas of meadows remain unchanged. One weakness of my sampling was that I did not focus on sampling areas that were representative of the entire meadows. This weakness could also be addressed by examining the patterns of tree invasion with aerial photos.

Finally, to best manage different meadow systems, it is important that research be conducted to understand how different management techniques might impact different meadow types. With the current state of knowledge, it is difficult to say if and how these meadows should be managed differently. Gaining a better understanding of this would help managers prescribe the best management techniques for a meadow based on its specific environmental characteristics.

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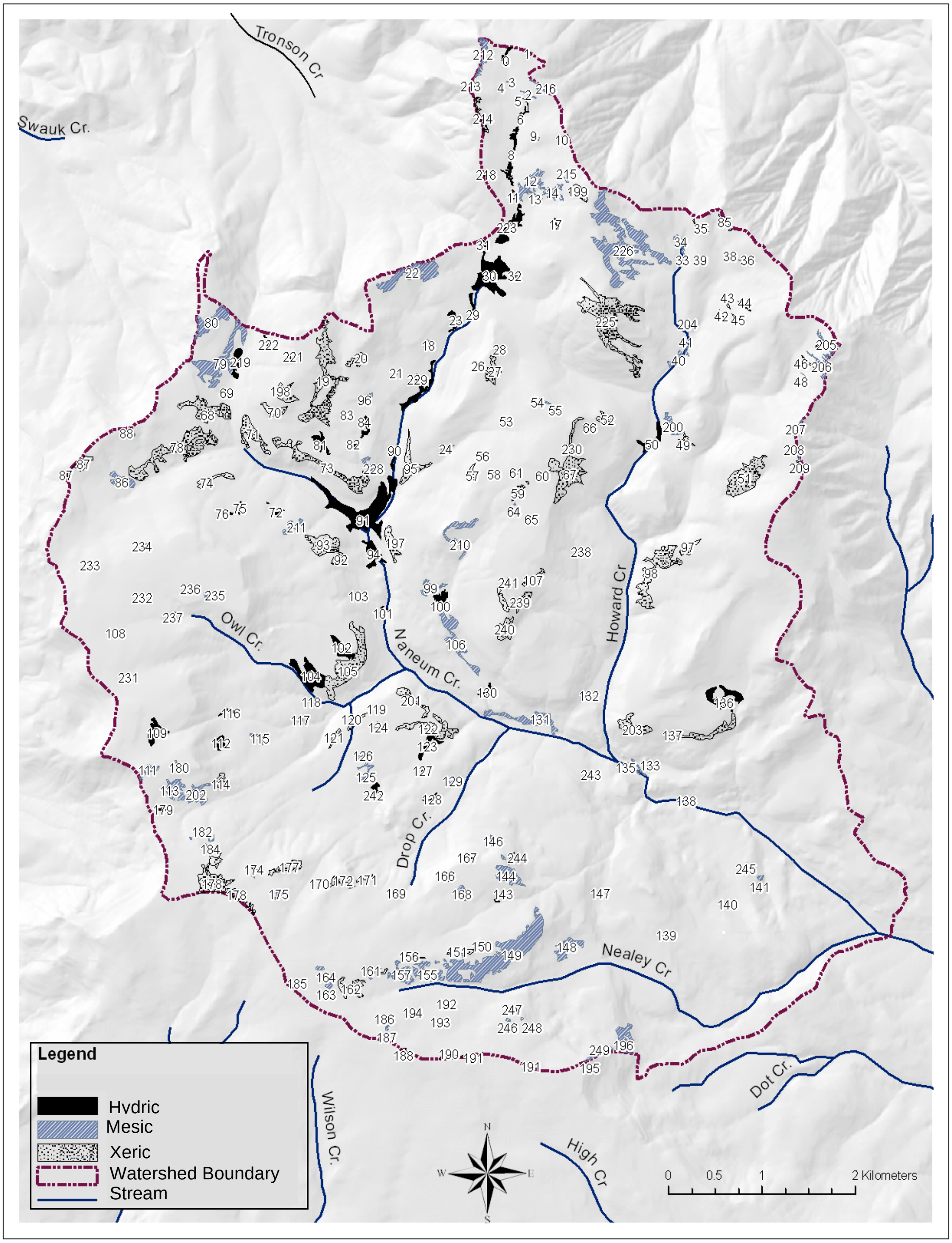
APPENDIX

