

THE INFLUENCE OF ENVIRONMENTAL ATTRIBUTES ON
TEMPORAL AND STRUCTURAL DYNAMICS OF WESTERN JUNIPER DEVELOPMENT
AND ASSOCIATED FUEL LOADING CHARACTERISTICS

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The Influence of Environmental Attributes on Temporal and Structural Dynamics of Western Juniper Woodland Development and Associated Fuel Loading Characteristics

Introduction

Since Eurasian settlement of the Intermountain West, dramatic changes in vegetation composition and structure have occurred in the sagebrush steppe ecosystem. Western juniper (*Juniperus occidentalis* spp. *occidentalis* Vasek), although indigenous to the Intermountain West, has increased since the late 1800s. Prior to Eurasian settlement, western juniper typically occurred as open, savannah-like stands (Nichol 1937, West 1988) or was confined to less productive areas that lacked sufficient fine fuels to carry fire (Cottman and Stewart 1940, Barney and Frishknecht 1974, West 1984). Since Eurasian settlement, western juniper woodlands have expanded in range to occupy more productive sites. By 1990 over 90% of the 3.2 million hectares dominated by western juniper had developed since the 1890s (USDI-BLM 1990).

Post settlement encroachment and development of western juniper woodlands in sagebrush steppe communities has been widely studied. Causes of post settlement woodland expansion have been related to fire suppression, livestock grazing, increases in atmospheric CO₂, and relatively wet climatic conditions around the turn of the 20th century (Miller and Tausch 2001). However, the replacement of sagebrush steppe communities by juniper woodlands is most often attributed to a reduction in fire frequency (Burkhardt and Tisdale 1969, Miller and Rose 1999). Heavy livestock grazing between 1880 and 1930 may

have indirectly facilitated woodland expansion by reducing fine fuels. The advent of organized fire suppression, particularly following WWII, also decreased the frequency and extent of wildfire. Aboriginal Americans may also have impacted juniper woodlands through their influence on fire regimes (West 1999). From 1850 to 1916, winters were milder and precipitation was greater than the current long-term average across much of the Intermountain West (Antevs 1938, Wahl and Lawson 1970, LaMarche 1974, Graumlich 1987). It is likely that an amalgamation of these factors has reduced the occurrence of natural and/or introduced fire leading to a shift in disturbance regimes that influence plant community dynamics. The result has transformed pre-settlement plant community composition and structure from a dynamic fire-driven community comprised of sagebrush steppe vegetation to one of two forms: 1) an increase in woody species, primarily western juniper, fostering decreases in fire occurrence and increases in fuel loading and fire severity (Bunting 1994, Miller and Rose 1999, Tausch 1999); or 2) an increase in exotic annuals, especially annual bromes, resulting in dramatic increases in fire frequency and size (Whisenant 1990, Knick 1999, Tausch 1999).

Concerns related to post settlement woodland encroachment in sagebrush steppe communities are increased soil erosion (Wilcox and Breshears 1994), changes in soil fertility, losses in forage production, changes in wildlife habitat, and alterations of pre-settlement plant communities and ecological processes. Although little information exists for comparison, recent concerns have also arisen over excessive loading of heavy fuels in late phase juniper woodlands and the impending change in fire behavior from frequent, low intensity events to

infrequent, large, high intensity canopy fires (Tausch 1999, Miller and Tausch 2001).

Justification

Considerable work has been done documenting juniper woodland expansion in the Intermountain West. However, little is known about the environmental variables that influence rates of tree establishment and structural attributes of woodlands across landscapes. Understanding the influence of environmental variables on both spatial and temporal dynamics of juniper woodland expansion may prove valuable for planning and maintaining juniper control programs.

Most studies of western juniper have addressed site-specific questions at limited spatial scales. Consequently, there is a lack of research on broader scale patterns of woodland development occurring across heterogeneous landscapes. Broadening the scale of research allows comparisons of woodland expansion characteristics across heterogeneous environments.

Changes in the amount, composition, and structure of fuels during the transition from open sagebrush steppe communities to closed juniper woodlands have profound influences on the size, intensity, frequency, and behavior of fire. However, limited data exist quantifying changes in fuels during this transition; thus, consequences to fire behavior have been difficult to predict.

Study Objectives

The major impetus for the study was to determine the influence of environmental variables on rates and structural attributes of woodland development and associated changes in fuel loading characteristics during the transition from sagebrush steppe communities to closed juniper woodlands in the High Desert and Humboldt ecological provinces.

Specific study objectives were to:

1. Describe the spatial and temporal patterns of woodland expansion across southeastern Oregon and southwestern Idaho.
2. Determine the influence of environmental variables (e.g. elevation, aspect, etc.) on the temporal attributes of post settlement western juniper encroachment (both initial and successive tree establishment) into mountain big sagebrush communities in southeastern Oregon and southwestern Idaho.
3. Determine the influence of environmental variables on western juniper woodland structure (e.g. stand density) among stands encroaching into mountain big sagebrush communities in southeastern Oregon and southwestern Idaho.
4. Estimate changes in the amount and structure of fuel loads associated with woodland development under varying environmental conditions in juniper stands encroaching into mountain big sagebrush communities on Juniper Mountain, Idaho.

Literature Review

Current Distribution

Western juniper occupies nearly 3.2 million ha from the Cascade Range through the Modoc Plateau into adjacent parts of Washington, Oregon, and Idaho, and southward into northwestern Nevada (Hickman 1993)(Figure 1).

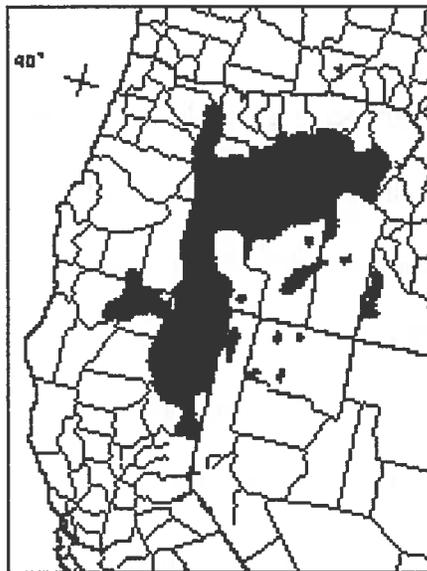


Figure 1. Map of the current distribution of western juniper.

Western juniper reaches its greatest extent in central Oregon east of the Cascade Range (Young et al. 1981). Western juniper's current range is primarily north of the polar front gradient that parallels the Oregon/Nevada border at latitude 42° (Neilson 1987). The climate north of this latitude is continental, with hot and dry summers, cold winters, and precipitation occurring primarily as snow and early spring and late fall rain. Western juniper occupies the most xeric of the conifer-dominated vegetation zones in the Pacific Northwest (Gedney 1999). Western juniper is usually not associated with other conifers except where juniper woodlands adjoin ponderosa pine (*Pinus ponderosa*) forests. Annual precipitation

averages less than 15 inches in the majority of its range (Gedney 1999). In the Intermountain West, most western juniper woodlands grow at elevations between 600 and 1,800 m. Above 2,100 m, extremes in temperatures and severe winter conditions limit growth of western juniper (Miller and Rose 1995).

General Species Description

Overview

Western juniper is a long-lived perennial evergreen typically comprised of a single stem. Varieties of western juniper differ in growth characteristics. *Juniperus occidentalis* ssp. *australis* reaches an average height of 8 m, with a maximum height of 15 m, whereas *Juniperus occidentalis* ssp. *occidentalis* typically grows to 7 m in height, and rarely grows over 12 m. Average circumference of the largest stem 150 cm above the ground of *Juniperus occidentalis* ssp. *australis* is 213 cm, while only 107 cm for *Juniperus occidentalis* ssp. *occidentalis* (Vasek 1966). *Juniperus occidentalis* ssp. *occidentalis* occurs but is not limited to the High Desert and Humboldt Ecological Provinces and thus is the variety in question and will be referred to as western juniper in this paper.

The long scale-like leaves of the mature western juniper tree average 3 mm in length and occur in whorls of occasionally two and most often three. Prominent glands on the dorsal surface exude resin that dries white during the fall (Vasek 1966). Structural adaptations of leaves that increase drought resistance include low surface to volume ratios, thick cuticle layers, and sheltered stomata. Most

stomata are located on the underside of leaves (Miller and Shultz 1987) and an overlapping adjacent leaf covers stomata located on the upper surface.

Bark of western juniper is cinnamon brown, furrowed, shreddy, and/or flaky (Hitchcock 1969, Vasek 1966); bark becomes more deeply furrowed and less flaky with age. Seedlings of western juniper typically produce rapid spring root extension with minimal top growth. During this time there is a greater downward growth than lateral growth of roots. As seedlings become established, their roots extend laterally making them highly competitive for nutrients and seasonal moisture in upper soil layers. As a mature tree, western juniper lacks a central taproot; rather, it has laterally extensive roots that often penetrate deep into the cracks of bedrock. Root-to-shoot ratios decrease with age affording western juniper competitive ability over species such as big sagebrush (Kramer et al. 1996). Western juniper is slow growing and long lived (Evans 1988). Individuals can survive for 1,000 years or longer (Sowder and Mowat 1965) and the oldest western juniper is reported to be approximately 1600 years old (Waichler et al. 2001).

Life History

Reproduction

Western juniper is a sub-monoecious species that flowers in the spring and generally sheds pollen in April. Its yellowish-brown staminate cones are terminal, ovoid, 3 to 4 mm long, and have 12 to 15 microsporophylls. Ovulate cones, referred to as berries, are 6 to 8 mm long, sub-lobose to ellipsoid, bluish-black when mature, and very glaucous. They have resinous pulp and mature in

September of the second season in Oregon, Washington, and Idaho. Ovulate cones rarely have one and commonly have two to three developed seeds. Seeds have thick, bony outer coats and thin, membranous inner coats. The membranous coat surrounds a fleshy endosperm within which a straight embryo with cotyledons occurs (Cronquist et al. 1972, Johnsen and Alexander 1974, Sowder and Mowat 1965, Vasek 1966).

Seed Production and Dissemination

Good seed production in western juniper does not occur every year. In fact, seed production has historically been rather sporadically linked to climate and, during the last decade (1990's), seed production in western juniper has been very limited (Miller per comm.). Seed production typically begins at 20 years of age or more, but few seed cones are produced until the tree reaches 50 to 70 years of age (Eddleman 1984, Eddleman et al. 1994) during which time full reproductive potential is achieved (Miller and Rose 1995).

Seeds are disseminated during fall and winter primarily by birds, mammals, water, and gravity (McCaughey et al. 1986). In a southwestern Idaho study, western juniper seed dispersed an average of 1.42 m down-slope and 0.60 m upslope during a 4-month summer period, and an overall average of 1.29 m during a 6-month winter period (Burkhardt and Tisdale 1976). Primary disseminators of seed are American robins (*Turdus migratorius*), Townsend solitaires (*Myadestes townsendi*), and coyotes (*Canis latrans*). Seeds of many western juniper species are thought to germinate more readily post animal consumption (Springfield 1976). Animals ingest the fruit but are unable to digest the seeds. Western juniper

is often found growing along fencerows, seeds having been deposited there by perched birds (Johnsen 1974, Maser and Gashwiler 1978, Sowder and Mowat 1965).

Germination and Seedling Development

Seed germination of western juniper occurs during April in Oregon. Seeds of many juniper species show delayed germination because of dormant embryos or hard seed coats. Seed germination has been described as "erratic and unpredictable" (Young et al. 1988). Tueller (1976) reports that germination in western juniper "is not a straight-forward process, but one that requires a specific sequence of environmental conditions for natural germination and seedling establishment." Western juniper appears to establish most successfully in microclimates associated with woody nurse plants. Common nurse plants are big sagebrush and established western juniper (Burkhardt and Tisdale 1976, Eddleman 1987, Miller and Rose 1995). In a central Oregon study, Eddleman (1984) found that most seedlings established in ameliorated microclimates on the north side of existing trees. Miller and Rose (1995) reported growth rates ranged from 2.4 cm/year in interspaces to 3.4 cm/year under sagebrush nurse plants.

Young plants are normally vigorous, single-stemmed, with pyramidal growth forms. Western juniper is very hardy in the early growth stage, resists disease and insect attacks well, and is not preferred as a food item by livestock or wild ungulates. It is considered palatable browse for elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), mountain cottontails (*Sylvilagus nuttallii*), porcupines (*Erethizon dorsatum*) and black-tailed jackrabbits (*Lepus californicus*) (Maser and

Gashwiler 1978). However, palatability varies by individual tree (Sowder and Mowat 1965) and Rosentreter and Jorgensen (1986) describe its overall palatability as "low."

Sapling and Pole Stages to Maturity

During its sapling and pole stages, western juniper has straight boles with crowns that vary from tapered to round. Although early growth rates vary by site, growth throughout its range is slow relative to most conifer species.

Height of mature trees, depending on site conditions, typically ranges from 4 to 10 m. Occasionally, trees reach exceptional heights, such as the state champions in Oregon and Idaho, which are 24 (Oregon Department of Forestry 2004) and 17 m (Mahoney 2003), respectively.

Pre-settlement Morphology

Pre-settlement western juniper (i.e. trees greater than 150 years old) is characterized as having massive and irregular tapering trunks and deeply furrowed, stringy bark (Waichler et al. 2001). Crowns of pre-settlement trees typically have few but heavy branches from near the base, are round-topped, have relatively sparse canopies, and lack strong terminal leaders. Pre-settlement trees tend to have a high proportion of decadent growth, a general non-symmetrical appearance (Holmes et al. 1986), annual lateral and terminal growth less than 5 cm, and frequently have yellow-green lichen growing on the trunk and limbs.

Post Settlement Morphology

In contrast to the pre-settlement growth form, post-settlement western juniper (i.e. trees less than 150 years old) has moderately tapering trunks and flaky

bark. Crowns of post settlement trees, depending on site potential and competition, are usually symmetrical, cone-shaped, and densely limbed from near the base. Post-settlement trees lack yellow-green lichen growing on the limbs and trunk and can achieve annual lateral and terminal leader growth that exceeds 10 cm in relatively open stands (Burkhardt and Tisdale 1969).

Soils and Topography

Soils

Western juniper is found in each of the 18 soil classes in the Intermountain West, however most western juniper is located on four soil classes: 1) Xeric frigid soils on grass-shrub plains, 2) Xeric-Aridic mesic soils on terraces and flood plains, 3) Xeric-Aridic frigid soils on grass-shrub plains, and 4) Aridic-Xeric frigid soils on plateaus and uplands (Soil Survey Staff 1994 and 1996).

Western juniper grows on soils developed in parent materials originating from metamorphic, sedimentary, and igneous sources. Included are tuff, welded tuff, pumice, volcanic ash, rhyolite, andesite, granite, basalt, and eolian soils; and colluvial or alluvial mixtures of these soils. Western juniper forms complex patterns on zonal, intrazonal, and azonal soils. Profile development is often weak. Soils are commonly shallow (25 to 38 cm) but range to deep (more than 122 cm). Fractured bedrock or broken indurated subsoil layers commonly occur under shallow overburdened soils. Surface horizons are often of medium texture, and subsoils of medium to fine texture; however, textures can vary from sandy to clayey. Indurated layers can occur and are associated with accumulations of clay,

calcium carbonate, and silica and may be less than 1.5 cm to several centimeters thick (Dealy et al. 1978, Driscoll 1964).

Soils supporting western juniper at high densities are frequently Mollisols. Argixerolls, Haploxerolls, and Haplaquolls are common great groups. Soils supporting scattered western juniper are commonly Aridisols – including Camborthids, Durargids, and Haplargrids. However, lithic Argixerolls also commonly support stands of widely scattered trees. Other soils on which western juniper can be found are Durixerolls and Cryoborolls of the order Mollisols, Torriorthents of the order Entisols, and Chromoxerets of the order Vertisols (Dealy et al. 1978).

Topography

Western juniper is found on all exposures and slopes. In central Oregon, it commonly occurs as large contiguous stands on level topography. In other areas, it grows less contiguously on terraces, moderately sloping alluvial fans, canyon slopes, and steep rocky escarpments (Dealy et al 1978, Driscoll 1964).

Associated Vegetation

Shrub Species

Big sagebrush (*Artemisia tridentata*) and low sagebrush (*Artemisia arbuscula*) are the most common shrub species associated with western juniper throughout its range. Mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana*) is the subspecies of big sagebrush most often displaced by western juniper. Other shrubs common to western juniper communities in the northern portion of its range are mountain snowberry (*Symphoricarpus oreophilus*), gray

rabbitbrush (*Chrysothamus nauseosus*), green rabbitbrush (*Chrysothamus viscidiflorus*), antelope-bitterbrush (*Purshia tridentata*), wax currant (*Ribes cereum*), curl-leaf mountain mahogany (*Cercocarpus ledifolius*) and horsebrush (*Tetradymia* spp.). Less common shrubs are stiff sagebrush (*Artemisia rigida*), spiny hopsage (*Atriplex spinosa*), broom snakeweed (*Gutierrezia sarothrae*), prickly phlox (*Leptodactylon pungens*), and desert gooseberry (*Ribes velutinum*) (Burkhardt and Tisdale 1969, Dealy et al. 1978, Driscoll 1964).

Grass or Grasslike Species

Common grass or grasslike species associated with western juniper in northern areas are bluebunch wheatgrass (*Agropyron spicatum*), cheatgrass (*Bromus tectorum*), Idaho fescue (*Festuca idahoensis*), Sandberg bluegrass (*Poa secunda*), bottlebrush squirreltail (*Sitanion hystrix*), and Thurber needlegrass (*Stipa thurberiana*). Less common are threadleaf sedge (*Carex filifolia*), Ross sedge (*Carex rossii*), sixweeks fescue (*Festuca octoflora*), prairie junegrass (*Koeleria cristata*), needle-and-thread (*Stipa comata*), Columbia needlegrass (*Stipa columbiana*), and western needlegrass (*Stipa occidentalis*) (Burkhardt and Tisdale 1969, Dealy et al. 1978, Driscoll 1964).

Response to Competition and Disturbance

Mature western juniper is intolerant of shade and competes poorly with other conifers on upper slopes. However, on highly productive upper slopes supporting quaking aspen, western juniper is extremely competitive and often dominates in the absence of fire.

Western juniper is highly adapted to semi-arid environments and successfully out-competes other types of vegetation for available soil moisture and nutrients. Presence of western juniper significantly impacts the amount of precipitation reaching the soil surface. Its crown intercepts more than half of the annual precipitation relative to bare ground (Young et al. 1984) and the orientation of the limbs within the crown funnels water directly to the stem. This adaptation greatly reduces soil moisture in surface horizons available to competing vegetation. Western juniper is an evergreen species, whereas most competitors lack the ability to rapidly initiate photosynthesis in response to favorable climatic conditions. The ability to maintain leaf area through winter allows uptake of early spring moisture before most competitors germinate or break dormancy (Miller and Shultz 1987). Western juniper maintains an extensive lateral root system that can extend several times the diameter of the crown allowing water and nutrient uptake from an area much larger than that beneath the tree canopy. Western juniper is the dominant overstory species as it encroaches into sagebrush steppe plant communities, and thus is able to intercept solar energy that otherwise would be available to understory vegetation.

Under mature western juniper trees in central Oregon, soil Ca, K, and pH are higher than in interspace soils and soils under young trees. These changes appear to also increase the ability of western juniper to compete with other vegetation (Doescher et al. 1987). The advantageous uptake and utilization of soil moisture and nutrients in addition to shading by western juniper reduce understory vegetation establishment and vigor (Jeppesen 1977). Young et al. (1984) found

that herbage production of vegetation in stands of western juniper on big sagebrush sites averaged less than 50 kg/ha. Mature western juniper trees are better competitors for light, water, and nutrients than herbs and shrubs. As tree density increases, herbaceous and shrub biomass declines (Clary and Jameson 1981, Doughty 1987, Vaitkus and Eddleman 1987) and more bare ground is usually exposed in woodlands than in shrub steppe communities.

Western juniper is a fire sensitive species historically restricted to sites with limited fine fuels. Since the advent of effective fire suppression and livestock grazing, western juniper has expanded to more productive sites previously dominated by mountain big sagebrush, bitterbrush, curl-leaf mountain mahogany, quaking aspen, and riparian communities (Miller and Rose 1995, Wall et al. 2001, Miller et al. 2000).

Fire resistance of western juniper varies with age. Seedlings, saplings, and poles are highly vulnerable to fire (Martin 1978). Mature trees have some resistance to fire because of a thicker bark layer. In addition, mature stands typically lack sufficient fine fuel biomass and fuel continuity to carry fire under normal conditions. Pre-settlement stands remain in existence because, historically, intense natural fires did not occur and human-caused fires have been controlled (Burkhardt and Tisdale 1969 and 1976, Dealy et al. 1978). Western juniper is easiest to control with fire management when trees are less than 2 m tall (Bunting 1984). The taller trees become, the more intense fire must be to obtain good control. As stand closure is approached and trees begin to dominate, understory

fuels become inadequate for burning trees under any weather conditions that management can safely tolerate (Martin 1978, Miller et al. 2000).