Spatial Distribution of Meadows in the Upper Naneum Watershed



Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
1	Mesic	146.37	1,782.07	3.68	CVX
2	Mesic	197.07	1,757.33	3.43	CVX
3	Mesic	119.57	1,747.40	5.62	CC
4	Mesic	84.81	1,753.34	8.40	CS
5	Hydric	198.48	1,740.98	0.55	CVX
6	Hydric	215.67	1,733.83	4.78	CVX
7	Hydric	215.87	1,732.31	3.20	CC
8	Hydric	134.74	1,718.58	7.73	CC
9	Mesic	249.77	1,770.34	7.70	CVX
10	Mesic	227.34	1,796.84	14.80	CS
11	Hydric	109.67	1,700.74	5.56	CC
12	Mesic	217.26	1,743.17	12.49	CVX
13	Mesic	235.89	1,733.28	12.67	CVX
14	Mesic	242.46	1,765.30	14.11	CS
15	Mesic	253.67	1,793.69	16.77	CS
16	Mesic	254.15	1,814.73	17.33	CS
17	Hydric	279.87	1,777.94	10.62	CC
18	Mesic	136.54	1,671.99	11.17	CC
19	Xeric	128.09	1,749.42	17.64	CVX
20	Xeric	165.78	1,748.90	14.75	CVX
21	Mesic	121.45	1,668.97	4.20	CS
22	Mesic	141.43	1,772.53	17.58	CVX
23	Hydric	163.19	1,663.80	10.35	CC
24	Mesic	159.96	1,642.00	15.36	CC
25	Mesic	164.37	1,639.43	16.07	CS
26	Xeric	301.73	1,767.25	17.99	CVX
27	Xeric	112.47	1,760.21	11.47	CVX

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
28	Xeric	113.95	1,758.07	11.02	CVX
29	Hydric	151.55	1,662.38	9.29	CC
30	Hydric	211.87	1,675.00	6.08	CC
31	Hydric	125.02	1,683.17	4.05	CC
32	Hydric	248.38	1,712.42	16.15	CVX
33	Mesic	213.71	1,668.41	0.56	CC
34	Mesic	153.75	1,678.15	10.12	CVX
35	Xeric	212.15	1,697.69	11.61	CVX
36	Mesic	211.10	1,671.48	9.11	CVX
37	Mesic	179.98	1,672.60	11.25	CS
38	Mesic	241.23	1,667.09	11.56	CVX
39	Xeric	215.13	1,694.44	5.99	CVX
40	Mesic	149.16	1,600.36	13.78	CC
41	Mesic	166.85	1,606.87	4.72	CC
42	Xeric	263.91	1,673.69	15.78	CVX
43	Xeric	291.93	1,686.89	15.62	CVX
44	Xeric	296.11	1,730.88	17.20	CVX
45	Xeric	267.53	1,722.32	19.88	CVX
46	Xeric	267.82	1,750.21	19.87	CVX
47	Xeric	274.01	1,769.91	20.57	CVX
48	Mesic	285.14	1,723.65	20.51	CVX
49	Xeric	223.14	1,628.98	21.44	CVX
50	Hydric	152.76	1,564.23	7.89	CVX
51	Xeric	204.63	1,724.99	19.07	CVX
52	Xeric	101.05	1,726.26	14.03	CVX
53	Mesic	272.27	1,738.02	16.43	CVX
54	Mesic	57.37	1,789.90	19.93	CVX

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
55	Mesic	91.81	1,797.61	22.19	CS
56	Mesic	315.48	1,717.89	21.64	CS
57	Xeric	285.09	1,726.72	23.12	CVX
58	Mesic	239.54	1,747.50	2.66	F
59	Xeric	203.39	1,749.80	3.63	CVX
60	Mesic	205.92	1,768.82	5.74	CVX
61	Mesic	220.06	1,759.90	4.17	CVX
62	Xeric	187.20	1,758.38	4.13	CVX
63	Mesic	208.10	1,740.51	7.78	CC
64	Mesic	249.01	1,735.70	4.80	CVX
65	Mesic	277.30	1,745.33	2.23	CVX
66	Mesic	134.64	1,730.50	12.99	CC
67	Xeric	126.42	1,730.38	21.40	CS
68	Xeric	97.81	1,675.66	12.51	CVX
69	Mesic	193.41	1,642.81	4.72	CC
70	Xeric	200.13	1,740.03	19.08	CVX
71	Xeric	226.43	1,658.85	16.64	CVX
72	Hydric	30.27	1,668.29	8.89	CVX
73	Xeric	173.51	1,642.59	12.61	CVX
74	Xeric	39.94	1,699.38	7.89	CVX
75	Hydric	46.99	1,690.49	2.83	CS
76	Hydric	74.89	1,696.78	6.96	CC
77	Hydric	67.27	1,673.40	10.18	CVX
78	Xeric	139.44	1,694.34	16.20	CVX
79	Mesic	137.42	1,692.15	13.09	CVX
80	Mesic	140.40	1,767.76	16.11	CVX
81	Hydric	146.17	1,664.09	5.26	CC

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
82	Hydric	135.30	1,635.96	9.01	CC
83	Hydric	144.85	1,673.59	5.51	CVX
84	Hydric	196.43	1,661.19	5.90	CVX
85	Xeric	148.49	1,690.50	5.25	CVX
86	Mesic	122.26	1,723.34	10.00	CVX
87	Xeric	161.50	1,807.51	11.59	CVX
88	Xeric	154.90	1,797.38	17.25	CVX
89	Mesic	138.24	1,780.18	18.43	CVX
90	Hydric	148.62	1,570.59	8.77	CC
91	Hydric	161.76	1,546.27	4.70	CC
92	Xeric	83.42	1,625.13	17.42	CVX
93	Xeric	99.20	1,644.63	8.05	CVX
94	Hydric	123.59	1,532.80	2.68	CC
95	Xeric	200.12	1,601.28	16.26	CVX
96	Mesic	140.59	1,681.31	10.80	CVX
97	Xeric	275.14	1,628.65	9.02	CVX
98	Xeric	256.94	1,567.05	12.27	CVX
99	Mesic	171.03	1,594.14	10.11	CVX
100	Hydric	186.64	1,581.45	3.84	CS
101	Hydric	152.65	1,512.35	7.49	CC
102	Hydric	123.73	1,624.25	5.24	CC
103	Hydric	67.01	1,562.76	22.72	CC
104	Hydric	164.58	1,632.97	9.54	CVX
105	Xeric	120.04	1,608.39	15.26	CVX
106	Mesic	195.04	1,540.61	16.20	CVX
107	Xeric	125.00	1,712.24	14.79	CVX
108	Mesic	95.25	1,862.43	3.08	CS

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
109	Hydric	109.70	1,852.42	6.39	CC
110	Mesic	183.17	1,879.81	22.04	CVX
111	Mesic	92.01	1,883.39	5.20	CVX
112	Hydric	74.10	1,722.06	9.02	CS
113	Mesic	136.10	1,837.02	10.72	CVX
114	Xeric	84.25	1,777.95	19.85	CVX
115	Mesic	95.19	1,689.40	6.19	CVX
116	Hydric	119.71	1,707.20	7.12	CC
117	Mesic	139.67	1,633.56	23.27	CS
118	Mesic	71.82	1,601.25	13.45	CVX
119	Xeric	341.44	1,610.76	8.30	CVX
120	Xeric	145.77	1,615.68	7.89	CVX
121	Xeric	323.11	1,625.02	8.32	CVX
122	Xeric	104.69	1,570.29	11.15	CVX
123	Hydric	128.38	1,580.63	7.15	CC
124	Mesic	115.24	1,608.50	3.80	CVX
125	Mesic	73.10	1,638.05	5.30	CVX
126	Mesic	41.68	1,633.34	5.96	CS
127	Hydric	329.26	1,598.11	3.10	CC
128	Hydric	122.06	1,613.05	8.97	CC
129	Mesic	97.19	1,583.37	10.49	CC
130	Hydric	154.53	1,467.59	10.51	CC
131	Mesic	174.76	1,423.99	17.60	CVX
132	Mesic	90.94	1,437.72	5.72	CS
133	Mesic	162.49	1,354.28	14.14	CC
134	Mesic	96.16	1,354.68	7.66	CVX
135	Mesic	38.21	1,360.39	10.07	CVX