Woodland Expansion

Evidence of Post Eurasian Settlement Woodland Expansion

Prior to settlement, western juniper was primarily confined to rock outcrops, shallow soils on fractured bedrock, and deep pumice soils where fire was excluded by limited fine fuels (Dealy et al. 1978, Martin 1978, Miller and Rose 1995, 1999). Currently, populations of western juniper widely occupy more productive sites with deep, well-drained soils that historically supported sagebrush steppe, riparian, and aspen communities (Burkhardt and Tisdale 1976, Miller and Rose 1995, Miller et al. 2000). Expansion of western juniper throughout the Intermountain West is well documented in the literature (Cottman and Stewart 1940, Burkhardt and Tisdale 1976, Tausch et al. 1981, Tausch and West 1988, 1995, Miller and Rose 1995, 1999, Gedney et al. 1999, O'Brien and Woodenberg 1999). Evidence of a post-settlement expansion exists as old surveys, photographs (Rogers 1982, Creque et al. 1999, Gruell 1999), and tree ring chronologies. Other evidence supporting the post-settlement expansion of juniper is the low proportion of pre-settlement age class trees relative to trees establishing during the past 150 years. Although western juniper can survive for 1,000 years or longer (Sowder and Mowat 1965), Miller et al. (1999) estimated 10% or less of today's woodlands are comprised of trees that established prior to 1860. In comparing 2 U.S. Forest Service surveys conducted during 1938 and 1988 across eastern Oregon, Gedney et al. (1999) reported a 600% increase in density and area during the 50-year

period. Although studying a different species of juniper, Cottam and Stewart (1940) also reported a 600% increase in area and density of Utah juniper (*Juniperus osteosperma*) in southwest Utah between 1864 and 1940.

Causes of Woodland Expansion

Causes of woodland expansion have been related to fire suppression, livestock grazing, climate change, and increases in atmospheric CO₂ (Miller and Tausch 2001).

Climate

During the years 1850 to 1916 winters were milder and precipitation was greater than the current long-term average across the Great Basin (Antevs 1938, Wahl and Lawson 1970, LaMarche 1974, Graumlich 1987). Analyses of tree ring data in the literature show that relatively wet climatic conditions associated with this time period coincide with the initiation and peak period of juniper establishment in parts of Oregon and Idaho (Adams 1975, Burkhardt and Tisdale 1976, Eddleman 1987, Miller and Rose 1995, Gruel 1999, Miller and Rose 1999). Wet, mild climatic conditions promote vigorous establishment and growth in juniper (Fritts and Xiangdig 1986, Holmes et al. 1986).

Livestock Grazing

Tree ring data show that the introduction of livestock during the 1860s and successive heavy grazing from the 1870s through the early 1900s coincides with initial expansion of juniper woodlands throughout the Great Basin (Adams 1975, Burkhardt and Tisdale 1976, Eddleman 1987, Miller and Rose 1995, Gruel 1999, Miller and Rose 1999). However, most have concluded that livestock grazing

likely facilitated juniper woodland expansion through the reduction of fine fuels, the increase in shrub density and cover (Miller and Rose 1995), and the reduction of competition from herbaceous species (Cottam and Stewart 1940, Madany and West 1983, Burwell 1998, 1999).

Many reports in the literature corroborate that heavy livestock grazing predominantly influenced woodland expansion through the reduction of herbaceous biomass that historically fueled a higher frequency of fire (Campbell 1954, Ellison 1960, Burkhardt and Tisdale 1976, Miller and Rose 1999). Miller and Rose (1999) reported the role of fire in south central Oregon was significantly reduced after 1870, shortly following the introduction of large numbers of livestock in the 1860s, and 46 years prior to organized fire suppression. These findings parallel those reported from ponderosa pine forests in the Pacific Northwest (Heyerdahl et al. 2001) and Southwest (Savage and Swetnam 1990, Swetnam and Betancourt 1998), where the occurrence of fire substantially declined between 1874 and 1900. Further evidence linking livestock grazing and reductions in fire was reported from Arizona where fire declined shortly after increases in Navaho sheep herds (Savage and Swetnam 1990). Blackmore and Vitousek (2000) studied reductions in standing biomass due to grazing and the resulting effects on fire behavior. The results of their modeling efforts indicated that grazed grasslands had a much lower fire potential than that of ungrazed grasslands.

Increased grazing pressure and absence of fire in sagebrush-grass communities can cause a shift toward greater dominance of shrub cover (Miller

and Rose 1999). Safe sites for seed germination and enhanced growth rates for juniper seedlings are provided by increased sagebrush cover (Miller and Rose 1995). Several authors have reported the importance of shrubs facilitating the establishment of trees (e.g. Everett and Ward 1984, Eddleman 1987, Miller and Rose 1995). The shift from herbaceous-dominated communities to sagebrush-dominated communities reduces the amount of fine fuels required to carry surface fires, allowing western juniper to increase its dominance over the shrub and herbaceous components of plant communities.

Rising Atmospheric CO₂

Increasing atmospheric CO₂ levels during the second half of the 20th century has been cited as facilitating woodland expansion throughout the West (Johnson et al. 1993, Knapp and Soule 1996). Soule and Knapp (1999) speculated that increased atmospheric CO₂ concentration is a contributing factor to western juniper expansion in central Oregon by increasing water use efficiency and growth rates. However, tree ring data reported in the literature fail to substantiate the relationship of initial and peak woodland establishment periods with increasing atmospheric CO₂ (Adams 1975, Burkhardt and Tisdale 1976, Eddleman 1987, Miller and Rose 1995, Gruel 1999, Miller and Rose 1999). The initial post-settlement increase and peak establishment of juniper occurred during the late 1800s and early 1900s, whereas accentuated increases in CO₂ began around the 1950s. However, peak canopy expansion (i.e. expansion of tree crowns) occurred during the second half of the 20th century. Thus, elevated CO₂ may be accelerating canopy expansion in juniper woodlands (Miller and Tausch 2001). Influences of

elevated CO₂ levels on tree growth (Knapp et al. 2001) or on the interactions between western juniper and understory species are not well understood at this point.

Fire Histories

Fire histories in sagebrush steppe communities can be developed from fire scars collected from adjacently growing ponderosa pine or from legacy pre-settlement juniper. Cross dating of charred juniper material and developing stand chronologies can also be employed to study fire history. Currently, our best fire history information in semi-arid sagebrush steppe communities is from the mountain big sagebrush – Idaho fescue association. This is primarily an artifact of the sporadic incidence of pre-settlement ponderosa pine within or adjacent to these communities. Two studies estimate pre-settlement fire free periods varying between 3 and 28 years (Miller and Rose 1999) and between 8 and 29 years (Gruell 1999) in the mountain big sagebrush – Idaho fescue association. They also report that mean fire return intervals (MFRI) have significantly increased after the 1860s throughout much of this cover type.

Growth of juniper is generally slow during the first 45 to 50 years. In eastern Oregon, Miller and Rose (1999) reported that 45 years are necessary for a tree to reach a 3 m height in mountain big sagebrush communities. It has been well established in the literature trees less than 3 m are most susceptible to fire mortality (Jameson 1962, Dwyer and Pieper 1967, Bunting 1984), thus, assuming this threshold, pre-settlement fire return intervals for the mountain big sagebrush – Idaho fescue communities must have been less than 45 years to limit western

juniper encroachment into mountain big sagebrush communities. Burkhardt and Tisdale (1976) concluded that fire-frequency intervals of 30-40 years would be sufficient to keep western juniper from invading a sagebrush-grassland community.

Encroachment of western juniper into low sagebrush communities has consequences that differ from those found in mountain big sagebrush communities. Pre-settlement mean fire return intervals in low sagebrush were much longer than those in mountain big sagebrush as a consequence of lower vegetative production (Miller and Rose 1999). Estimates of pre-settlement fire-free periods in low sagebrush communities vary from 90 (Young and Evans 1981) to 138 years (Miller and Rose 1999). Growth of western juniper is slower in the low sagebrush alliance compared to those in mountain big sagebrush communities. Miller and Rose (1999) noted that a western juniper 3 m tall in a mountain big sagebrush stand would be 40 to 50 years old, but, 75 to 95 years may be required to reach the same height in a low sagebrush community. Therefore, they concluded that a 100-year fire return interval would be sufficient to control the expansion of western juniper in the low sagebrush alliance. Increasing dominance of western juniper had little effect on the composition of associated vegetation (Miller et al. 2000). Herbaceous cover did not change between young and mature western juniper stands. However, low sagebrush communities can become nearly fire proof if perennial grasses are grazed (Young and Evans 1981) because of reduced accumulation of fine fuels that aid the spread of fire (Agee 1993).

Changes in fire frequency have many consequences that could have led to the expansion of western juniper. Historically, fire limited the habitat of western juniper primarily to rock outcrops on slopes and ridges (Burkhardt and Tisdale 1969). These areas make up the pre-settlement habitat of western juniper and comprise only three to five percent of the current western juniper woodlands in the Intermountain West (Burkhardt and Tisdale 1976, Waichler et al. 2001). Pre-settlement habitat had insufficient amounts of fine fuels in the understory to carry a surface fire. Stand closure on these less productive sites was insufficient to allow crown-to-crown heating needed for independent crown fire. Fire scarred snags in pre-settlement stands suggest the occurrence of lightning strikes that burned individual trees (Clark and Starkey 1990).

Fire suppression, livestock grazing, and the cessation of aboriginal burning have changed the fire regime. The cumulative result of factors preventing the reoccurrence of fire has been significant increases in fire return intervals. As fire regimes shift to longer intervals between events, western juniper stands are able to establish and develop under an altered disturbance regime trending toward stand closure with significant reductions in the diversity and abundance of shrub and herbaceous understory species.

Post Settlement Woodland Development

At current levels of livestock grazing and fire control, the conversion of sagebrush steppe communities to western juniper woodlands represents the final phase of vegetation succession in parts of Oregon, California, and Idaho (Miller and Tausch 2001). Its rapid expansion is partially attributed to its being well

adapted to many northwestern soils and climates (Bedell 1987, Leonard et al. 1987, Megringer and Wigand 1987). However, it is largely thought that post-settlement increases in fire return intervals in addition to relatively wet climatic conditions around the turn of the century have been the most significant factors promoting western juniper expansion.

Prior to settlement, fire return intervals were sufficient to limit the encroachment of juniper into more productive sagebrush steppe communities on deeper soils (Miller and Tausch 2001). However, as fire-free periods began increasing in duration, juniper readily invaded these communities. The period of time necessary for the complete conversion of sagebrush steppe juniper woodland is likely variable across a given landscape and dependent on both rate of tree establishment and site potential. Miller and Rose (1999) reported, in eastern Oregon, post-settlement western juniper stands were in various stages of woodland development ranging from open to closed communities even though initial tree establishment began during the 1860s for all the stands investigated, thereby suggesting site related factors may be influencing the rate at which stand closure is reached. Reports in the literature indicate that the minimum time required to reach stand closure is 60 to 90 years (Barney and Frischknecht 1974, Miller and Rose 1995, Miller et al. 1999) with the potential for rapid stand closure within 45 to 50 years following establishment (R.F. Miller unpublished data). Milne et al. (1996) reported that woodland dominance across a landscape also affects the rate of encroachment and closure of adjacent open areas. They concluded that when

woodland dominates about 60% of the landscape, residual open sagebrush steppe communities are replaced at an accentuated rate.

Fuels in Juniper Woodlands

Changes in Fuels

During woodland development, understory plant composition, structure, production, and fuel characteristics change. It has been reported that in many juniper woodlands, the understory is often sparse (e.g. Tausch and Tueller 1990) and species diversity and seed reserves frequently decline with woodland development (Erdman 1970, Koniak and Everett 1982). However, Miller et al. (2000) found the influence of western juniper canopy cover on herbaceous species diversity and richness varied depending on the site. They found no significant reduction in herbaceous species richness or diversity on deep, well-drained soils, although they did see declines in cover, diversity, and richness where restrictive soil layers were present within 45 cm of the surface. Although cover is often indicative of production, no biomass data were recorded in this study.

In contrast to the herbaceous layer, there have been several accounts of shrubs declining across all soil types in big sagebrush communities during woodland development (Cottam and Stewart 1940, Barney and Frischknecht 1974, Adams 1975, West 1984, Tress and Klopatek 1987, Tausch and West 1988, 1995, Miller et al. 2000). Miller et al. (2000) concluded that the decline in mountain big sagebrush cover during woodland succession is not proportional to the increase in juniper cover. They reported that as the woodland canopy approaches 50% of

maximum potential for the site, big sagebrush cover and biomass decline to approximately 20-25% of maximum potential.

As the crown of an established western juniper expands over time, understory herbaceous production declines from the combined effects of shading, tree litter accumulation, and reductions in soil moisture (Agee 1994). Thus, trees create their own fine fuel break, so these stands may be virtually fireproof except under the most severe burning conditions. Numerous studies have reported relatively rapid declines in understory vegetation as pinyon and juniper increase in density (e.g. Schott and Pieper 1985, 1987, Tausch et al. 1981, Tausch and West 1995). Juniper and pinyon-juniper woodlands typically have a greater percentage of intact understory at higher elevation sites and on slopes with low exposure (West et al. 1978, Tausch and Tueller 1990) indicating a moisture threshold may exist in which the competitive ability of understory species is greatly diminished. This also suggests that stand flammability thresholds may occur at different phases of woodland development or stand densities depending on a site's environmental attributes (i.e. exposure, moisture, elevation). Numerous studies have also documented dramatic increases in herbaceous production following removal of juniper by chaining, cutting, or burning (Bates et al. 1998, Clary 1971, Miller and Wigand 1994, Everett and Sharrow 1983), again suggesting that juniper limits understory vegetation through interspecific competition. Under closed canopies, natural compaction of heavy fuels and their low surface area-to-volume ratio, such as downfall and thick duff, suffocates oxygen and usually produces creeping, smoldering fires. Because of increased shrub growth, open canopies effectively

transform vertically compact fuel into vertically expanded fuel where combustible energy becomes instantaneously exposed to oxygen. Thus a change in vertical distribution of fuel can transform creeping, smoldering fires into running conflagrations (Agee 1997), or vice versa as the case may be.

Many western juniper woodlands have advanced to a point where prescribed fire is no longer a viable management option. For example, in extremely dense stands, prescribed burning would be both hazardous and expensive. However, some reports in the literature suggest that a temporal window or threshold may exist in which western juniper stands are still susceptible to fire. For instance, Bunting (1990) reported that western juniper sites with less than 600 kg/ha of fine fuels did not burn. Wink and Wright (1973) found a minimum of 454 kg/ha of fine fuels and 907 kg/ha of fine fuels optimal to carry fire through Ashe juniper stands.

In Texas, woodlands with tree canopy cover exceeding 35% were capable of supporting a crown fire (Bryant et al. 1983). Assuming this threshold exists in other areas, numerous stands throughout the Intermountain West already support juniper canopies exceeding this threshold with many more having the potential (Miller and Tausch 2001). Recent pinyon/juniper woodland surveys of the East Walker River watershed in eastern California and Nevada indicate closed woodlands currently comprise about 33% of the woodland-dominated area. Surveys also indicate that the area of closed woodland will likely double in the next 40 to 50 years (Miller and Tausch 2001). Similar increases will likely occur

in the majority of woodlands throughout the Intermountain West, thus the potential for increasing risk of catastrophic wildfire needs further research and confirmation.

Fuel Loading Methodology

Downed Woody Material

Changes in fuel loading can be measured by inventorying surface fuels along the successional gradient of western juniper expansion within similar sites. Brown (1974) discusses methods to inventory weight, volume, and depth of downed woody material. Downed woody material is defined as dead twigs, branches, stems, and boles (trunks) of trees and shrubs that have fallen and lie on or are suspended above the ground. An inventory can provide detailed information of weights and volumes of dead fuels per area by diameter size class. The diameter size classes for woody material are defined as 0 – 0.6, 0.6 – 2.5, and 2.5 – 7.6 cm, indicative of 1-hour, 10-hour, and 100-hour fuels respectively. Data are collected using the line intersect technique.

Duff Loading

The relationship between depth and established bulk density of duff can be used to estimate weight recognizing that accuracy may be low (Brown et al. 1982). Measurement of duff depth was adopted for estimating weight because collecting and weighing duff is impractical for large inventories, the literature on duff bulk density seems substantial enough to use in estimating weight from depth, and depth of duff is a quickly obtained measurement useful for planning and evaluating fuel reduction projects. Although these inventory methods were

originally designed for forested ecosystems, the methods have proven applicable for rangeland and woodland fuels inventory (Brown et al. 1982, Bushey 1985).

Western Juniper Biomass Estimators

Gholz (1980) developed regression models (Table 1) for estimating western juniper component biomass, volume, surface area, and biomass increment using trees located along a northeast-facing slope at the summit of Horse Ridge in central Oregon at an elevation of 1,356 m. Vegetation at the site was classified as a juniper-sagebrush association.

Table 1. Regression models for estimating component biomass for western juniper with basal circumference (cm) as the independent variable. Equations follow the form $\ln(Y) = A + B * \ln(X)$ with variances ($S^2_{y,x}$) in logarithmic units (adapted from Gholz 1980).

Dependent Variable	A	B	$S^2_{y,x}$	R^2
Stem wood biomass (kg)	-8.5947	2.6389	0.029	0.995
Stem bark biomass (kg)	-10.251	2.6333	0.152	0.974
Whole stem biomass (kg)	-8.3939	2.6344	0.029	0.995
Live branch biomass (kg)	-7.3115	2.3337	0.068	0.985
Dead branch biomass (kg)	-11.8460	2.8323	0.664	0.908
Leaf biomass (kg)	-4.2430	1.5606	0.024	0.988

All live trees in seven 20 meter radius circular plots randomly located within a 1 ha area were nondestructively sampled. Ten western juniper trees, randomly selected from three size classes (0-75, 76-150, >151 cm in basal circumference), were destructively sampled. Stems and branches were sub-sampled, dried, and weighed. Surface areas of sub-samples were estimated and net aboveground primary production was estimated as the average annual biomass increment over the last five years. Regression models were developed using basal

circumference as the independent variable. The study area had 246 ± 20 live western juniper/ha.

Big Sagebrush Biomass Estimators

Rittenhouse and Sneva (1977) developed regression models for estimating photosynthetic and woody aerial biomass of big sagebrush using samples collected from two different sites about 3.5 km apart on the Northern Great Basin Experimental Range located west of Riley, Oregon during a two year period. The first site was on a low terrace with deep soils that supported big sagebrush, green rabbitbrush, basin wild rye, bottlebrush squirreltail, Sandberg bluegrass, Idaho fescue, and Thurber needlegrass. The second site was on an alluvial fan with moderately deep soils supporting big sagebrush (*Artemisia tridentata* ssp. *wyomingensis* and *Artemisia tridentata* ssp. *vaseyana*), granitegilla, bottlebrush squirreltail, Sandberg's bluegrass, Idaho fescue, and Thurber needlegrass.

In July, whole big sagebrush plants were cut at ground level following measurements of height (H) and two measurements of crown width (W). The first (W_1) defined as the longest intercept of canopy with the second (W_2) taken on a perpendicular line bisecting the W_1 line. Plant height was measured to the tallest actively growing plant tissue. Photosynthetic biomass (i.e. ephemeral leaves) was removed from the woody portion, oven dried at 60°C , and expressed as grams on an oven-dry basis. Woody biomass was expressed as grams on an air-dry basis. Regression models were developed using sagebrush height and crown area as independent variables. Regression equations for estimating component biomass of big sagebrush are given in Tables 2 and 3.

Table 2. Regression equations for estimating photosynthetic biomass of big sagebrush using height (H), crown width (W_1 or W_2), and or elliptical crown area (A) as independent variables. Equations follow the form $\log(Y) = \beta_0 + \beta_1 * \log(X_1) + \dots + \beta_p * \log(X_p)$ with variances ($S^2_{y,x}$) in logarithmic units (adapted from Rittenhouse and Sneva 1977).

	Statistic					
	β_0	β_1	β_2	β_3	$S^2_{y,x}$	R^2
log W_1	-1.51	1.83			0.216	0.88
log $W_1 + \log W_2$	-1.53	1.47	0.413		0.208	0.89
log $W_1 + \log H$	-2.46	1.05	1.28		0.125	0.96
log $W_1 + \log W_2 + \log H^*$	-2.44	0.786	0.32	1.24	0.114	0.97
log W_2	0.90	1.62			0.316	0.73
log $W_2 + \log H$	-2.52	0.738	1.67		0.157	0.94
log $(W_1 + W_2)/2$	-1.47	1.88			0.195	0.90
log $(W_1 + W_2)/2 + \log H$	-2.36	1.13	1.19		0.114	0.97
log A	-1.86	0.929	1.19		0.234	0.85
log A + log H	-2.71	0.507	1.36		0.132	0.96
log H	-2.68	2.39			0.227	0.86

Table 3. Regression equations for estimating woody biomass of big sagebrush using height (H), crown width (W_1 or W_2), and or elliptical crown area (A) as independent variables. The equations follow the form $\log(Y) = \beta_0 + \beta_1 * \log(X_1) + \dots + \beta_p * \log(X_p)$ with variances ($S^2_{y,x}$) in logarithmic units (adapted from Rittenhouse and Sneva 1977).

	Statistic					
	β_0	β_1	β_2	β_3	$S^2_{y,x}$	R^2
log W_1	-2.06	2.55			0.326	0.86
log $W_1 + \log W_2$	-2.08	2.03	0.585		0.317	0.87
log $W_1 + \log H$	-3.43	1.40	1.86		0.204	0.95
log $W_1 + \log W_2 + \log H^*$	-3.41	1.03	0.450	1.81	0.192	0.95
log W_2	-1.21	2.25			0.456	0.72
log $W_2 + \log H$	-3.52	0.999	2.37		0.237	0.93
log $(W_1 + W_2)/2$	-1.99	2.61			0.300	0.88
log $(W_1 + W_2)/2 + \log H$	-3.30	1.51	1.74		0.190	0.95
log A	-2.58	1.30			0.330	0.85
log A + log H	-3.78	1.89	0.717		0.191	0.95
log H	-3.73	3.35			0.324	0.86

Methods

Study Area

The study areas are located in the semiarid region of the Intermountain West on Steens Mountain, in southeastern Oregon, and the Owyhee Mountains in southwestern Idaho (Figure 2).

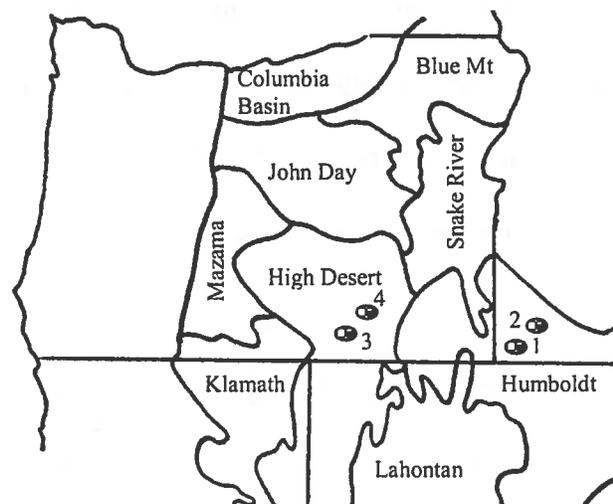


Figure 2. Map of the study locations. 1 = Juniper Mountain, Idaho, 2 = South Mountain, Idaho, 3 = South Steens Mountain, 4 = North Steens Mountain. (Ecological Provinces derived from Anderson et al. 1998 and Bailey 1994). Surrounding ecological provinces also given.

Owyhee Mountains

The Owyhee Mountains are located in Owyhee County, Idaho between the towns of Grand View, Idaho and Jordan Valley, Oregon. The geomorphology of this area is characterized as an uplifted region with doming and fault blocking common. The Owyhee Mountains are predominantly comprised of granite, however, most of the uplands are rhyolites and welded tuffs with silicic volcanic flows, ash deposits, and wind-blown loess. Topographic characteristic of this area include mountains dissected by deep canyons, rocky tablelands, and rolling plains ranging in elevation between 1200 and 2100 m. Mean annual precipitation ranges

between 300 mm at lower elevations increasing to > 560 mm at higher elevations and is primarily received in fall, winter and early spring. Average temperatures vary from -6.6°C in January to 34.5°C in July. The growing season ranges from 90 to 120 days but is less than 60 days at higher elevations. Soils vary from shallow rock outcrops to moderately deep gravelly, sandy, or silt loams (Harkness 1998). Predominant soil taxa are Aridisols, Entisols, Alfisols, Inceptisols, and Mollisols that occur in combination with mesic and frigid soil temperature regimes and xeric and aridic soil moisture regimes. Cryic temperature regimes occur at higher elevations typically above the western juniper woodland belt (600 – 2100 m).

The NRCS describes the area as having sagebrush-grassland potential natural vegetation. Vegetation is predominantly of two types, sagebrush-grasslands and western juniper woodlands (Burkhardt and Tisdale 1976). The major plant cover types occupying most of the valley slopes and bottoms are: 1) mountain big sagebrush (*Artemisa tridentata* ssp. *vaseyana* Rydb.) associated with either bluebunch wheatgrass (*Agropyron spicatum* Pursh) or Idaho fescue (*Festuca idahoensis* Elmer) on relatively deep, well-drained soils and 2) low sagebrush (*Artemisia arbuscula* ssp. *arbuscula* Nutt.) associated with bluebunch wheatgrass, Idaho fescue, or Sandberg bluegrass (*Poa secunda* Presl.) over restrictive layers of claypan or bedrock (Burkhardt and Tisdale 1976).

Steens Mountain

Steens Mountain is an isolated volcanic fault-block that lies in the extreme northwest Basin and Range Province (Fenneman 1931) in Harney County, south-

southeast of Burns (42° north latitude, 118° west longitude). The mountain is approximately 80 km long and oriented in a northeast direction (Baldwin 1981). Elevation of Steens Mountain ranges from 1268 to 2949 m, with a steep east-facing escarpment and a gentle west-facing slope.

Climate is characteristic of the northern Great Basin in that it is cool and semiarid. Mean annual precipitation at lower elevations is 220-280 mm and increases to ≥ 700 mm at higher elevations (NOAA 1993). The majority of the annual precipitation is received as snow in November, December, and January and as rain March through June.

Geomorphology of Steens Mountain is characterized as nearly level basins and valleys that are bordered by long, gently sloping alluvial fans. North-south trending mountain ranges and few volcanic plateaus rise sharply above the valleys. Large alluvial fans have developed at the mouths of most canyons. Pliocene volcanic and shallow intrusive igneous rocks occur, along with andesite, breccias, and basalt flows. Alluvial deposits, playas, marshes, and flat deposits occur in the valleys. The soil taxa comprising this area are Aridisols and Mollisols with frigid and mesic soil temperature regimes and xeric and aridic soil moisture regimes.

Western juniper woodlands on Steens Mountain form a discontinuous belt between 1450 and 2100 m in elevation. Above 2100 m, extremes in temperatures and severe winter conditions limit western juniper establishment (Miller and Rose 1995). Limited distribution below 1500 m is likely an artifact of late spring frosts (Billings 1954) coupled with limiting moisture. Plant alliances characteristic of western juniper woodlands are mountain big sagebrush, low sagebrush and

quacking aspen (*Populus tremuloides* Michx.) (Miller and Rose 1995). Other woody species commonly associated with these alliances are green rabbitbrush (*Chrysothamnus viscidiflorus* Hook.), chokecherry (*Prunus virginiana* L.), and antelope bitterbrush (*Purshia tridentata* Pursh). Common diagnostic grass species that separate alliances to the plant association level are bluebunch wheatgrass, Idaho fescue, basin wildrye (*Elymus cinereus* Scribn. & Merr.), Sandberg bluegrass, bottlebrush squirrel-tail (*Sitanion hystrix* Nutt.) and Columbia needlegrass (*Stipa columbiana* Macoun).

Sampling Procedures

Overview

To describe the spatial and temporal attributes of woodland expansion across southeastern Oregon and southwestern Idaho, space was substituted for time by sampling stands in different phases of woodland development. Stands were selected stands that represented a large proportion of the High Desert and Humboldt Ecological Provinces and elevations in which western juniper is actively expanding. To gain a regional perspective of woodland expansion, four transects extending a total of 68 km and 340 plots were measured in 2001. Criteria employed for locating transects follow: 1) to achieve sample size and sampling efficiency, transects were located along tenable roads easily accessed with a vehicle, 2) to ensure sampling covered environmental extremes, transects spanned the elevational gradient from below to above the juniper belt, and 3) to ensure representation, transects covered a wide array of environments to represent as much environmental heterogeneity as possible of sites occupied by western juniper

across the ecological provinces. Suitability of transect locations was determined by field reconnaissance and with the aid of aerial photos. All transects extended the elevational gradient from below to above the juniper woodland belt, with the exception of Juniper Mountain, in which the woodland belt extended to its summit. Transects were identified by their respective location as follows: North Steens, South Steens, South Mountain, and Juniper Mountain (Figure 2).

Extensive Sampling

To characterize western juniper woodlands developing on heterogeneous landscapes an extensive sampling procedure was adopted during the first field season. The extensive procedure was designed to rapidly sample a large number of stands to gain a regional perspective of spatial and temporal dynamics of woodland development. Circular plots were established perpendicularly to each transect line in sets of three every 500 meters. A variable plot radius was employed to improve sampling efficiency (Figure 3).

The extensive plot radius was selected at each location based on a cursory estimation of stand density: 15, 20, and 30 meter radii were employed on plots with greater than 600 trees/ha, between 200 and 600 trees/ha, and with less than 200 trees/ha, respectively. Employing smaller plot radii for stands with higher tree densities improved sampling efficiency by reducing time spent on tree measurements.

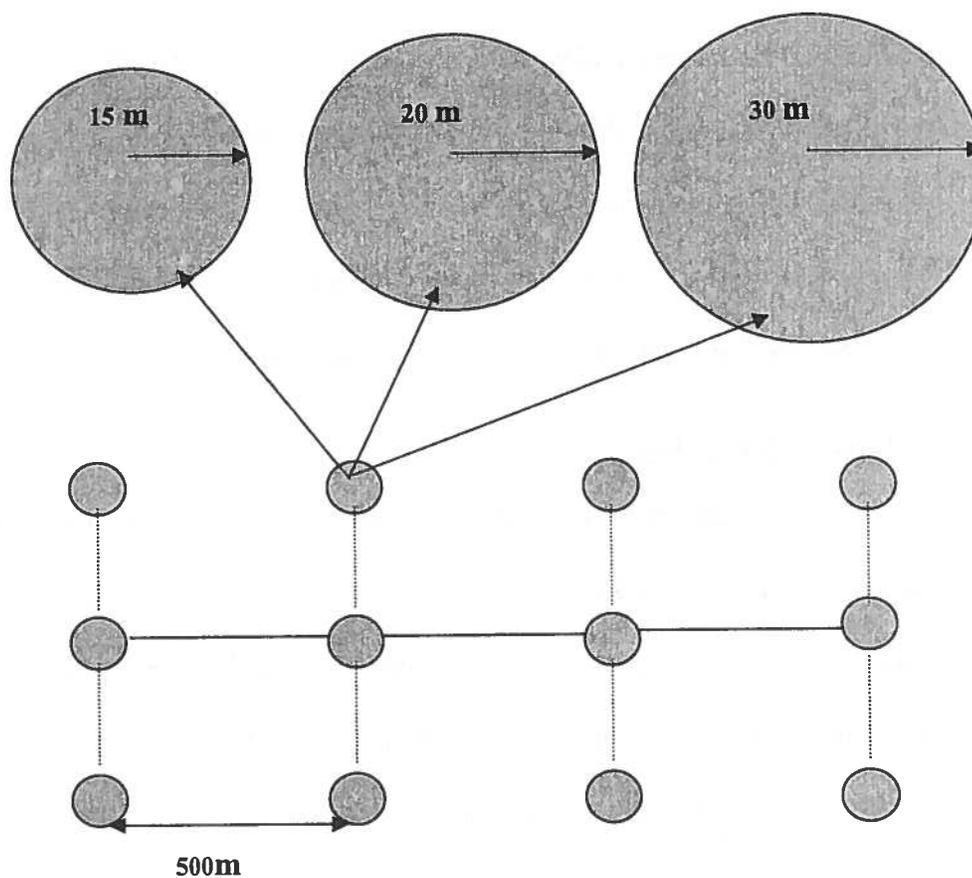


Figure 3. Extensive plot layout and design.

The selection of plot location was based on ecological site characteristics (e.g. aspect, topography, soil, and vegetation alliance) being uniform across an area of at least 0.5 ha. Vegetation alliances were denoted by the dominant shrub species present. UTM coordinates, percent slope, aspect, elevation, micro-topography, topographic position, and soil depth were recorded for each plot. Topographic positions were identified by the stand's location on the landscape (Figure 4). Micro-topography was determined by curvature along the contour of sloping terrain (Figure 5).

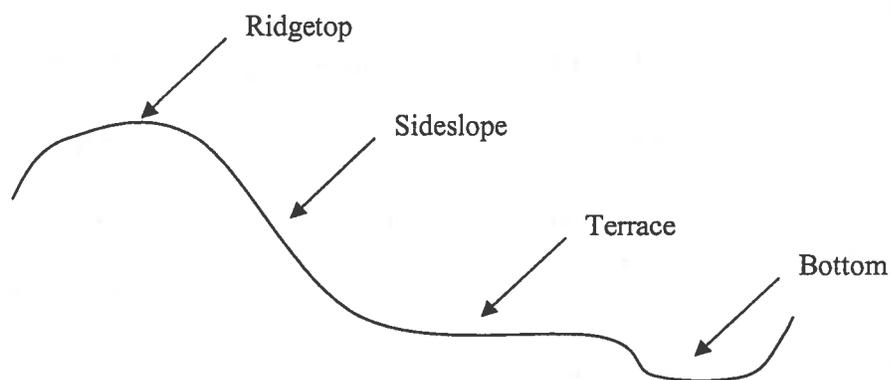


Figure 4. Classification of topographic positions.

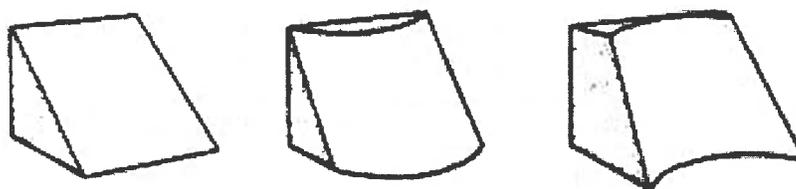


Figure 5. Classification of micro-topography (slope curvature) as flat, convex, and concave.

Phase of woodland development (i.e. I, II, III) was assigned to each stand following the guidelines developed by Miller et al. (2000) (Table 4). Phases can be described as:

- Phase I - trees are present but shrubs and herbs are the dominant vegetation that influence ecological processes on the site;
- Phase II - trees are co-dominant with shrubs and herbs and all three vegetation layers influence ecological processes on the site;
- Phase III - trees are the dominant vegetation and the primary plant layer influencing ecological processes on the site.

Tree canopy cover during phase I is typically less than 10 percent, comprised primarily of juveniles (< 1m) and few saplings (1 – 3 m), whereas phase II stands can be comprised of interspersed older dominant trees among

young trees and commonly approach cover values of 10 to 49 percent.

Characteristics employed for differentiation between phases II and III follow: 1) leader growth exhibited by understory trees is suppressed by intraspecific competition as stands approach a full stocking of dominant trees in phase III (threshold ~ terminal 10 cm, lateral 6 cm), and 2) during phase II a portion the shrub layer remains intact, whereas during phase III live shrubs are nearly to completely absent and dead shrub skeletons are common to abundant.

Table 4. Characteristics of phases of western juniper stand development in several mountain big sagebrush associations. Estimated maximum western juniper cover is 25 – 41% in Thurber needlegrass, 34 – 58% in Idaho fescue, and 60 – 75% in Columbia needlegrass associations (adapted from Miller et al. 2000).

Characteristic	Phases of Woodland Development		
	Phase I	Phase II	Phase III
Tree Canopy (% of Max Potential)	Open, actively expanding ($\leq 10\%$)	Actively expanding (10 to 49%)	Expansion reduced (50 to 80%)
Leader Growth ¹ (cm/yr)	terminal > 10 lateral > 10	terminal > 10 lateral > 10	terminal < 10 lateral < 10
Crown Lift ²	Absent	Absent	Present where tree canopy > 40%
Potential Berry Production	Low	Moderate to high	Low to moderate
Tree Recruitment	Active	Active	Reduced, limited primarily to beneath trees
Understory Leader Growth (cm/yr)	Leader growth (terminal >10 lateral >6)	Leader growth (terminal > 10 lateral > 6)	Leader growth (terminal < 10 lateral < 6)
Shrub Layer	Intact	Nearly intact to significant	$\geq 75\%$ dead thinning

¹During phase III, leader growth in mature trees is usually confined to the upper 1/3 of the canopy.

²Crown lift is the mortality of lower tree limbs usually due to intraspecific competition.

Plant species present were recorded in order of importance to identify the cover class. Cover by functional class was estimated. Functional classes included trees, shrubs, perennial grasses, perennial forbs and annuals. Tree density was counted and recorded in classes. Classes were based on tree height and age consisting of the following: 1) juvenile < 1 m, 2) sapling 1-3 m, 3) sub-dominant 3 m to 75% of the potential height yielded by a particular site, 4) dominant > 75% of the potential height, and 5) pre-settlement > 150 years. Potential height was assumed to be the height of the tallest tree present in the primary canopy of the stand. Pre-settlement trees were identified in the field by considering differences in morphology between pre- and post-settlement age class trees following Waichler et al. (2001). Major morphological differences follow: 1) pre-settlement trees, trees older than 150 years, tend to have rounded, nonsymmetrical crowns with a high proportion of decadence, whereas younger trees are more regular and conical in shape, 2) pre-settlement bark is typically more deeply furrowed and less flaky than trees younger than 150 years old, 3) lateral and terminal leader growth associated with pre-settlement trees is generally limited to less than 5 cm/yr, while 5 cm/yr is commonly exceeded by post settlement age class trees, especially in relatively open stands, and 4) the presence of slow forming lichen (i.e. *Letharia vulpina* and *Letharia columbiana*) on the branches and bark of pre-settlement trees is common, whereas it is typically absent on trees younger than 150 years.

To estimate the period of initial western juniper post-settlement encroachment, the three tallest post settlement trees were aged. An increment core was collected at 30 cm above ground level. Samples were mounted, sanded, and

rings were counted. If coring missed the pith, the pith radius was estimated graphically (Villaba and Veblen 1997). During the second field season, 300 juvenile trees (15 to 45 cm) were sampled and aged from interspace areas to correct for core sample height.

Intensive Sampling

To facilitate a more detailed investigation of age and stand structure and associated fuel loading characteristics across phases of woodland development and varying environmental conditions, an intensive sampling procedure was adopted on a 40% sub-sample of the extensive plots located along the Juniper Mountain transect in 2002. A total of 30, 46 x 60 m intensive plots were located along the Juniper Mountain transect between 1500 and 2015 m in elevation for this portion of the study.

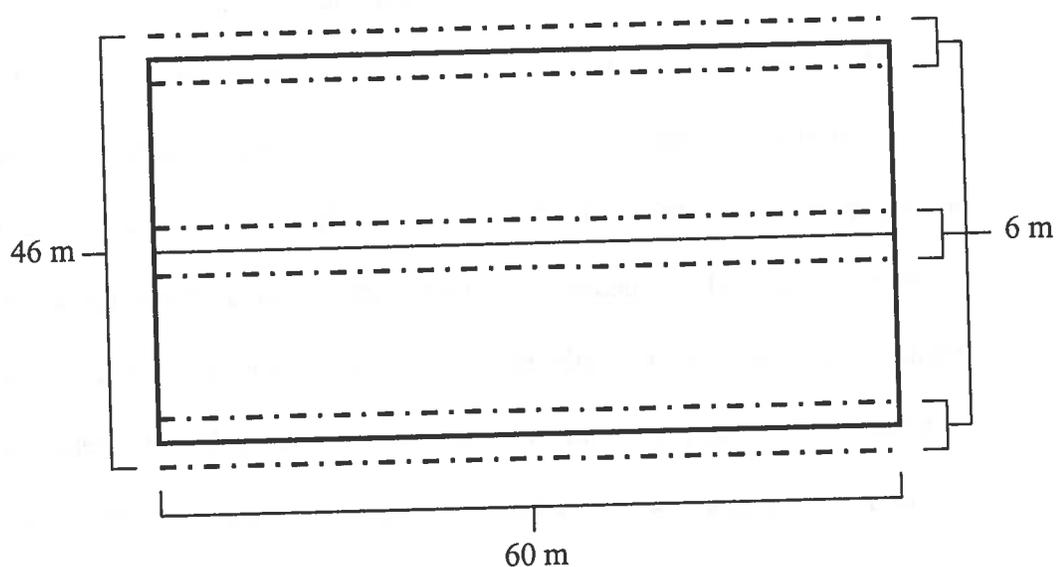


Figure 6. Belt transects (6 x 60 m) established at each intensive plot for tree measurements. Intensive plots were positioned parallel along the contour of sloping terrain.

Three 6 x 60 m belt transects were established (Figure 6) for tree measurements in each intensive plot. Tree density was determined by recording each tree rooted in the 6 x 60 m belt transect in one of the tree classes described in the procedures for the extensive plots. Basal diameter above the root crown was measured at 30 cm above ground on each tree. When a tree branched at the base, the basal area of each trunk present was measured. Basal diameter was used to estimate tree component biomass (Gholz 1980), yielding an estimate of the contribution to live fuel loading by juniper. Tree height, crown height and average crown diameter was measured for the live portion of individual tree canopies, and the percent of the crown that was dead was estimated. Tree canopy cover was determined for each stand from the sum of the individual crown areas divided by the area sampled. Dominant and subcanopy trees were differentiated in the field as described in the extensive sampling procedure, and only crown areas of dominant trees were employed for estimating canopy cover at the stand level. Where present, ten trees per tree class (i.e. juvenile, sapling, sub-dominant, and dominant), totaling forty trees per intensive plot, were aged to determine stand chronology. All trees with a pre-settlement growth form encountered in plots were aged. An increment core was collected from trees greater than 6 cm in basal diameter 30 cm above ground level. Samples were mounted, sanded, and rings were counted. If coring missed the pith, the pith radius was estimated graphically (Villaba and Veblen 1997). Trees less than 6 cm in basal diameter were cut at ground level and a 4 – 8 cm disk was retrieved from the base. Disk samples were sanded and rings were counted. A sample of 300 juveniles (15 to 45 cm) was

collected from interspace areas and the mean age of a tree 30 cm tall was determined to correct age for core sample height.

Ring widths (i.e. distance between successive growth rings) on core samples were measured, divided by the overall mean ring width, and resulting relative growth rates were plotted graphically to estimate years transpired since establishment until stand closure for phase III woodlands. For phase III stands, relative growth curves were evaluated to determine when a constriction in ring widths occurred. A persistent constriction in ring widths to below the long term average was assumed to be indicative of increasing intraspecific competition, increasing canopy density, and high juniper dominance over site processes, and thereby indicative of stand closure. This procedure yielded estimates of time in years transpired since initial post settlement tree establishment, estimated during extensive sampling, until stand closure.