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
136	Hydric	146.90	1,540.04	8.53	CC
137	Xeric	162.63	1,489.74	25.12	CVX
138	Mesic	200.74	1,324.34	12.91	CC
139	Mesic	153.38	1,497.20	7.72	CVX
140	Mesic	43.31	1,378.71	21.00	CS
141	Mesic	83.91	1,334.95	24.15	CS
142	Hydric	128.11	1,729.62	8.99	CC
143	Hydric	157.86	1,731.33	11.76	CC
144	Mesic	105.02	1,758.13	14.81	CVX
145	Mesic	43.88	1,757.85	26.47	CVX
146	Mesic	238.38	1,690.90	15.35	CC
147	Mesic	129.46	1,523.46	0.90	CC
148	Mesic	107.69	1,596.29	12.13	CVX
149	Mesic	141.49	1,759.04	18.97	CVX
150	Xeric	173.11	1,805.71	2.98	CVX
151	Xeric	220.63	1,813.49	13.80	CVX
152	Mesic	255.66	1,808.53	5.19	CVX
153	Xeric	4.06	1,805.32	4.15	CVX
154	Mesic	179.80	1,803.28	5.30	CVX
155	Mesic	149.88	1,798.54	11.33	CS
156	Xeric	71.38	1,831.66	5.32	CVX
157	Mesic	138.76	1,827.17	9.72	CS
158	Mesic	131.46	1,805.75	7.74	CS
159	Xeric	139.15	1,847.28	7.24	CS
160	Xeric	153.43	1,854.50	6.38	CS
161	Mesic	115.20	1,860.95	7.99	CS
162	Xeric	150.01	1,869.54	6.40	CS

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
163	Mesic	158.58	1,880.61	5.44	CS
164	Mesic	160.49	1,889.19	4.61	CS
165	Mesic	134.67	1,896.04	2.66	CS
166	Xeric	166.23	1,798.50	1.60	CVX
167	Xeric	196.67	1,782.40	15.66	CVX
168	Mesic	121.63	1,805.75	6.47	CC
169	Mesic	189.25	1,791.94	10.13	CVX
170	Xeric	301.94	1,842.25	11.01	CVX
171	Xeric	52.34	1,797.50	17.67	CVX
172	Xeric	121.71	1,836.82	7.37	CVX
173	Mesic	59.80	1,815.87	4.94	CC
174	Xeric	26.88	1,853.38	21.04	CVX
175	Mesic	49.66	1,869.07	9.49	CS
176	Mesic	39.54	1,877.13	14.56	CVX
177	Xeric	166.07	1,849.33	9.76	CVX
178	Xeric	201.30	1,902.49	3.65	CS
179	Hydric	105.30	1,835.65	4.95	CS
180	Mesic	181.82	1,867.47	6.21	CS
181	Mesic	276.98	1,865.54	13.73	CVX
182	Mesic	55.97	1,835.92	18.63	CVX
183	Mesic	45.24	1,863.91	19.83	CVX
184	Mesic	164.03	1,835.77	15.90	CVX
185	Mesic	115.08	1,896.33	7.25	CS
186	Mesic	339.05	1,873.71	15.16	CVX
187	Mesic	157.03	1,881.00	0.00	CVX
188	Xeric	208.64	1,881.60	1.23	CVX
189	Xeric	28.36	1,856.36	1.81	CVX

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
190	Xeric	10.53	1,850.28	8.18	CVX
191	Xeric	53.82	1,835.47	5.56	CVX
192	Xeric	18.33	1,807.71	8.34	CVX
193	Mesic	31.70	1,826.06	5.60	CVX
194	Mesic	62.64	1,837.80	7.84	CVX
195	Mesic	25.22	1,777.67	26.25	CVX
196	Mesic	64.35	1,601.24	21.82	CS
197	Xeric	251.60	1,585.22	22.79	CVX
198	Xeric	192.64	1,789.38	14.63	CVX
199	Xeric	243.53	1,848.37	19.64	CVX
200	Mesic	249.24	1,607.60	21.27	CS
201	Xeric	56.36	1,580.17	14.39	CVX
202	Mesic	147.13	1,800.89	14.26	CS
203	Xeric	204.07	1,515.69	21.95	CVX
204	Mesic	187.87	1,644.30	16.41	CVX
205	Mesic	280.11	1,795.27	13.16	CS
206	Mesic	276.01	1,791.77	13.63	CS
207	Mesic	270.17	1,820.23	16.75	CVX
208	Mesic	261.43	1,826.76	10.30	CS
209	Xeric	235.19	1,826.36	12.50	CVX
210	Mesic	172.46	1,716.11	15.12	CVX
211	Mesic	93.42	1,669.86	6.01	CVX
212	Mesic	125.44	1,791.31	7.42	CS
213	Xeric	128.63	1,796.62	10.66	CS
214	Xeric	120.53	1,803.67	11.82	CS
215	Mesic	263.81	1,821.53	19.01	CS
216	Mesic	153.82	1,760.46	1.65	CS

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
217	Mesic	180.86	1,763.19	2.55	CS
218	Xeric	128.98	1,758.06	7.01	CS
219	Hydric	160.34	1,660.94	9.16	CC
220	Hydric	275.10	1,720.51	16.07	CS
221	Xeric	271.59	1,808.71	20.06	CVX
222	Xeric	287.39	1,736.70	14.77	CVX
223	Hydric	238.62	1,688.78	6.61	CC
224	Mesic	180.71	1,600.02	23.73	CVX
225	Xeric	142.36	1,809.00	19.41	CVX
226	Mesic	123.01	1,762.95	20.21	CS
227	Mesic	204.82	1,631.71	25.78	CVX
228	Mesic	180.71	1,600.02	23.73	CVX
229	Hydric	156.63	1,618.87	10.22	CC
230	Xeric	111.72	1,786.71	24.52	CVX
231	Mesic	47.06	1,849.69	5.76	CC
232	Mesic	96.40	1,851.82	3.45	CS
233	Mesic	328.12	1,851.35	14.87	CVX
234	Mesic	341.06	1,839.17	12.22	CVX
235	Mesic	151.52	1,831.04	3.76	CS
236	Mesic	170.09	1,837.81	3.23	CS
237	Xeric	124.98	1,816.27	12.43	CVX
238	Mesic	182.35	1,599.17	6.17	CVX
239	Xeric	168.58	1,709.77	15.74	CVX
240	Xeric	150.05	1,680.02	21.09	CVX
241	Mesic	172.29	1,733.32	4.25	CVX
242	Hydric	77.16	1,633.83	5.06	CS
243	Mesic	76.75	1,422.55	19.69	CS

Meadow identification	Meadow type	Aspect	Elevation	Slope	Landscape position
244	Xeric	65.12	1,714.98	29.43	CVX
245	Mesic	207.64	1,363.02	11.96	CVX
246	Mesic	122.05	1,794.58	4.87	CVX
247	Xeric	66.12	1,772.94	27.14	CVX
248	Mesic	56.11	1,784.75	5.20	CS
249	Mesic	54.30	1,677.09	26.08	CVX

Note. CVX = convex slope, CC = concave slope, CS = continuous slope.