Fuels were also measured in each plot. The number of intersections by downed dead woody material were tallied by diameter class along the upslope boundary (meter tape) of the middle 60m transect (Figure 6) and biomass for each diameter class (one, ten, hundred and thousand hour fuels) was estimated (Brown 1974). The average depth and diameter of the litter mat under each aged tree was recorded and biomass estimates for duff were generated (Brown et al. 1982). The average depth of litter was determined by measuring the height of the duff profile in centimeters to mineral soil in the four cardinal directions from each tree halfway between canopy dripline and bole. The four measurements were then averaged to determine the average depth of the litter mat around each aged tree. Duff depth

was estimated for stands by averaging all the duff measurements of aged trees and biomass estimates were generated as a function of bulk density and depth of duff with the following equation (Brown et al. 1982):

$$\text{Duff loading (kg/m}^2\text{)} = 0.15 * \text{bulk density (kg/m}^3\text{)} * \text{mean depth (m)}$$

Shrubs and grasses were measured within five regularly located belt transects (2 x 12 m) partitioned into 6, 1 m² microplots (Figure 7). Microplots were placed on alternating sides of the transect starting on the left facing the center of the plot. Elliptical crown diameter and maximum height measurements were obtained on mountain big sagebrush plants to estimate crown area, percent cover, and shrub biomass (Rittenhouse and Sneva 1977). Perennial grasses and forbs were measured and clipped to determine basal area, percent cover, and biomass in 20, 1 m² microplots. Bare ground, litter, rock, and microphytic crust cover was visually estimated for each 1 m² vegetation microplot.

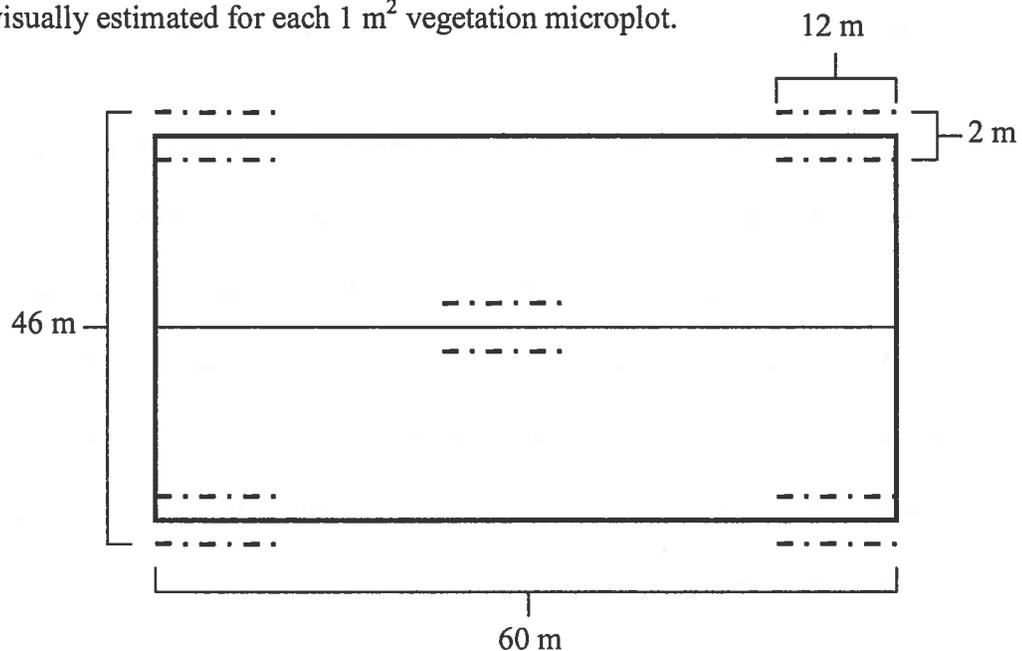


Figure 7. Vegetation belt transects (2 x 12 m). Orientation of vegetation belt transects to 46 x 60 m intensive plots are denoted by dashed lines.

Data Analyses

Spatial and Temporal Dynamics of Woodland Expansion

Descriptive Analyses

Following data collection in the field, sampled stands were successively stratified by study location, presence/absence of trees, phase of woodland development, presence/absence of pre-settlement age class trees, and associated shrub species. This yielded estimates of the extent of the study area supporting juniper, the status of woodland expansion across the landscape, and the pre-settlement composition of juniper. The pre-settlement age class and total tree densities were determined to describe general changes in the abundance of juniper across the study area since settlement. Decadal frequency of initial stand establishment was graphically summarized and compared by study area.

Relationship of Presence of Pre-settlement Trees with Post-settlement Stand Initiation

A one-way analysis of variance (ANOVA) was conducted to determine the effect of the presence (i.e. age class = 1) or absence (i.e. age class = 0) of pre-settlement trees within stands on post settlement woodland age. The following ANOVA model describing Y , post settlement woodland age (i.e. average age of the three tallest post settlement age class trees present in a stand), was fit to data from all 186 stands that were associated with mountain big sagebrush sampled across the entire study area:

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij},$$

where $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and ε_{ij} and $\varepsilon_{i'j'}$ are independent and where:

Y_{ij} is the post settlement woodland age of the j^{th} stand for the i^{th} factor level (presence/absence of pre-settlement trees);

μ is the overall mean of post settlement woodland age;

α_i is the fixed effect of the i^{th} age class; and

ε_{ij} is the random effect of each stand that adds variability to the value of Y .

The model assumes that variance in post settlement woodland age among stands with same values of the explanatory variables is similar to the variance in tree age among stands with different values of explanatory variables. Initial exploratory analyses indicated that the ANOVA model assumption of normality, or at least symmetry, of the residuals appeared to be adequately satisfied (Figure 1 appendix) as was the ANOVA model assumption of homogeneity of variance with respect to predicted value (Figure 2 appendix), so no transformation of the response was necessary.

Influence of Environmental Variables on Post-settlement Juniper Establishment

Relationship of Rate of Post Settlement Juniper Establishment with Environmental Variables

To address the question of the relationship of Y , the rate of post-settlement juniper establishment, with site exposure and elevation among stands associated with mountain big sagebrush the following model was fit to data from all phase III stands; analyses were limited to phase III stands because they have approached a full stocking of dominant trees in the primary canopy and nearly a full stocking of subdominant trees in the secondary canopy, thus yielding better estimates of rate of juniper establishment from post settlement stand initiation to stand closure ($n = 77$):

$$Y_i = \beta_0 + \beta_1 * X_{1i} + \beta_2 * X_{2i} + \varepsilon_i$$

where $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and ε_i and $\varepsilon_{i'}$ are independent, the β 's are the linear regression coefficients and where:

Y_i is the post settlement rate of juniper establishment in the i^{th} stand. The post settlement rate of juniper establishment is the density of trees less than 130 years of age divided by the post-settlement age of each stand sampled, yielding the number of post-settlement trees established per hectare per year.

X_{1i} is the site exposure index calculated employing the following equation for the i^{th} stand:

$$\text{Site exposure} = \text{percent slope} * \cos(\pi * (\text{aspect} - 190)/180)$$

(Balice et al. 2000);

X_{2i} is the elevation measurement in meters for the i^{th} stand;

β_1 is the estimate of the regression of Y on site exposure;

β_2 is the estimate of the regression of Y on elevation; and

ε_i is the random effect of each stand that adds variability to the value of Y.

This model assumes a linear relationship between rate of post settlement juniper establishment and the explanatory variables. In addition, the model assumes that variance in post settlement tree establishment among stands with similar values of the explanatory variables is the same as the variance in post-settlement rate of tree establishment among stands with different values of explanatory variables. Initial exploratory analyses indicated that the model assumption of normality, or at least symmetry, of the residuals appeared to be adequately satisfied (Figure 3 appendix) as was the model assumption of homogeneity of variance with respect to predicted value (Figure 4 appendix) so no transformation of the response was necessary.

Relationship of Time Required to Reach Stand Closure with Environmental Variables

During 2002, 30 stands on Juniper Mountain, Idaho were revisited and tree ages were intensively sampled. Ring widths (i.e. distance in mm between successive growth rings) on core samples were measured, relativized by the overall mean growth ring width, and the resulting relative growth rates were plotted overtime to determine the time required to reach stand closure. A persistent constriction of ring widths to below the overall average ring width was considered indicative of accentuated competition among trees, increased control of site resources by juniper, declines in understory herbaceous and shrub components, and stand closure. Thirteen stands were classified as being in phase III of stand development using criteria described in the extensive procedure and validated by analyzing relative growth rate curves. Thus, to address the question of the relationship of time required to reach stand closure with site exposure and elevation among phase III stands associated with mountain big sagebrush the following model was fit to the data ($n = 13$):

$$Y_i = \beta_0 + \beta_1 * X_{1i} + \beta_2 * X_{2i} + \varepsilon_i$$

where $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and ε_i and $\varepsilon_{i'}$ are independent, the β 's are the linear regression coefficients and where:

Y_i is the time (years) transpired since initial tree establishment until stand closure (i.e. point in time in which ring widths constrict to below long term average ring width) in the i^{th} stand.

X_{1i} is the site exposure index calculated employing the following equation for the i^{th} stand:

$$\text{Site exposure} = \text{slope} * \cosine(\pi * (\text{aspect} - 190)/180) \text{ (Balice et al. 2000);}$$

X_{2i} is the elevation measurement for the i^{th} stand;

β_1 is the estimate of the regression of Y on site exposure;

β_2 is the estimate of the regression of Y on elevation; and

ε_i is the random effect of each stand that adds variability to the value of Y.

This model assumes a linear relationship between time transpired until stand closure and the explanatory variables. In addition, the model assumes that variance in time transpired until stand closure among stands with same values of the explanatory variables is the same as the variance in post-settlement age among stands with different values of explanatory variables. Initial exploratory analyses indicated that the model assumption of normality, or at least symmetry, of the residuals appeared to be adequately satisfied (Figure 5 appendix) as was the model assumption of homogeneity of variance with respect to predicted value (Figure 6 appendix) so no transformation of the response was necessary.

Influence of Environmental Variables on Woodland Structure

Relationship of Total Juniper Density with Environmental Variables in Phase III Stands

To address the question of the relationship of Y, juniper density (trees/ha), with site exposure (index) and elevation (m) among stands associated with mountain big sagebrush the following model was fit to data from all phase III stands ($n = 77$); analyses were limited to phase III stands because tree density has approached maximum for site potential allowing comparisons of potential stand structure over the sampled range of environmental variables:

$$Y_i = \beta_0 + \beta_1 * X_{1i} + \beta_2 * X_{2i} + \varepsilon_i$$

where $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and ε_i and ε_j are independent, the β 's are the linear regression coefficients and where:

Y_i is total tree density (trees/ha) for the i^{th} stand;

X_{1i} is the site exposure index calculated employing the following equation for the i^{th} stand:

$$\text{Site exposure} = \text{slope} * \cos(\pi * (\text{aspect} - 190)/180) \text{ (Balice et al. 2000);}$$

X_{2i} is the elevation measurement for the i^{th} stand;

β_1 is the estimate of the regression of Y on site exposure;

β_2 is the estimate of the regression of Y on elevation; and

ε_i is the random effect of each stand that adds variability to the value of Y .

This model assumes a linear relationship between total tree density and the explanatory variables. In addition, the model assumes that variance in total tree density among stands with same values of the explanatory variables is the same as the variance in total tree density among stands with different values of explanatory variables. Initial exploratory analyses suggested the need for log transformation of the response variable to equalize variance over the range of explanatory variables. After log transformation of the response variable, the model assumption of normality, or at least symmetry, of the residuals appeared to be adequately satisfied (Figure 7 appendix) as was the model assumption of homogeneity of variance with respect to predicted value (Figure 8 appendix).

Relationship of Dominant Juniper Density with Environmental Variables in Phase III Stands

In phase III woodlands, an important structural characteristic to consider independently is the density of dominant or overstory trees (i.e. trees taller than

juveniles and saplings). Not only are these trees likely more important in maintaining juniper's dominance over the site, but differences in dominant tree density over environmental gradients lend insight to the temporal window required for a particular stand to reach a state of woodland dominance given knowledge of environmental constraints. These differences may also be indicative of variation in phase III stand structure as woodlands develop under different environmental conditions. As part of the investigation, density of dominant trees was measured. To address the question of the relationship of Y , dominant tree density (trees/ha), with site exposure (index) and elevation (m) among stands associated with mountain big sagebrush the following model was fit to data from all phase III stands ($n = 77$):

$$Y_i = \beta_0 + \beta_1 * X_{1i} + \beta_2 * X_{2i} + \varepsilon_i$$

where $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and ε_i and $\varepsilon_{i'}$ are independent, the β 's are the linear regression coefficients and where:

Y_i is dominant tree density (trees/ha) for the i^{th} stand;

X_{1i} is the site exposure index calculated employing the following equation for the i^{th} stand:

$$\text{Site exposure} = \text{slope} * \cosine(\pi * (\text{aspect} - 190)/180) \text{ (Balice et al. 2000);}$$

X_{2i} is the elevation measurement for the i^{th} stand;

β_1 is the estimate of the regression of Y on site exposure;

β_2 is the estimate of the regression of Y on elevation; and

ε_i is the random effect of each stand that adds variability to the value of Y .

This model assumes a linear relationship between dominant tree density and the explanatory variables. In addition, the model assumes that variance in

dominant tree density among stands with same values of the explanatory variables is the same as the variance in dominant tree density among stands with different values of explanatory variables. Initial exploratory analyses suggested the need for log transformation of the response variable to equalize variance over the range of explanatory variables. After log transformation of the response variable, the model assumption of normality, or at least symmetry, of the residuals appeared to be adequately satisfied (Figure 9 appendix) as was the model assumption of homogeneity of variance with respect to predicted value (Figure 10 appendix).

Changes in Fuel Loading Associated with Stand Development Under Varying Environmental Conditions

One-way analyses of covariance (ANCOVA) were conducted to determine the effect of PHASE (i.e. phases I, II, and III of stand development) controlling for stand elevation and site exposure on the following eight fuel loading response variables: tree biomass/ha, shrub biomass/ha, herbaceous (fine) biomass/ha, duff biomass/ha, one hour fuel biomass/ha, ten hour fuel biomass/ha, hundred hour fuel biomass/ha, and thousand hour fuel biomass/ha. The following ANCOVA model describing Y, any of the eight fuel loading response variables, adjusted for elevation and site exposure was fit to data from 30 stands associated with mountain big sagebrush on Juniper Mountain, Idaho:

$$Y_{ij} = \mu + \alpha_i + \beta_1(X_{1ij} - X_{1ave}) + \beta_2(X_{2ij} - X_{2ave}) + \varepsilon_{ij}$$

where $\varepsilon_i \sim N(0, \sigma_\varepsilon^2)$ and ε_{ij} and $\varepsilon_{i'j'}$ are independent, the β 's are the linear regression coefficients and where:

μ is the overall mean value of Y;

α_i is the fixed effect of the i^{th} phase of woodland development;

β_1 is an estimate of the regression of Y on X_1 ;

X_{1ij} is the elevation measure of the j^{th} stand from the i^{th} PHASE;

X_{1ave} is the average elevation measure of the j^{th} stand from the i^{th} PHASE;

β_2 is an estimate of the regression of Y on X_2 ;

X_{2ij} is the site exposure measure of the j^{th} stand from the i^{th} PHASE;

X_{2ave} is the average exposure measure of the j^{th} stand from the i^{th} PHASE;

ε_{ij} is the random effect of each stand that adds variability to the value of Y.

This model assumes a linear relationship between fuels biomass and the explanatory variables. In addition, the model assumes that variance in tree age among stands with same values of the explanatory variables is similar to the variance in tree age among stands with different values of explanatory variables. Initial exploratory analyses consistently indicated that distributions of the fuel loading response variables over the 3 phases of woodland development showed more variability in phases II and III than phase I, thus all response variables were analyzed on the natural logarithmic scale to equalize variance prior to fitting the models. Following log transformation of response variables, the model assumption of normality, or at least symmetry of the residuals, appeared to be adequately satisfied as was the model assumption of homogeneity of variance with respect to predicted value (Appendices 11 – 26).

Results

Spatial and Temporal Attributes of Woodland Expansion

Post Settlement Woodland Expansion

About 95% of western juniper trees have established since 1850 in southwestern Idaho and southeastern Oregon. Across all stands sampled, pre-settlement age class tree density averaged about 13 trees/ha and current tree density averaged 322 trees/ha, representing about a 25-fold increase in juniper density. Considering only phase III stands (i.e. stands that have achieved a dominant canopy), tree density has increased from about 16 trees/ha prior to settlement (i.e. mid 1800s) to around 600 trees/ha currently, representing a 38-fold increase.

An average of all transects indicates 63% of stands have established after 1850 and thus were comprised strictly of post-settlement age class trees, 28% had at least one pre-settlement tree present, 4% had a primary canopy comprised principally of pre-settlement trees (i.e. primary canopy > 75% pre-settlement trees), and 4% lacked the presence of trees. On Juniper Mountain and South Mountain (n = 156), 42% of stands established after 1850 and were comprised strictly of post-settlement age class trees, 9% had a canopy predominantly comprised of pre-settlement trees (i.e. primary canopy > 75% pre-settlement trees), 42% had a minimum of one pre-settlement tree present in the stand, and 7% lacked presence of trees (n = 156). On north and south Steens Mountain (n = 184), 80% of the stands established after 1850 and were comprised strictly of post settlement trees, 0.5% were occupied predominantly by pre-settlement trees (i.e.

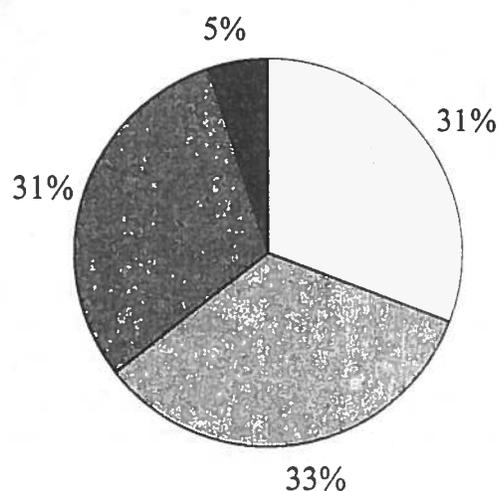
primary canopy > 75% pre-settlement trees), and 17% had at least one pre-settlement tree present, and 2% lacked presence of trees (n = 184).

Distribution of Western Juniper by Plant Alliance

Western juniper occurred in 96% of all stands sampled across the four study areas (i.e. South Mountain, Juniper Mountain, North Steens, and South Steens) (n=340). Stands associated with mountain big sagebrush occurred most frequently across the transects accounting for 186 sampled stands (55%), followed by low sagebrush, mountain mahogany, snowberry, bitterbrush, and basin big sagebrush with 82 (24%), 41 (12%), 19 (6%), 8 (2%), and 4 (1%) stands, respectively. Approximately 96% of the 186 stands associated with mountain big sagebrush had western juniper present. Nearly 70% of these stands were comprised strictly of post settlement trees (i.e. trees less than 130 years), 26% had at least one pre-settlement tree (i.e. trees greater than 130 years) present, 1% had a primary canopy comprised predominantly of pre-settlement trees (i.e. primary canopy \geq 75% pre-settlement trees), and 3% lacked trees. Low sagebrush had the highest proportion of stands dominated by pre-settlement trees (i.e. \geq 75% of the primary canopy was comprised of pre-settlement trees) accounting for 11% of sampled stands. Low sagebrush also had the highest proportion of mixed age stands (i.e. at least one pre-settlement tree present in the stand) accounting for 33% of sampled stands. Stands associated with low sagebrush, mountain mahogany, snowberry, bitterbrush, and basin big sagebrush had western juniper present in 91%, 98%, 95%, 100%, and 100% of sampled stands, respectively.

Phases of Stand Development

An average over all study locations indicates that approximately 31% of the sampled stands were classified in each of the three phases of development employed in this study (Figure 8). However, woodland development was more advanced across the landscape in Idaho compared to Oregon (Figure 9). An average of the two study locations in Idaho indicates that 82% of woodlands that are encroaching into mountain big sagebrush communities are in phases II and III of woodland development, whereas, phases II and III accounted for 54% of the stands associated with mountain big sagebrush on Steens Mountain, Oregon. Approximately 18% of stands in southwestern Idaho can be characterized as relatively intact mountain big sagebrush communities compared to 46% in southeastern Oregon.



□ Phase I ■ Phase II ■ Phase III ■ OG

Figure 8. Average proportion of stand development phases across the study area. Phase I = trees present but shrubs and grasses dominate the site, Phase II = trees co-dominate the site with shrubs and grasses, Phase III = trees dominate the site and shrubs and grasses have declined, and OG = stands with $\geq 75\%$ of the trees older than 150 years.

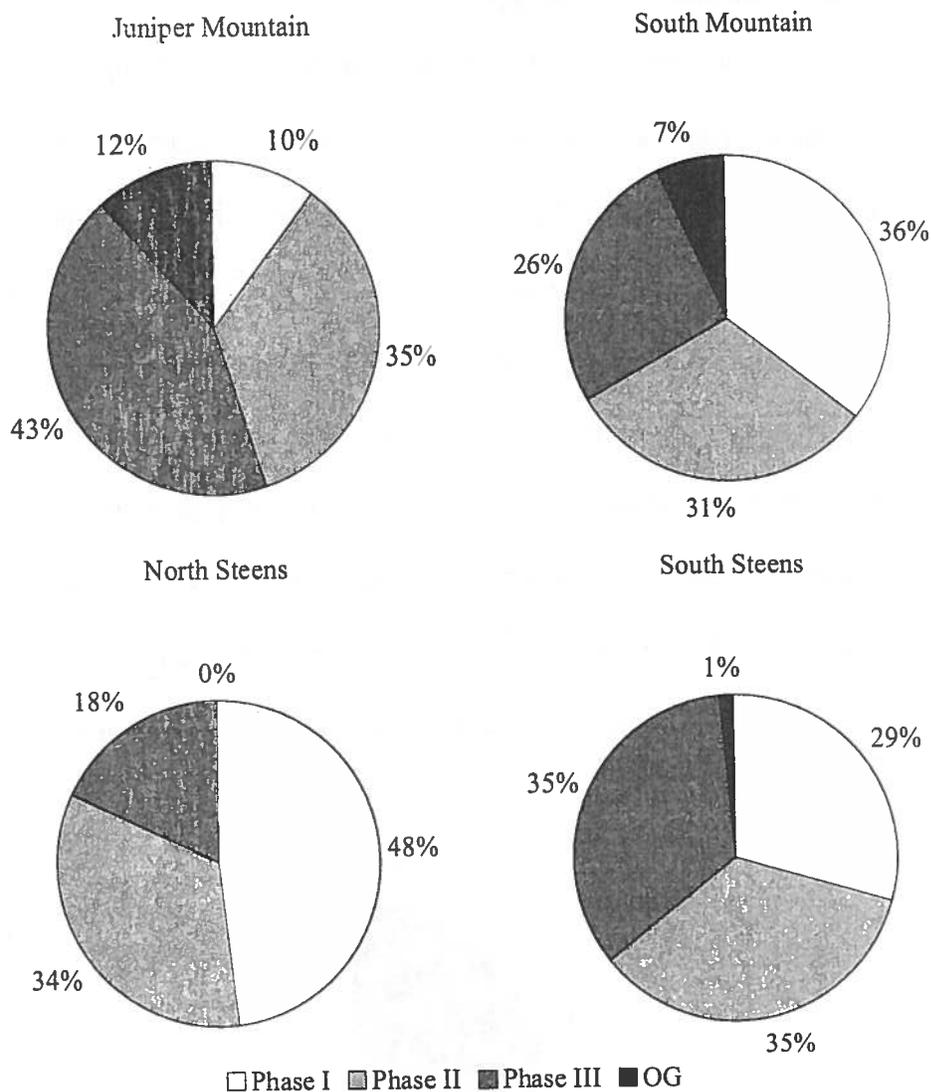


Figure 9. Proportion of stand development phases for each study location. Phase I = trees present but shrubs and grasses dominate the site, Phase II = trees co-dominant the site with shrubs and grasses, Phase III = trees dominate the site and shrubs and grasses have declined, and OG = stands with $\geq 75\%$ of the trees older than 150 years.

Pre-settlement Tree Composition and Stand Initiation

Stand Initiation in Southwestern Idaho and Southeastern Oregon

Juniper and South Mountains in southwestern Idaho had a higher proportion of pre-settlement woodlands (i.e. dominant overstory was comprised of $\geq 75\%$ pre-settlement age class trees) than North and South Steens Mountain,

Oregon (Figure 9). In addition, the proportion of Idaho stands supporting pre-settlement trees (i.e. presence of at least one pre-settlement age class tree) was also higher than the Oregon study locations (Figure 10), 58% and 23% respectively. However, although the Idaho study locations had a higher proportion of stands supporting old growth than Oregon, pre-settlement trees averaged 10 percent or less of total tree density for all locations (Figure 11).

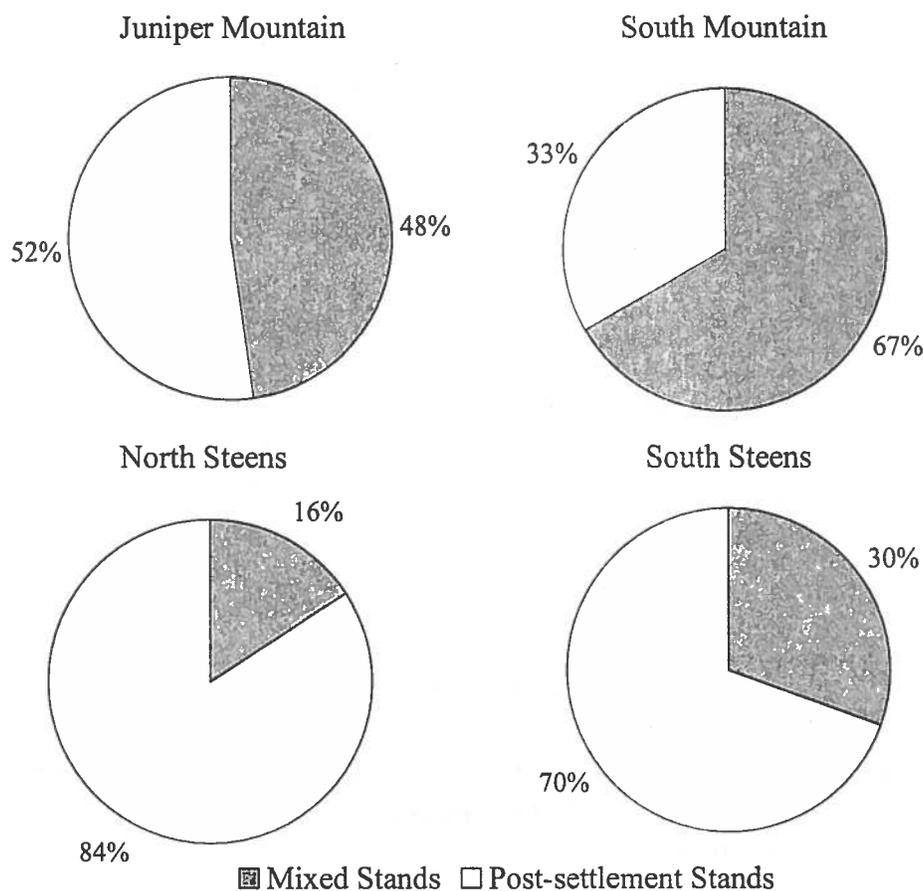


Figure 10. The proportion of mixed age and post settlement age stands for each study location. Mixed age stands supported at least one pre-settlement age class tree, but pre-settlement trees did not necessarily make-up the dominant overstory. Note that a higher proportion of Juniper and South Mountains supported pre-settlement trees than North and South Steens Mountain.

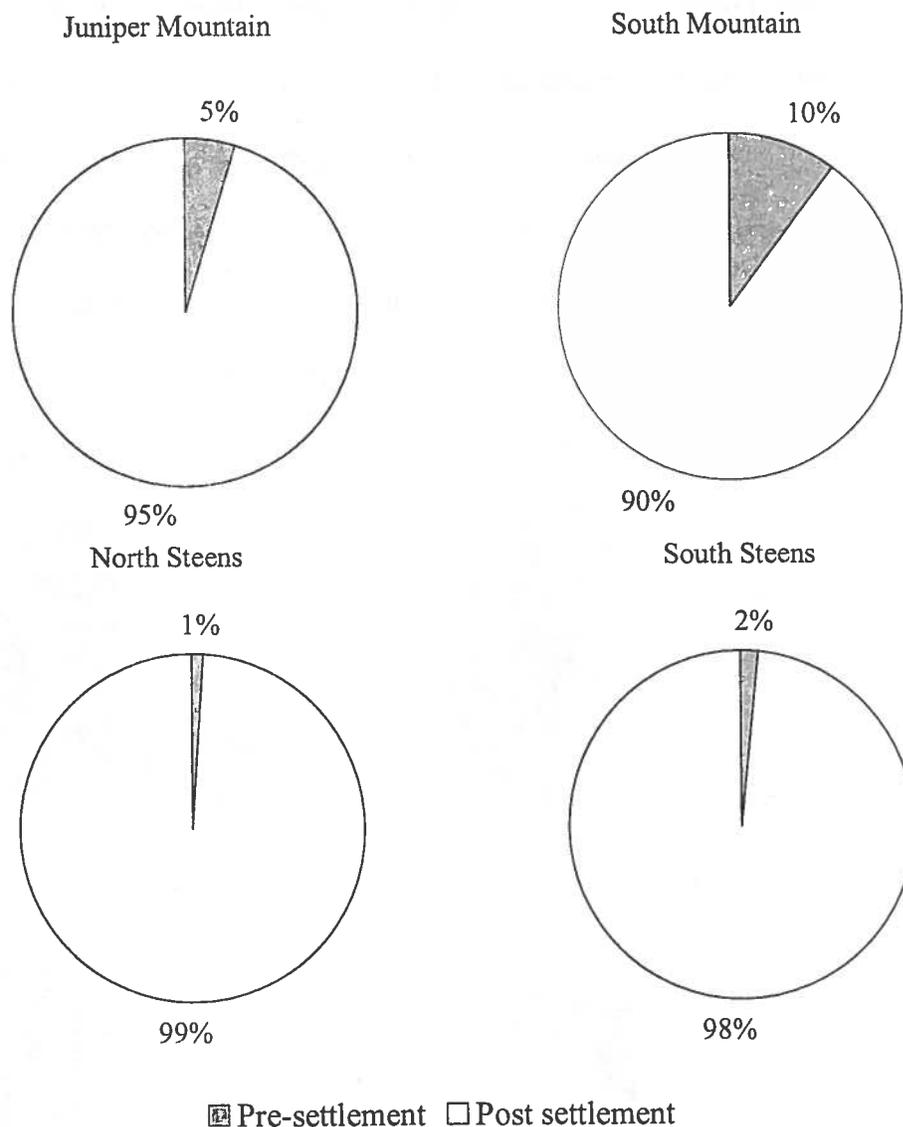


Figure 11. The proportion of total trees sampled ($n = 14,985$) that exhibited pre-settlement age class morphologic characteristics across the four study locations.

Relationship of Presence/Absence of Pre-settlement Trees with Post Settlement Woodland Age

The presence of at least one pre-settlement tree resulted in an earlier initiation of post settlement woodland expansion ($p < 0.0001$). We estimated that accelerated post settlement tree expansion began 24 years earlier in stands with at

least one pre-settlement tree present relative to stands that lacked the presence of trees prior to settlement (95% C.I.: 16 to 32 years) (Figure 12).

The presence of pre-settlement trees in a greater proportion of the Idaho stands was associated with an earlier initiation and more rapid rate of woodland expansion (Figure 13). Tree establishment in 15% of the sampled stands in southwestern Idaho occurred prior to 1850, whereas <1% of sampled stands in southeastern Oregon established during this time period. Greater than 99% of initial tree establishment occurred after 1850 in southeastern Oregon with a peak that occurred from the 1890s through the early 1900s. Approximately 21% of initial tree establishment occurred between 1870 and 1900 in southeastern Oregon. Conversely, greater than 50% of initial establishment corresponding to the southwestern Idaho sites occurred prior to the turn of the century.

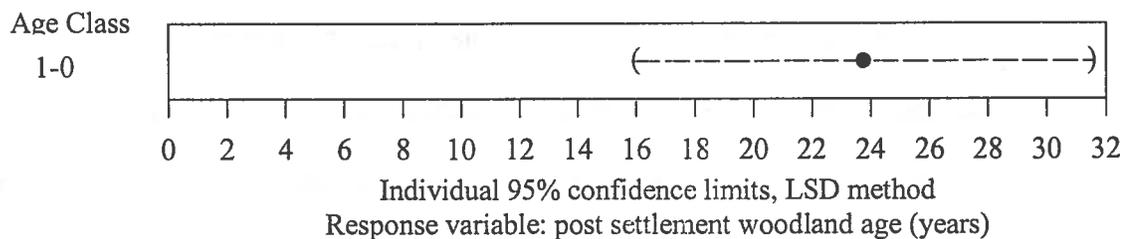


Figure 12. Confidence limits (95%) for the estimated difference in post settlement woodland age between stands that had trees present prior to settlement (i.e. age class = 1) and stands that lacked trees prior to settlement (i.e. age class = 0).

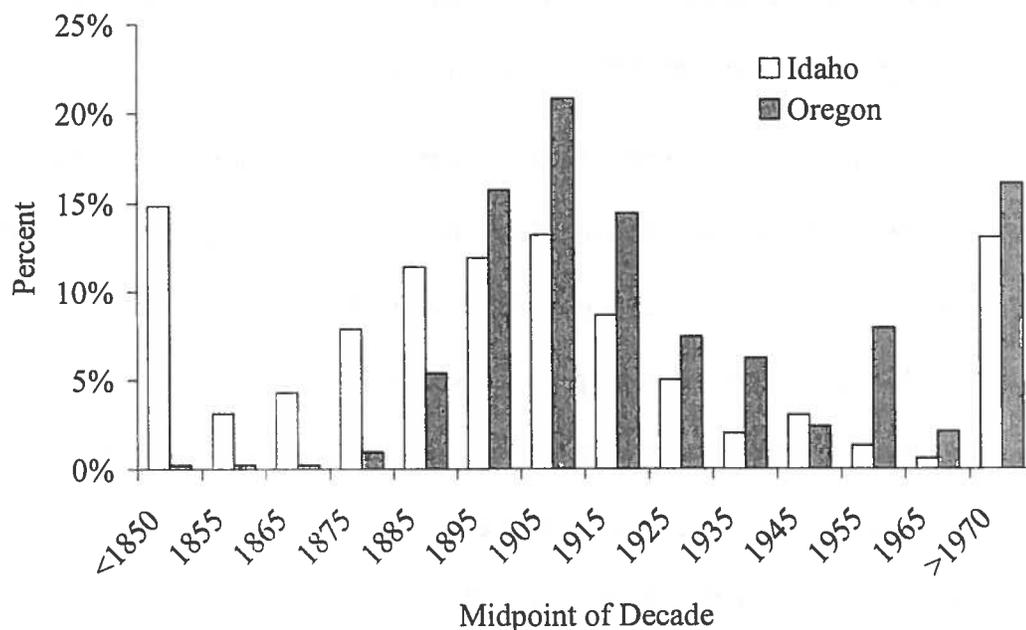


Figure 13. Combined decadal frequency of stand initiation for southwestern Idaho and southeastern Oregon study areas. Each column denotes the proportion of sampled stands that established during the corresponding time period. The final columns represent phase I stands or stands that lacked trees. Note the periods of earlier tree establishment for the Idaho study area.

When the chronology of individual tree establishment from 30 stands on Juniper Mountain, Idaho are plotted as a cumulative density curve (Figure 14), the result shows an establishment phase that occurred during the early 1800s. This initial phase of establishment was followed by a period of rapid population expansion beginning around 1850 and lasting through the mid 1900s. On Juniper Mountain, the initial establishment phase of rapid juniper expansion in sagebrush steppe communities occurred during the early 1800s, 50 or more years prior to settlement of the area.

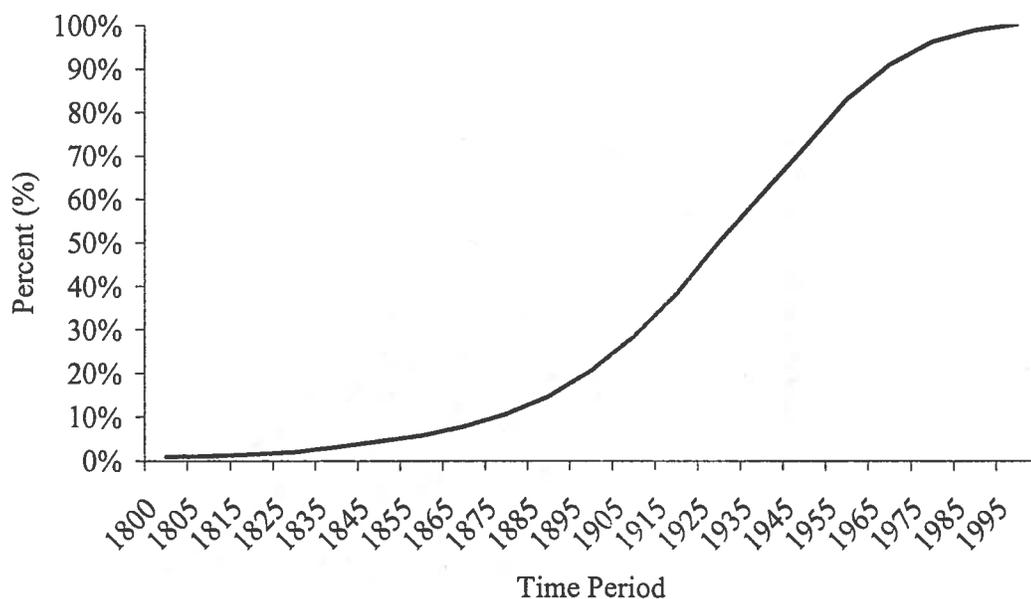


Figure 14. Cumulative distribution curve of tree establishment by decade for the combined data for 30 stands on Juniper Mountain, Idaho. Years represent midpoint of decadal time periods.

Influence of Environmental Variables on Rate of Woodland Development

Rate of juniper establishment (# trees established/ha/year) decreased with increasing site exposure (i.e. increasing southerly exposure) and increased with increasing stand elevation in stands associated with mountain big sagebrush (Figure 15). The regression model describing this relationship was (standard errors in parentheses below parameter estimates):

$$\text{Rate of Establishment} = -10.41 - 0.25 * \text{site exposure} + 0.009 * \text{stand elevation}$$

$$(4.73) (0.028) \qquad (0.0026)$$

with residual error = 2.4. The adjusted r^2 was 0.6.

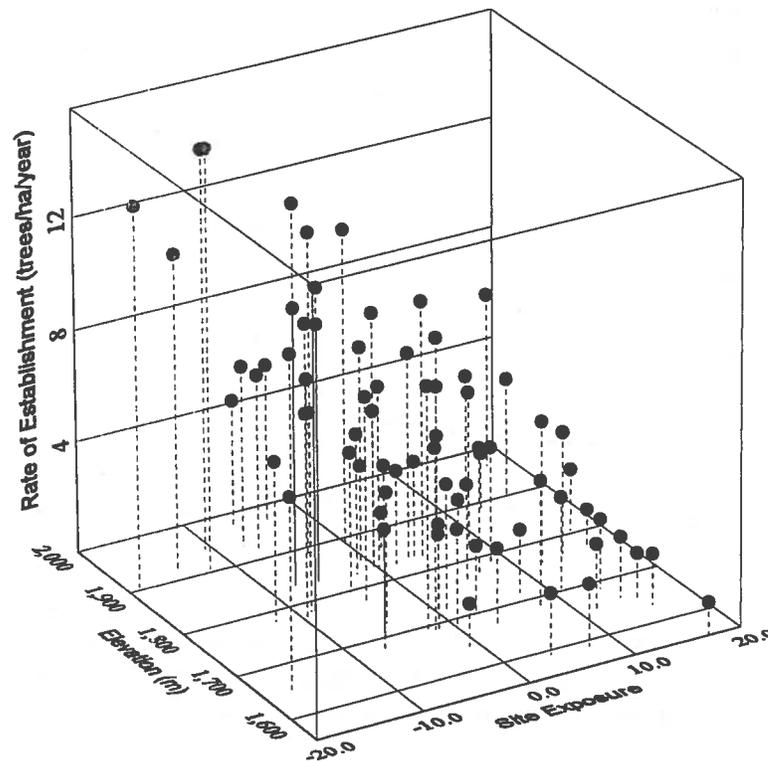


Figure 15. Relationship of rate of establishment with elevation (m) and site exposure in stands associated with mountain big sagebrush. Site exposure is an index based on aspect and slope calculated as follows: $\text{site exposure} = \text{slope} * \cos(\pi * (\text{aspect} - 180)/180)$. Site exposure becomes increasingly warmer to the right.

The rate of woodland establishment decreased with increasing site exposure and increased with increasing elevation. A 20-unit increase in site exposure (e.g. contrast of stands developing on similar hill slopes and elevation but facing south instead of north) was associated with a 4.9 trees/ha/year decrease in the mean rate of woodland establishment among stands developing at a similar elevation (95% CI: 3.8 to 6.0 trees/ha/year). A 200 m rise in elevation was associated with a 1.8 trees/ha/year increase in the rate of woodland establishment among stands with similar exposure (95% CI: 0.8 to 2.9 trees/ha/year).

similar elevations (95% CI: 0.22 to 0.74 year). A 100 m rise in elevation was associated with a 5-year decrease in the time required for a stand to reach closure on sites with similar exposure (95% CI: 0.37 to 10.81 years).

Influence of Environmental Variables on Stand Structure

Total Live Juniper Density

Total live juniper density increased with increasing elevation and decreased with increasing site exposure in stands associated with mountain big sagebrush (Figure 17). The final regression model describing this relationship was as follows with standard errors in parentheses below the estimates (response variable log transformed to meet model assumptions):

$$\text{Log (Total Tree Density)} = 2.59 - 0.036 * \text{site exposure} + 0.0022 * \text{stand elevation}$$

$$(0.705)(0.004) \qquad \qquad \qquad (0.0004)$$

with residual error = 0.356. The adjusted r^2 was 0.65.

A 5-unit increase in site exposure (e.g. contrast of stands on similar hill slopes and elevation but facing south instead of east) was associated with an 18% decrease in total tree density (95% CI: 14 to 22%). A 100 m rise in elevation was associated with a 22% increase in total tree density among stands with similar site exposure (95% CI: 14 to 30%).

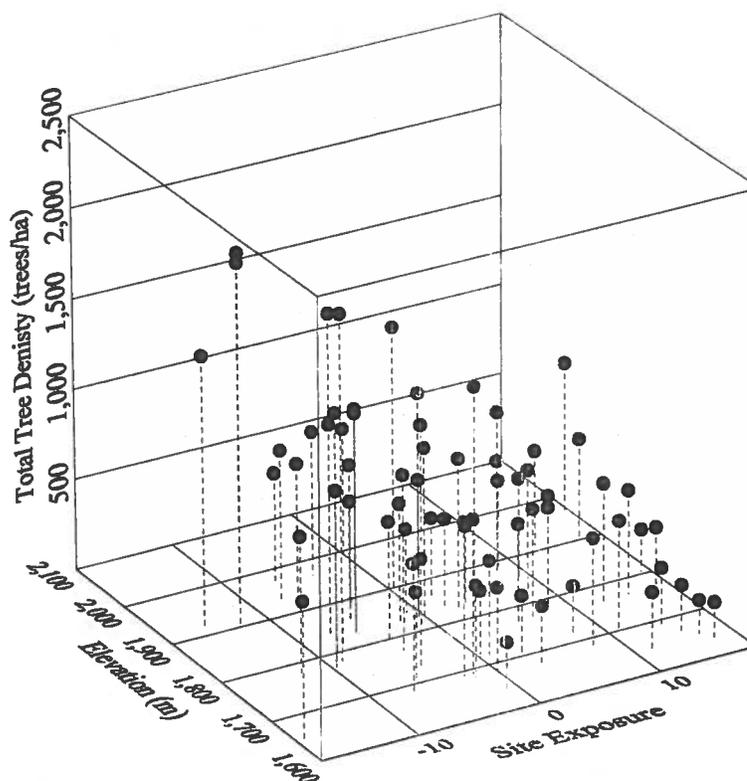


Figure 17. Relationship of total live juniper density with elevation (m) and site exposure in stands associated with mountain big sagebrush. Site exposure is an index based on aspect and slope calculated as follows: $\text{site exposure} = \text{slope} * \cos(\pi * (\text{aspect} - 180)/180)$. Site exposure becomes increasingly warmer to the right.

Dominant Juniper Density

Dominant juniper density (number of trees/ha comprising the upper 75% of the canopy) increased with increasing elevation and decreased with increasing site exposure (i.e. increasing southerly exposure) in stands associated with mountain big sagebrush (Figure 18). The final regression model describing this relationship was as follows with standard errors in parentheses below the estimates (response variable log transformed to meet model assumptions):

$$\text{Log (Dominant Tree Density)} = 2.62 - 0.026 * \text{site exposure} + 0.001 * \text{elevation}$$

(0.836) (0.005) (0.0001)

with residual error = 0.36. The adjusted r^2 was 0.49.

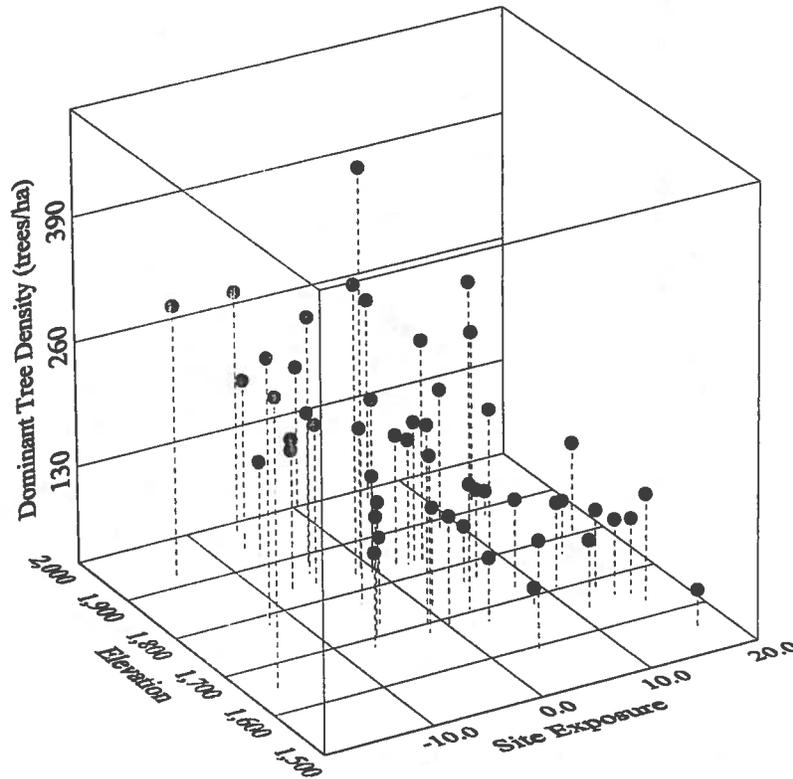


Figure 18. Relationship of dominant juniper density with elevation (m) and site exposure in stands associated with mountain big sagebrush. Site exposure is an index based on aspect and slope calculated as follows: $\text{site exposure} = \text{slope} * \cos(\pi * (\text{aspect} - 180)/180)$. Site exposure becomes increasingly warmer to the right.

A 5-unit increase in site exposure (e.g. contrast of stands on similar hill slopes and elevation but facing south instead of east) was associated with a 15.4% decrease in the density of dominant overstory trees (95% CI: 9.6 to 21%). A 100 m rise in elevation was associated with a 22% increase in dominant tree density among stands with similar site exposure (95% CI: 8 to 11%).

Changes in Fuels During Woodland Development

Elevation was significantly related to herbaceous, duff, and ten hour fuel biomass (Table 5). Site exposure was significantly related to herbaceous, shrub, tree, duff, and thousand hour fuel biomass (Table 5).

Table 5. Univariate results for the effect of PHASE adjusted on elevation and site exposure. If a covariate was significantly related to a response it means that the PHASE group means were significantly adjusted on the covariate.

Source	Response	Type III SS	df	MS	F	Sig.
Model	Herb ^a	9.4	4	2.35	18.04	<0.001
	Shrub ^b	62.4	4	15.61	57.8	<0.001
	Tree ^c	110.96	4	27.7	138.7	<0.001
	Duff ^d	13.67	4	3.42	113.9	<0.001
	One ^e	3.1	4	0.78	2.979	0.04
	Ten ^f	3.2	4	0.8	2.5	0.07
	Hundred ^g	8.6	4	2.14	1.02	0.42
	Thousand ^h	180.1	4	45.02	11.91	<0.001
β_0	Herb	0.4	1	0.4	3.04	0.04
	Shrub	1.46	1	1.46	5.42	0.012
	Tree	2.14	1	2.14	10.7	<0.001
	Duff	0.61	1	0.61	20.22	<0.001
	One	1.72	1	1.72	6.6	0.003
	Ten	3.25	1	3.25	10.16	<0.001
	Hundred	10.42	1	10.42	4.96	0.02
	Thousand	22.1	1	22.1	5.84	0.007
Elevation	Herb	1.42	1	1.42	11.2	0.003
	Shrub	0.05	1	0.045	0.17	0.69
	Tree	0.03	1	0.032	0.16	0.69
	Duff	0.31	1	0.31	10.2	0.004
	One	0.65	1	0.65	2.45	0.13
	Ten	1.52	1	1.52	4.78	0.04
	Hundred	3.67	1	3.67	1.75	0.19
	Thousand	12.1	1	12.1	3.19	0.086
Exposure	Herb	0.66	1	0.66	5.19	0.03
	Shrub	1.12	1	1.12	4.2	0.05
	Tree	3.1	1	3.1	15.5	<0.001
	Duff	0.25	1	0.25	10.4	0.003
	One	0.07	1	0.07	0.47	0.497
	Ten	0.22	1	0.22	1.18	0.287
	Hundred	1.89	1	1.89	0.9	0.28
	Thousand	24.8	1	24.8	6.56	0.017

Table 5. Univariate results for the effect of PHASE adjusted on elevation and site exposure. If a covariate was significantly related to a response it means that the PHASE group means were significantly adjusted on the covariate (Continued).

Source	Response	Type III SS	df	MS	F	Sig.
PHASE	Herb	7.06	2	3.53	27.9	<0.001
	Shrub	60.3	2	30.17	113.4	<0.001
	Tree	107.3	2	53.64	269.6	<0.001
	Duff	13.3	2	6.66	218.6	<0.001
	One	2.43	2	1.215	4.6	0.02
	Ten	1.43	2	0.714	2.25	0.13
	Hundred	5.22	2	2.61	1.24	0.50
	Thousand	143.3	2	71.63	18.9	<0.001
Error	Herb	3.29	26	0.13		
	Shrub	6.92	26	0.27		
	Tree	5.17	26	0.20		
	Duff	0.79	26	0.03		
	One	6.86	26	0.26		
	Ten	8.27	26	0.32		
	Hundred	54.5	26	2.10		
	Thousand	98.3	26	3.78		
Total	Herb	12.69	30			
	Shrub	62.4	30			
	Tree	110.96	30			
	Duff	13.67	30			
	One	3.1	30			
	Ten	3.2	30			
	Hundred	8.6	30			
	Thousand	180.1	30			

Adjusted $r^2 =$ ^a0.74 ^b0.9 ^c0.96 ^d0.95 ^e0.31 ^f0.28 ^g0.14 ^h0.65

Herbaceous, duff and ten hour fuel biomass increased with increasing elevation over the three phases of woodland development among stands developing on a similar exposure. Herbaceous, shrub, tree, duff and thousand hour fuel biomass decreased with increasing site exposure over the three phases of woodland development among stands developing at similar elevations. The estimated effects of elevation and exposure on fuel biomass and associated 95% confidence intervals are summarized in Tables 6 and 7.

Table 6. Summary of the effect of site exposure on the eight fuel loading response variables in the following model: $Y_{ij} = \mu + \tau_i + \beta_1(X_{1ij} - X_{1ave}) + \beta_2(X_{2ij} - X_{2ave}) + \varepsilon_{ij}$. The estimated effect should be interpreted as the percent reduction in median fuel biomass that was associated with a one unit increase in site exposure (i.e. increasingly warmer exposure).

Response	Reduction in Fuel Biomass (%)	95% Confidence Interval
Herbaceous Biomass	1.40	-0.13 to 2.91
Shrub Biomass	2.16	-0.06 to 4.33
Tree Biomass	3.58	1.68 to 5.45*
Duff Biomass	1.18	0.43 to 1.93*
One Hour Fuel Biomass	0.75	-1.5 to 2.95
Ten Hour Fuel Biomass	1.29	-1.17 to 3.7
Hundred Hour Fuel Biomass	3.31	-2.99 to 9.23
Thousand Hour Fuel Biomass	9.18	1.15 to 16.6*

*denotes 95% confidence intervals excluding a zero percent change

Table 7. Summary of the effect of elevation on the eight fuel loading response variables in the following model: $Y_{ij} = \mu + \tau_i + \beta_1(X_{1ij} - X_{1ave}) + \beta_2(X_{2ij} - X_{2ave}) + \varepsilon_{ij}$. The estimated effect should be interpreted as the percent increase in median fuel biomass that was associated with a one hundred unit increase in elevation (m).

Response	Increase in Fuel Biomass (%)	95% Confidence Interval
Herbaceous Biomass	29.36	9.92 to 52.23*
Shrub Biomass	5.03	-16.0 to 31.44
Tree Biomass	4.04	-15.12 to 27.53
Duff Biomass	12.61	3.81 to 22.17*
One Hour Fuel Biomass	18.33	5.41 to 48.02*
Ten Hour Fuel Biomass	30.64	2.33 to 66.79*
Hundred Hour Fuel Biomass	51.56	-19.36 to 184.85
Thousand Hour Fuel Biomass	110.12	-10.63 to 394.0

*denotes 95% confidence intervals excluding a zero percent change

There were significant differences across the three phases of woodland development in herbaceous, shrub, tree, duff, one hour, and thousand hour fuels biomass (Table 8). Herbaceous (fine fuel) and shrub biomass declined during the transition from open mountain big sagebrush communities to closed juniper woodlands. Median herbaceous biomass was estimated to have declined 59% during this transition (95% C.I.: 45 to 70%), while median shrub biomass declined

95% (95% C.I.: 92 to 97%) among stands at a similar elevation and with similar exposure. Median tree biomass was estimated to have increased by 54.1 fold during the transition from open to closed juniper woodland communities (95% C.I.: 37 to 79 fold). Mean shrub and herbaceous biomass mass was 4,962 and 1,914 kg/ha in open mountain big sagebrush communities and 309 and 718 kg/ha in phase III woodlands.

Table 8. Estimated changes in fuels biomass during transitions from phase I to phases II and III of western juniper stand development. Confidence limits (95%) for estimates are also given.

Response	Phase I → Phase II ^a		Phase I → Phase III ^b	
	Estimate (%)	95% C.I. (%)	Estimate (%)	95% C.I. (%)
Herbaceous	84 ^c	56 125	41	30 55*
Shrub	25	22 32*	5	3 8*
Tree	480	294 798*	5410	3700 7900*
Duff	405	329 490*	431	374 500*
One hour	115	64 204	166	108 257*
Ten hour	82	44 155	127	79 205
Hundred hour	50	9.7 255	39	12 134
Thousand hour	806	155 4200*	965	108 8626*

^a Estimated changes in biomass from phase I to phase II

^b Estimated changes in biomass from phase I to phase III

^c Interpret as median herbaceous biomass in phase II was 84% of what it was in phase I.

*95% C.I.s that exclude 100% (i.e. no change in median biomass).

The measured shrub and herbaceous species averaged 87% of the total live fuels biomass in phase I stands, whereas this combination averaged only about 2% of the total live fuels biomass in phase III stands (Figure 19), indicating a dramatic shift in the composition of live fuel loading. Duff biomass also significantly increased during the transition from phase I to phase III. Median duff biomass was estimated to have increased by 4.31 fold during this transition (95% C.I.: 3.74 to 5 fold).

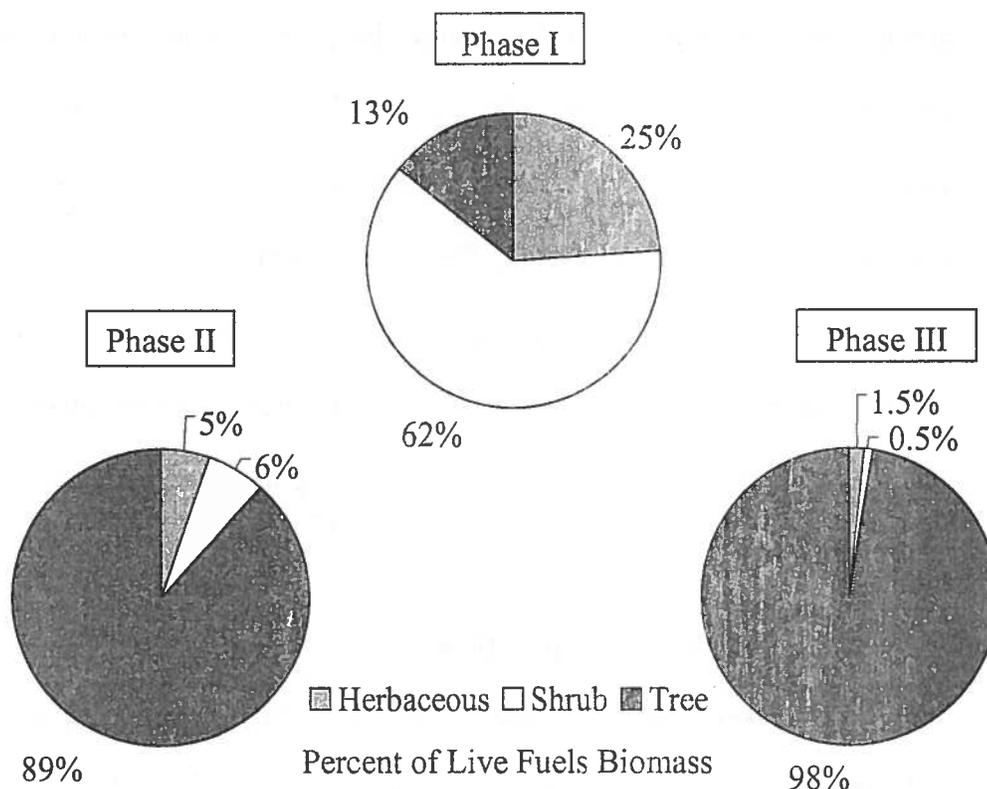


Figure 19. Relative live fuels biomass, displayed as a percent of total live fuels biomass, associated with three phases of woodland development.

Discussion

Temporal and Spatial Attributes of Woodland Expansion

The proportion of trees greater than 150 years old relative to trees less than 150 years suggests western juniper has greatly increased in the Owyhee Mountains and on Steens Mountain since the late 1800s. Ninety-five percent of trees established after the 1850s, which is consistent with estimates by Miller et al. (1999) and Miller and Tausch (2001). As evidenced by the presence of western juniper in 96% of plots sampled in this study, juniper is able to encroach upon a variety of plant alliances and under a broad range of environmental conditions. Although it appears the occurrence of western juniper within the woodland belt is not spatially limited by environmental or vegetative conditions, stand structure,

rates of stand development, and fuel loading characteristics do vary substantially across heterogeneous landscapes. Total juniper density, density of dominant trees comprising the primary canopy, rates of tree establishment, and certain live and dead fuels biomass vary significantly with environmental variables that are indicative of site potential. The recognition of temporal and spatial variation in western juniper woodlands is extremely important when assessing potential resource problems, assessing wildlife habitat values, and developing management plans at the landscape scale.

Pre-settlement Tree Composition

In contrast to post settlement western juniper being nearly ubiquitous at the landscape scale, distribution of pre-settlement trees was generally limited to ridge top areas and found only infrequently growing in deeper, well-drained soils associated with mountain big sagebrush on Steens Mountain. Pre-settlement trees were present in only 30% and 16% of stands sampled on North and South Steens in southeastern Oregon, respectively. Conversely, a scattering of pre-settlement trees was found on Juniper and South Mountains in southwestern Idaho. At least one pre-settlement tree was present in 48% and 67% of stands sampled on Juniper and South Mountains, respectively. Nonetheless, trees greater than 150 years old comprised less than 10% of total tree density among all study locations suggesting a dramatic shift has occurred in woodland structure at the landscape scale across both study areas.

Initiation of Western Juniper Expansion

Most reported age chronologies for western juniper in the mountain big sagebrush alliance place initiation years of juniper woodland expansion during the 1870s or later (Adams 1975, Eddleman 1987, Miller and Rose 1995, Gruell 1999). However, our data suggest that the initiation years of rapid woodland expansion occurred around 1850 on Juniper Mountain, Idaho. The start of rapid woodland expansion occurred prior to the introduction of livestock in significant numbers into southwestern Idaho during 1869 – 1889 (Burkhardt and Tisdale 1969). Only small bands of livestock were present during the early 1860s (Burkhardt and Tisdale 1969) to supply meat for the local mining towns, suggesting the impact to fine fuels and the fire regime during this time period was negligible.

Trees greater than 150 years old occurred in 48% and 67% of sampled stands on Juniper and South Mountains, respectively, but comprised less than ten percent of total tree density suggests an open, scattered stand of trees that established prior to 1850 across the study area. In other words, there was a higher density of trees across this area prior to settlement than in other areas where tree chronologies have been documented. Trees that established prior to 1850 in southwestern Idaho were not always restricted to rocky outcrops or less productive areas that lack fine fuels. This suggests a different fire regime that may have included a higher frequency of low intensity fires. In support of this conclusion, there was no evidence (i.e. large amounts of charred wood and stumps) suggesting the Idaho study area was previously occupied by a dense juniper woodland that experienced a mixed severity fire around 1850. Although the occurrence of fire

scars was not documented, they were observed on pre-settlement trees growing on relatively productive sites. In addition, Burkhardt and Tisdale (1976) estimated pre-settlement mean fire return intervals to have been 11 years in southwestern Idaho, suggesting the fire regime included frequent events that disallowed an accumulation of heavier fuels associated with woody species. Thus, we speculate that fire intensities may have been low enough to allow the survival of at least a scattering of legacy trees on deeper soil sites. This is in contrast to other areas where frequent fires (<20 years) excluded the establishment of western juniper on deeper soil sites (Miller and Rose 1999).

Seed dispersal of western juniper occurs by gravity, overland flow, and animal transport. Typically, gravity and overland flow as vectors do not provide means for long distance dispersal of seed. In a southwestern Idaho study, western juniper seed dispersed an average of 1.42 m down-slope and 0.60 m upslope during a 4-month summer period, and an overall average of 1.29 m during a 6-month winter period (Burkhardt and Tisdale 1976). In addition, most birds have limited gut-retention times and fly short distances to perch and process the fruit of western juniper, thus limiting the distance of most seed dispersal (Schupp 1993, Chambers et al. 1999). After feeding on Ashe juniper fruits, American robins flew an average distance of 145 feet to a post-foraging perch (Chavez-Rameriz and Slack 1994). Since long distance dispersal of western juniper seed is unlikely, we speculate that the presence of scattered but regularly distributed pre-settlement trees in Idaho likely provided an on-site seed source for earlier initiation of rapid woodland expansion. In support of this conclusion, it was found in this study that

stands with scattered pre-settlement trees exhibited earlier periods of rapid woodland expansion in comparison to stands that lacked older trees. Conversely, without the benefit of an on-site seed source, stands comprised strictly of post settlement trees exhibited a lagged establishment period of 16 to 32 years relative to stands with pre-settlement trees present.

Phases of Stand Development

An average across study locations indicates that nearly a third of the 340 sampled stands were classified in each of the three phases of development (i.e. phases I, II, and III) with about five percent being comprised of predominantly pre-settlement age class trees. The fact that only a third of stands are in phase III of woodland development suggests the majority of the study area is still in a state of vegetation transition. Miller et al. (2000) similarly concluded that the majority of the 2 million ha of western juniper in Oregon are still in transition from shrub steppe to closed juniper woodland. However, the southwestern Idaho study locations had a higher proportion of stands in phase III of woodland development, again likely an artifact of earlier initiation of woodland expansion because of the increased presence of older trees across the study area. Because of an earlier initiation of woodland expansion in southwestern Idaho, expansion is more advanced than in southeastern Oregon with large, contiguous, densely populated stands. Woodlands in southwestern Idaho may offer a glimpse of what's on the horizon for southwestern Oregon and other areas.

With a full stocking of 90 to 300 mature trees/ha in the primary canopy required for the trees to dominate a site, all phase II stands have sufficient tree

densities to become fully juniper dominated phase III stands once trees mature. Subsequently, the portion of the study area that will potentially be fully occupied by juniper is about 62% for South Steens Mountain, 41% for North Steens Mountain, 85% for Juniper Mountain, and about 52% for South Mountain. Our data suggest that the time period required for stand closure to occur is highly dependent on site environmental conditions. Thus, with a full stocking of established trees in phase II stands, stand closure at the projected levels can be expected within 40 to 80 years. In addition, woodland dominance at the landscape level influences the rate of woodland encroachment and closure on adjacent open areas. When woodlands dominated approximately 60% of the landscape the remaining openings declined more rapidly (Milne et al. 1996), which may greatly influence the time required for the initial tree establishment period observed in this study and hasten transitions between phases of stand development.

The Influence of Environmental Variables on Rate of Establishment, Stand Closure and Woodland Structure

Our data suggest that rate of western juniper establishment and density of trees increased with elevation and northerly exposure. The conceptual model shown in Figure 20 represents three hypothesized phases of stand development for western juniper encroachment in sagebrush steppe communities. In this model, transitions between phases occur as an artifact of density of established trees, canopy cover, and time.

The three dashed lines in the model (Figure 20) estimate tree establishment (trees/ha/year) for stands developing under varying environmental conditions. The top and bottom lines represent tree establishment for stands developing under the

environmental extremes on Juniper Mountain, Idaho. The middle dashed line represents tree establishment for stands developing under intermediate levels of environmental variables. The three dashed lines in the conceptual model represent tree establishment for specific levels of environmental variables, thus one also needs to realize that a continuum exists between them.

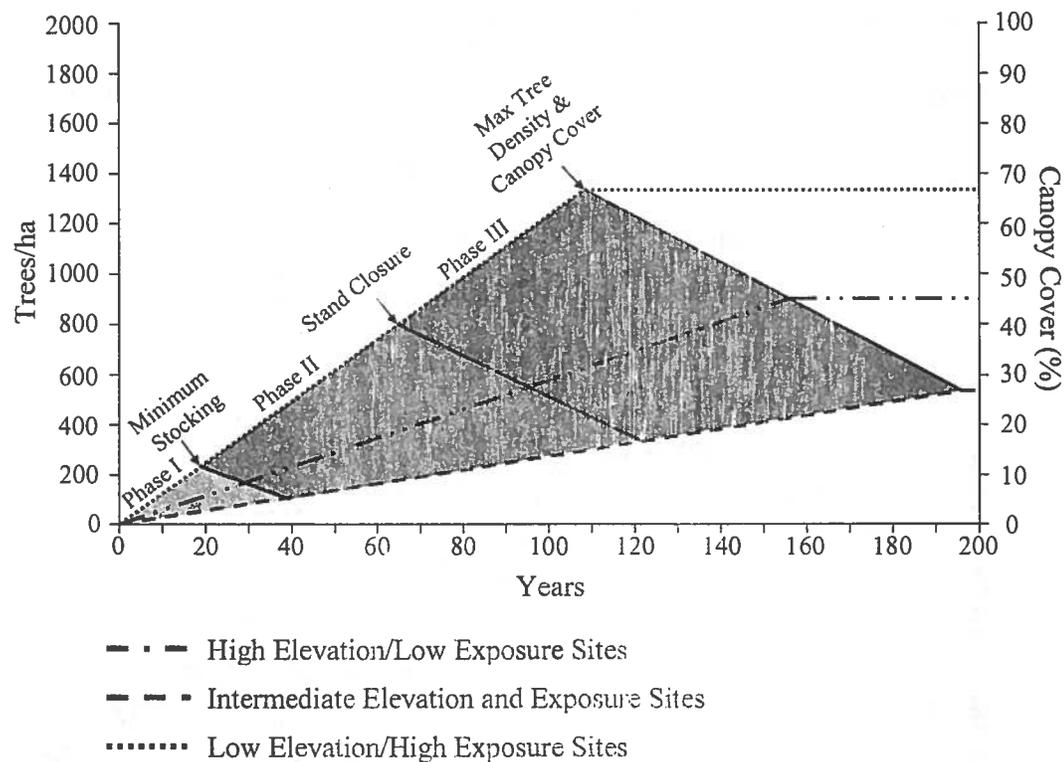


Figure 20. Display showing the hypothesized time periods from initial tree establishment to minimum stocking, stand closure, and estimated maximum potential for tree density and cover for stands developing under varying environmental conditions.

The environmental variables employed to explain variation in stand temporal and structural attributes in this study were stand elevation (m) and stand exposure (i.e. an index of a stand's exposure based on its slope and aspect). We assumed these environmental variables were indicative of site available moisture and, thus, the most rapid rates of tree establishment were associated with mesic

site conditions and slower rates of tree establishment were associated with increasingly drier site conditions. Stands that developed on mesic sites (i.e. high elevation, high northerly exposed sites) achieved a minimum stocking of about 250 trees/ha in about 20 years after initial tree establishment, whereas 40+ years were required to achieve a minimum stocking of fewer than 100 mature trees/ha on drier sites. Relative growth rates in closed stands indicate intraspecific competition among juniper trees began in the late 1950s and early 1960s (e.g. Figure 21). We speculate that this was a period of stand closure and rapid decline in understory vegetation, especially shrubs.

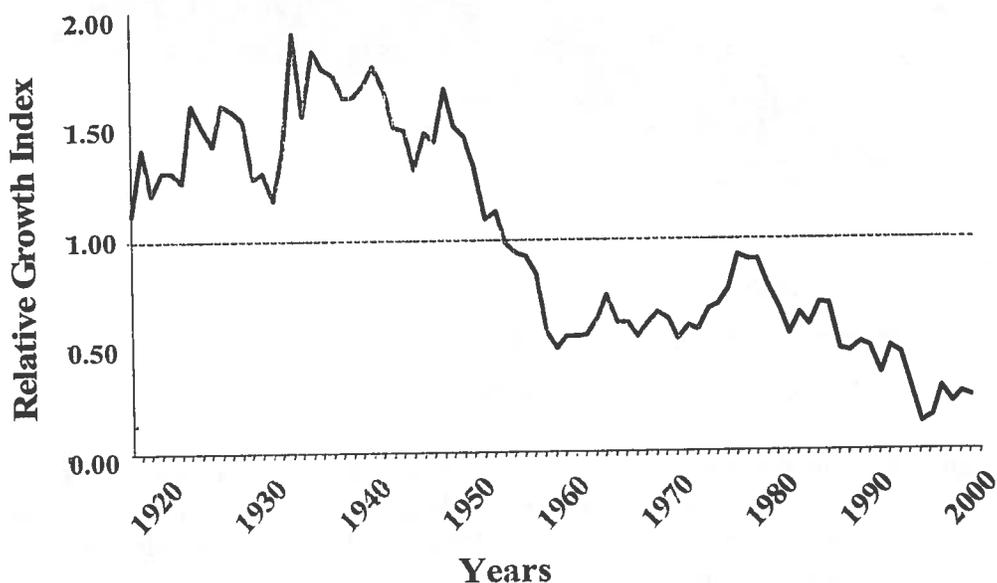


Figure 21. Display showing relative growth rates (ratio of annual ring width over mean ring width) over time for a late phase juniper stand on Juniper Mountain, Idaho. Notice the dashed line represents a 1:1 ratio with the overall mean tree ring width and during the time period 1950 to 1960 ring widths declined to well below the long term average suggesting increased competition among trees and stand closure.

The intermediately shaded area in the conceptual model shown in Figure 20 represents the time period from stand establishment to stand closure given a site's environmental characteristics. It was found that dry sites support fewer total trees in a closed state than mesic sites, <350 trees/ha as opposed to >800 trees/ha, respectively. However, stand closure occurred within >120 years on warm dry sites compared to 40 to 80 years on mesic sites. These results are similar to those reported by Miller et al. (2000), who concluded closed western juniper stand densities varied from 222 to 481 trees/ha in mountain big sagebrush/Thurber needlegrass associations to 247 to 716 trees/ha in mountain big sagebrush/Idaho fescue associations. They also concluded that the time required for woodland closure was highly variable depending on site potential and estimated the minimum time for stand closure on mesic sites (i.e. sites supporting mountain big sagebrush/Idaho fescue associations) was 60 to 70 years.

The model presented in Figure 20 or similar models may allow predictions of the time required for stands to achieve critical stages in their development, given knowledge of environmental variables. Since it is known that stands are most easily controlled early in development prior to displacement of understory shrub and herbaceous species (Martin 1978, Bunting 1984, Miller et al. 2000), this model may also yield predictions of windows of opportunity for less costly management. Once trees begin competing with one another and understory shrub and herbaceous components decline (i.e. late phase II and phase III), management is relegated to mechanical means of treatment prior to prescribed fire.

It has been reported that the minimum time required to reach stand closure is 60 to 90 years (Barney and Frischknecht 1974, Miller and Rose 1995, Tausch and West 1995, Miller et al. 1999) with the potential for rapid stand closure to occur within 45 to 50 years after initial tree establishment. These estimates were found to be reasonable in this study on more productive sites (i.e. northerly exposed sites at higher elevations), however, it was generally found that less productive sites (i.e. southerly exposed sites at lower elevations), although supporting fewer total trees in a fully closed state, require a longer time period to reach stand closure. Reported pre-settlement fire-return intervals in mountain big sagebrush communities vary from 15 to 25 years (Houston 1973, Burkhardt and Tisdale 1976, Martin and Johnson 1979, Miller and Rose 1999). Burkhardt and Tisdale (1976) concluded that fire return intervals of 30-40 years would be sufficient to disallow western juniper expansion into sagebrush steppe communities. Thus the fact that less productive sites support woodlands are currently in a state of stand closure is possibly an artifact that of more legacy trees (i.e. pre-settlement trees that survived fire) tending to occur in areas of lower productivity. Less productive areas, with lower amounts of fine fuels and lower overall fuel continuity, likely experienced less intense, patchy burns that allowed a scattering of juniper survival. Thus, a legacy seed source was present on these sites that may have facilitated earlier tree establishment periods once fire return intervals lengthened across the region.

Changes in Fuels During Woodland Development

We found that there were significant differences across the three phases of woodland development in herbaceous, shrub, tree, duff, one hour, and thousand hour fuels biomass. Live fuel loading biomass was about 12-25 times higher in phase III stands than mountain big sagebrush communities with dispersed young trees. This difference may be related to a more efficient use of site resources by the trees (Doughty 1987) and the fact that resources (i.e. carbon) can be tied up in trees for centuries in the absence of disturbance. Our data suggest this difference may also be accentuated in higher elevation, low exposure stands. The primary resource involved with improving site conditions for rapid establishment and thickening by juniper, appears to be moisture availability, as described by Nemani and Running (1989). Similarly we found that environmental characteristics indicative of site available moisture (i.e. site exposure and stand elevation) were strongly associated with post-settlement stand structural characteristics, rates of woodland establishment, and fuel loading characteristics. Herbaceous and shrub biomass has declined markedly during the transition from open shrub steppe communities to closed woodlands. The measured shrub and herbaceous species averaged 87% of the total live fuels biomass in shrub steppe dominated communities, whereas this combination averaged less than 2% of the total live fuel biomass in late phase juniper stands, indicating a dramatic shift in the composition of live fuel loading. Similar declines in understory live fuels biomass have been reported in the literature in juniper and pinyon-juniper

woodlands (Schott and Pieper 1985, 1987, Tausch et al. 1981, Tausch and West 1995).

Regardless of site conditions, substantial reductions occurred in 1 and 10 hour fuels (i.e. shrub and herbaceous biomass) during the transition from sagebrush steppe communities to closed juniper woodlands. It is the fine fuel component that fosters fire spread, especially low and moderate intensity fires (Pyne 1996). The differences detected among phases of woodland development in fine (herbaceous) and ladder (shrubs) fuels were important to the role of fire in sagebrush and juniper communities. Western juniper sites with less than 600 to 907 kg/ha of fine fuels do not burn unless under extreme conditions (Bunting 1990, Wink and Wright 1973). At some point during the transition from the phase II to phase III, a threshold is surpassed and the fire regime is changed. The results of this investigation parallel those reported by Miller et al. (2000), who found that as juniper approaches 50% of maximum potential for a particular site, mountain big sagebrush cover and biomass decline to approximately 20-25% of maximum potential, representing over a 75% reduction. We found that as stands approach phase III, median mountain big sagebrush biomass declined by about 95% (95% C.I.: 92 to 97%) which indicates that ladder fuels have essentially been lost prior to phase III, thereby further insulating trees from fire and securing juniper's dominance. Mountain big sagebrush serves an important role in the ecology of fire in the system, in which its structural presence fosters vertical expansion of fuels, thereby exposing combustible energy to oxygen. Mountain big sagebrush

also acts a ladder fuel carrying fire into the canopy of juniper, thus its absence further insulates late phase juniper stands from fire.

Fire appears to have largely ceased to be an important driving variable of vegetation across the landscape of sagebrush steppe and juniper ecosystems. Rather, site conditions, woodland development, and their interconnectivity presently seem most important in driving variation in the structure and composition of vegetation and fuel loading. The loss of understory fuels biomass during woodland development has reduced the amount of more easily burned fuel leading to a reduction in the frequency of fire, thereby adding to the rapidity and area of vegetation change. Barring some substantial environmental or management change, this decline in fine fuels and associated reductions in the frequency of fire will likely continue until juniper dominates most sites suitable to its survival. We found that potential for excessive heavy fuel loading exists under conditions of closed juniper woodlands, especially in stands that have developed on sites with favorable environmental conditions. As one would expect, tree biomass substantially increases as trees assume dominance over mountain big sagebrush communities. Median juniper biomass has increased an estimated 170 fold during the transition from mountain big sagebrush communities to closed juniper woodlands on Juniper Mountain (95% C.I.: 144 to 202 fold). Surface duff loading has also increased substantially during stand development. An increase in tree biomass fosters the natural compaction of heavy fuels and the low surface area-to-volume ratio of fuels surrounding trees, such as with thick duff, suffocates oxygen and usually produces creeping, smoldering fires, thereby excluding fire

from the system except under extreme environmental conditions (Agee 1997). The consequences of these changes in fuel loading may have profound implications to the size and severity of fires in sagebrush steppe and juniper woodland cover types. As tree densities increase and tree canopies expand in size, the continuity of crown fuels increases across the landscape. In Texas, juniper woodlands supported crown fires where canopies exceeded 35% (Bryant et al. 1983). As found in this study, western juniper cover now exceeds 50% in many areas that offer favorable conditions. These dense woodlands can easily support crown fire under certain climatic and environmental conditions. Repercussions of the unpredictable and highly intense behavior of crown fire in late phase juniper stands are not known, however, the potential for further landscape scale changes in vegetation is very real. Accentuated intensity and severity of fire occurring in closed stands may further alter site potential resulting in plant communities dominated by introduced weedy species (Miller and Tausch 2001).

There has been a dramatic shift in the amount and composition of fuels during the transition from open big sagebrush communities to late phase juniper woodlands. General differences in fuels related to stand development observed in this study on Juniper Mountain, Idaho include: 1) herbaceous biomass in late phase stands has declined past stand flammability thresholds identified in the literature (e.g. Bunting 1990, Wink and Wright 1973); 2) the contribution of mountain big sagebrush biomass to live fuels within the observed phase III woodland communities has virtually disappeared, whereas in phase I, it is a dominant component; 3) a substantial increase in duff loading has accompanied stand

development; 4) down dead woody fuels biomass was highly variable across phases of stand development and along an elevational and site exposure gradient; 5) fuels have become heavier and vertically compressed during stand development, and 6) overall, total fuel biomass on Juniper Mountain has increased from a mean of about 21,000 kg/ha in open mountain big sagebrush communities to often over 138,000 kg/ha in late phase woodlands.

Conclusion

The pattern of woodland development can be described in three phases (adapted from Miller et al. 2000). Phase I is primarily one of tree establishment (Figure 22). During this first phase, mountain big sagebrush and perennial grasses dominate the site with juvenile and sapling trees scattered throughout. Stand density approaches full stocking in 20 to 50 years depending on proximity to a seed source and environmental characteristics. Phase II (Figure 22) begins as a consequence of a stand achieving full stocking and is a period of rapid tree expansion as an artifact of increased growth rates as established trees mature. This is a period when trees are co-dominant with shrubs and herbs on the site. However, once a full stocking of trees approaches maturity, requiring 40 to 80+ years depending on environmental characteristics, intraspecific competition begins and an associated rapid decline in the understory occurs. Phase III (Figure 22) is the final period of a stand's development corresponding to high tree dominance and low abundance of shrubs and herbaceous species. This period is characterized by increasing intraspecific competition among trees as evidenced by constrictions in ring growth and crown lift. An important threshold in this model occurs during

the transition from phase II to III in which the fire regime changes and shrubs and herbaceous species play a limited role on the tree-dominated site.

As woodlands develop, community structure significantly changes impacting fire regimes, fire behavior, restoration options and costs, forage production and wildlife habitat. The threshold shown in Figure 22 represents a point in time when intra-specific competition among trees begins and the understory rapidly declines. The decline in fine and ladder fuels significantly changes the fire regime from a ground fire to canopy fire and prescribe fire is only feasible with mechanical treatment that greatly increases the cost of management. Although the potential for fire in Phase III is less than in Phases I and II, fire intensity and severity are much greater. Intervention of woodland expansion is best done during Phase I and during the early portion of Phase II.

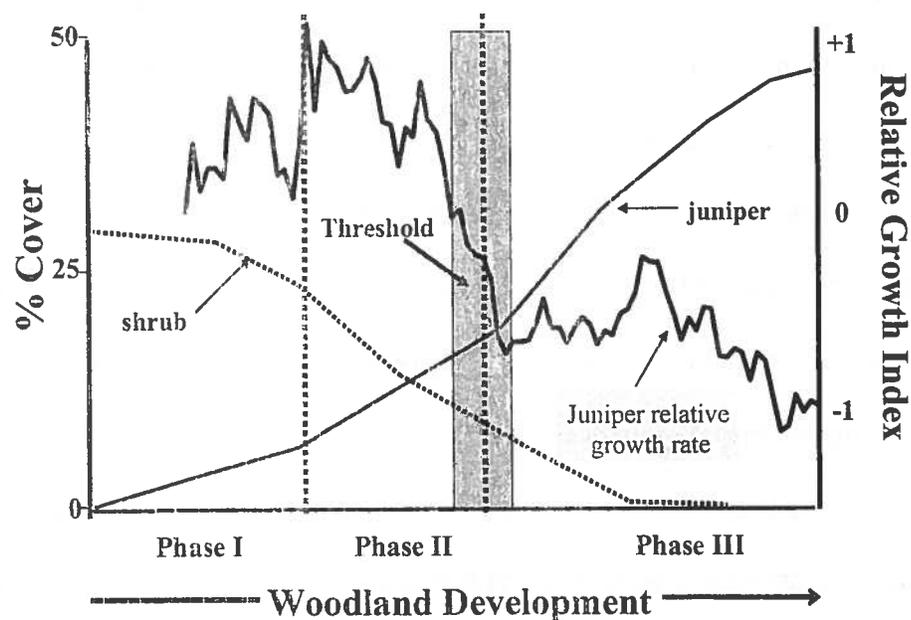


Figure 22. Relationship between shrub canopy cover, tree canopy cover and relative growth rates, and management intensity during different phases of woodland development.

Variation in rates and structure of woodland development exists across heterogeneous landscapes supporting western juniper. This variation can be explained largely by differences in environmental conditions in which stands are developing under. Thus, knowledge of environmental characteristics across landscapes that are either currently or at risk of supporting juniper expansion, affords land managers the ability to predict potential stand structure and time required for stands to achieve important management thresholds. If interest lies in developing juniper control programs at the landscape scale, this ability, along with knowledge of current phase of stand development, may allow prioritization of stands for control. Knowledge of these factors may also yield estimates of the frequency of treatment necessary to prevent juniper encroachment. For instance, our data suggest that stands on mesic sites (i.e. high elevation, northerly exposed sites) achieved stand closure in 60 to 80 years after initial tree establishment, conversely nearly twice as many years were required for stands developing on dry sites (i.e. low elevation, southerly exposed sites). Recall that stand closure represents a critical threshold in a stand's development in which the treatment options become limited and the cost of management increases substantially. Thus, a higher frequency of treatment for stands establishing on mesic sites would be necessary for prevention of juniper encroachment.

Our findings suggest that environmental heterogeneity plays a significant role in determining the temporal and structural attributes of western juniper woodland development and associated fuel loading characteristics. Thus, both the spatial and temporal environmental heterogeneity of the site or landscape in

question should be considered when conducting fuels and resource inventories, research, and management.

Scope of Inference and Study Limitations

This was an investigation of observational data in which environmental conditions could not be randomly assigned to stands, thus causal inferences should not be drawn.

Fuels biomass data for shrub and tree dominated communities are from only 30 stands on one mountain in which western juniper is actively expanding. They do not fully represent the range of variation present in the Humboldt Ecological Province or even Juniper Mountain. In many areas of this and other mountain ranges, species composition of the mountain big sagebrush and tree-dominated stands may have large variations from the stands sampled here. Specific live and dead fuels biomass levels could thus differ for other sites and inferences to other areas are speculative. Additional studies, particularly on a regional basis, will be needed to better establish the variation in fuels biomass associated with woodland development in the sagebrush steppe ecosystem. In addition, because of time and resource limitations, we were unable to sample fuel biomass directly in the field. Consequently, we employed established models from the literature (e.g. Gholz 1977, Rittenhouse and Sneva 1977) to estimate fuels. There are several obvious limitations to this method including site differences in relationships between model parameters and inter annual variation not accounted for in the models.

Another potential limitation of this study was that space had to be substituted for time when evaluating fuel load and vegetation changes during the transition from open sagebrush communities to late phase woodlands. Stands that are still open with relatively low tree dominance may be different from more developed woodlands in some unobvious way, which may be partially responsible for differences in live and dead fuel loading among stands.

A potential improvement for this investigation may have been to include other study areas in the fuel-loading component of the study allowing a clearer picture of broader scale differences in fuel loading associated with western juniper woodland development. Future research may consider model refinement with the inclusion of other indices of exposure, heat load, or soil moisture as independent variables to better explain fuel loading across environmental gradients.

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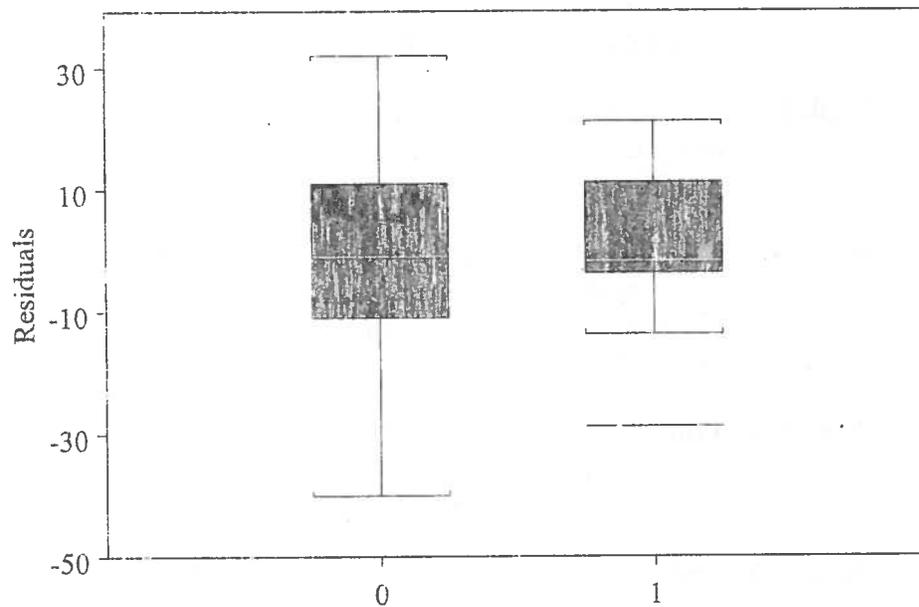
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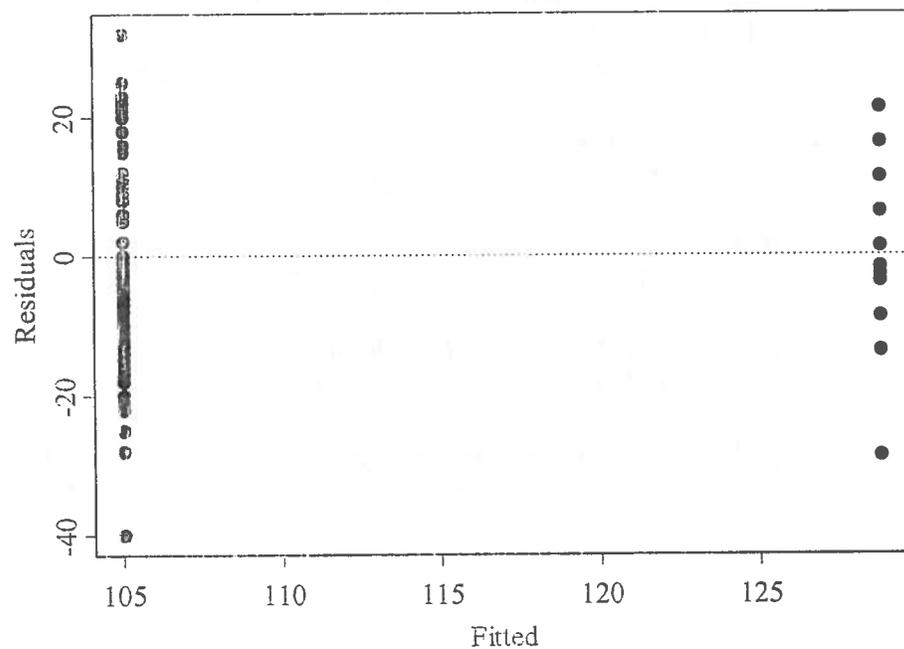
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Appendices

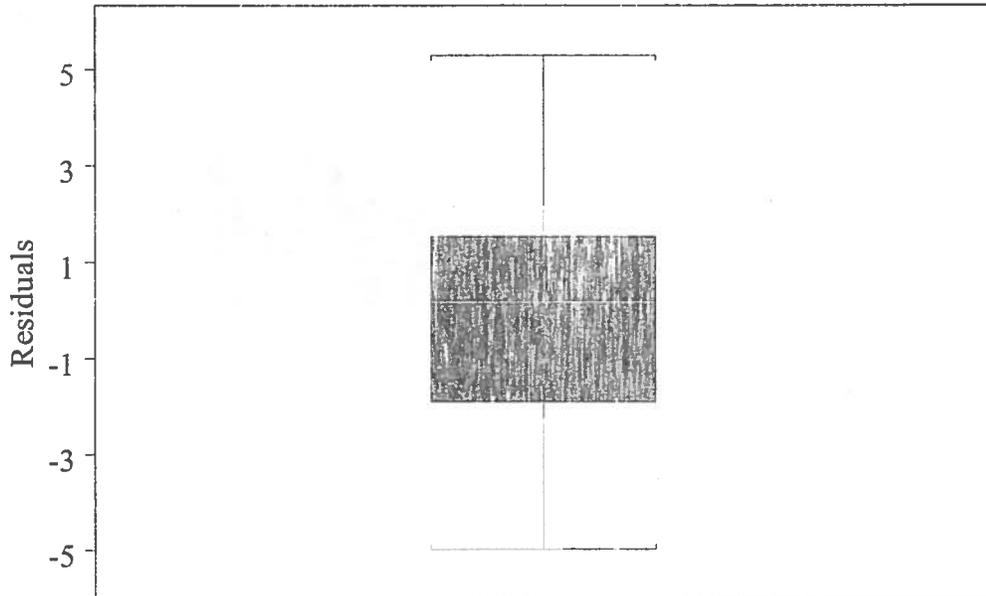
Appendix 1. Histogram of residuals showing adequate symmetry for the following ANOVA model describing the effect of presence/absence of pre-settlement age class trees on the initiation date of rapid post settlement expansion.



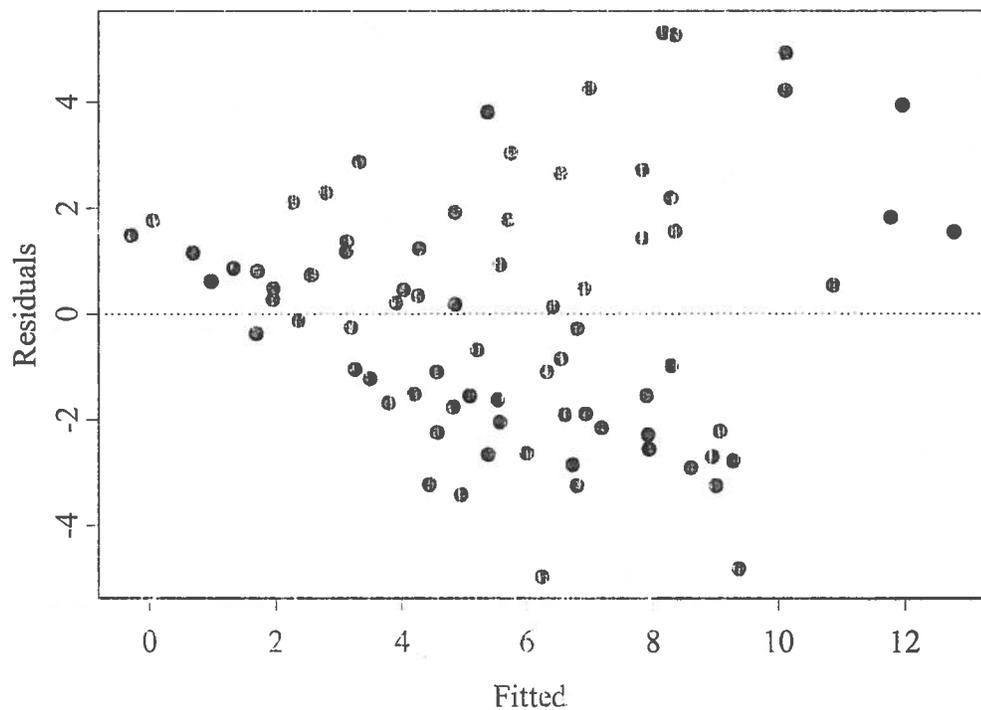
Appendix 2. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANOVA model describing the effect of presence/absence of pre-settlement age class trees on the initiation date of post settlement woodland expansion.



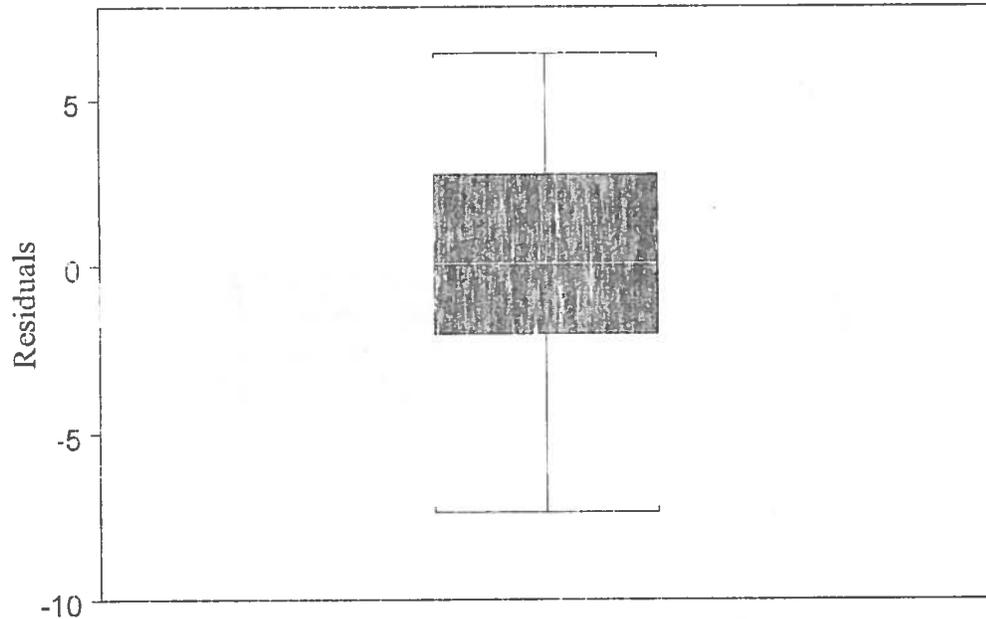
Appendix 3. Histogram of residuals showing adequate symmetry for the following regression model: Rate of Stand Establishment = $-10.41 - 0.25 * \text{site exposure} + 0.009 * \text{elevation}$.



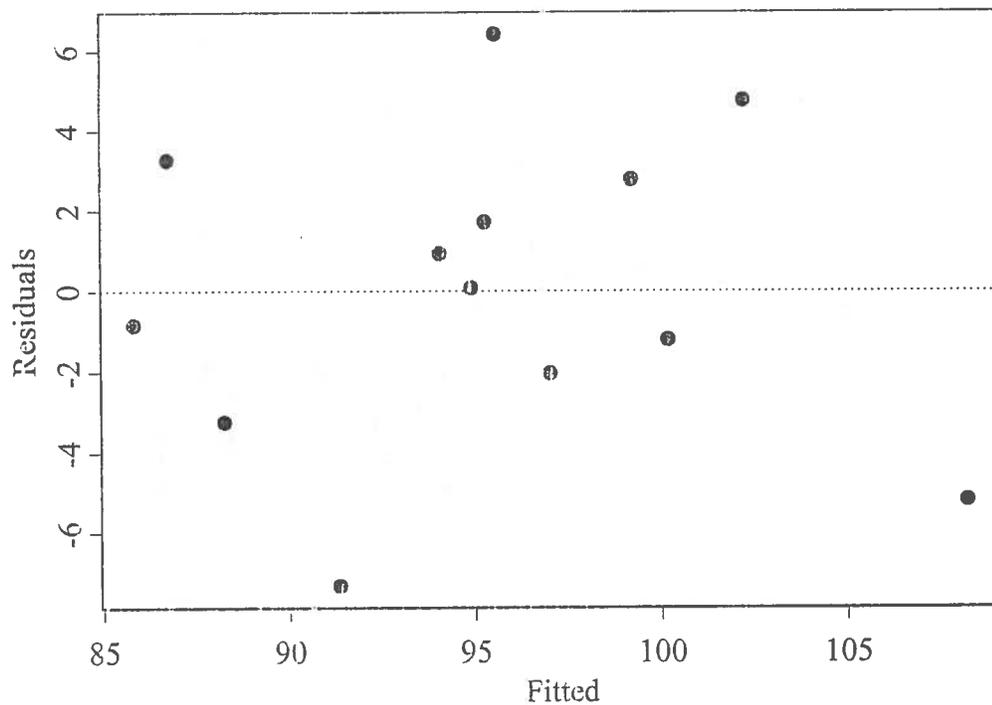
Appendix 4. Plot of studentized residuals by predicted value showing homogeneity of variance for the following regression model: Rate of Stand Establishment = $-10.41 - 0.25 * \text{site exposure} + 0.009 * \text{elevation}$.



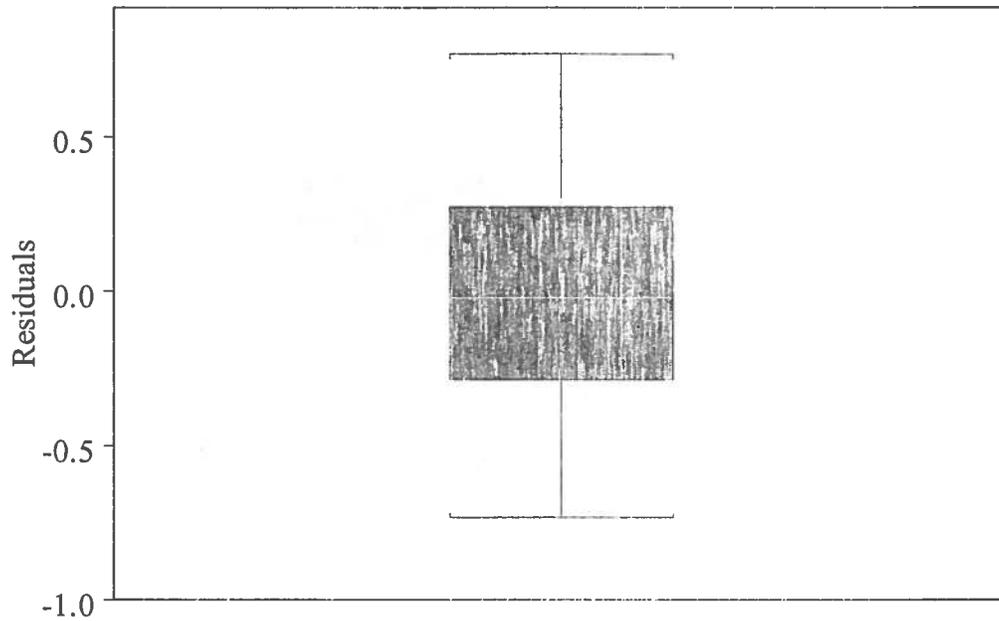
Appendix 5. Histogram of residuals showing adequate symmetry for the following regression model: $\text{Years Until Stand Closure} = 193.66 + 0.48 * \text{site exposure} - 0.052 * \text{stand elevation}$.



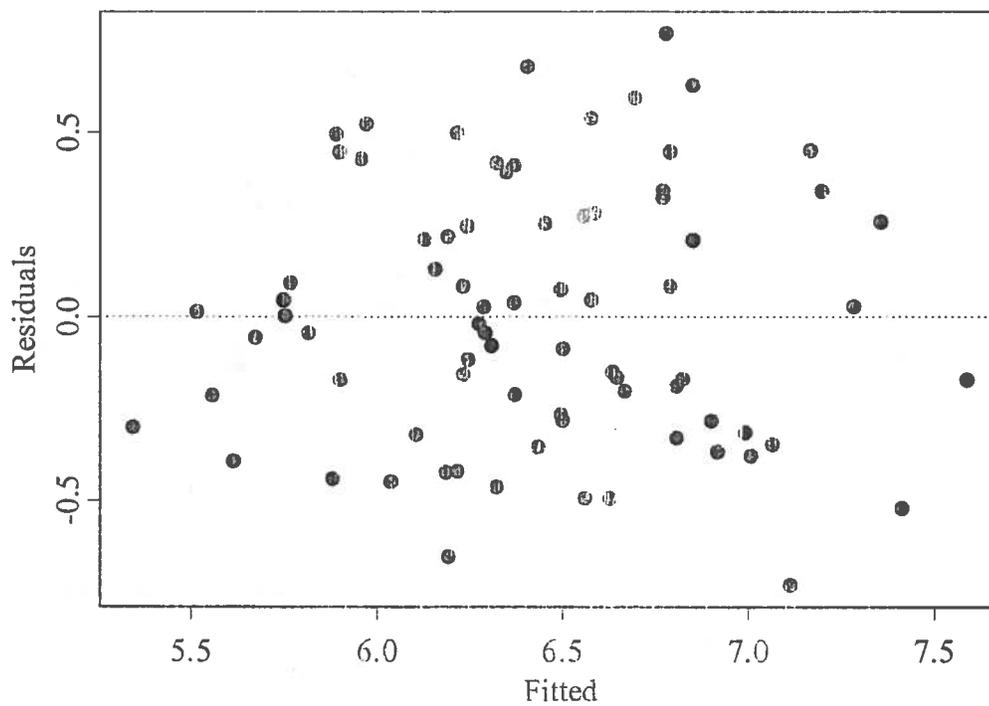
Appendix 6. Plot of studentized residuals by predicted value showing homogeneity of variance for the following regression model: $\text{Years Until Stand Closure} = 193.66 + 0.48 * \text{site exposure} - 0.052 * \text{stand elevation}$.



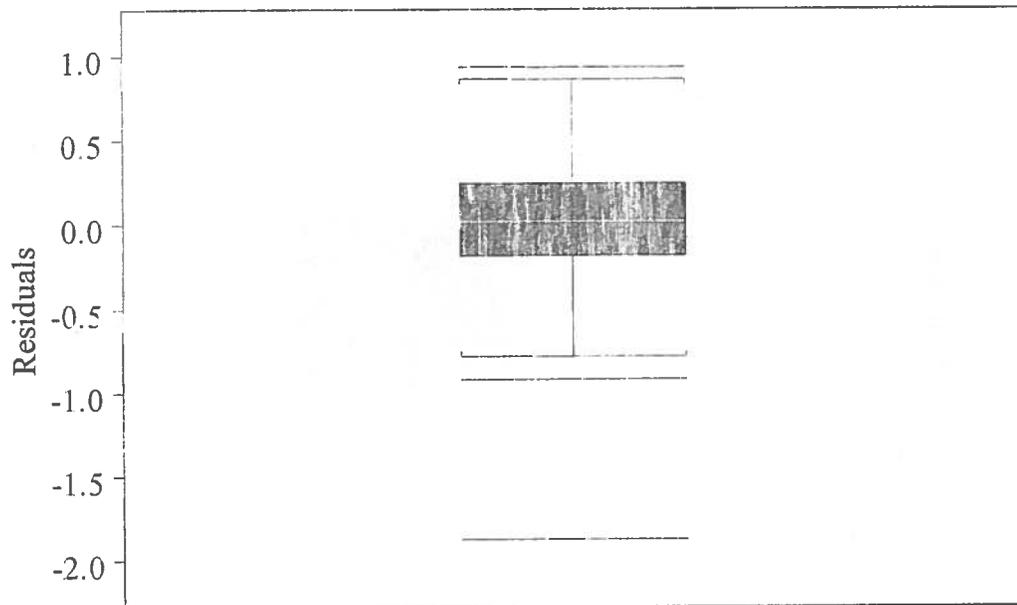
Appendix 7. Histogram of residuals showing adequate symmetry for the following regression model: $\text{Ln}(\text{Total Tree Density}) = 2.59 - 0.036 * \text{site exposure} + 0.0022 * \text{elevation}$.



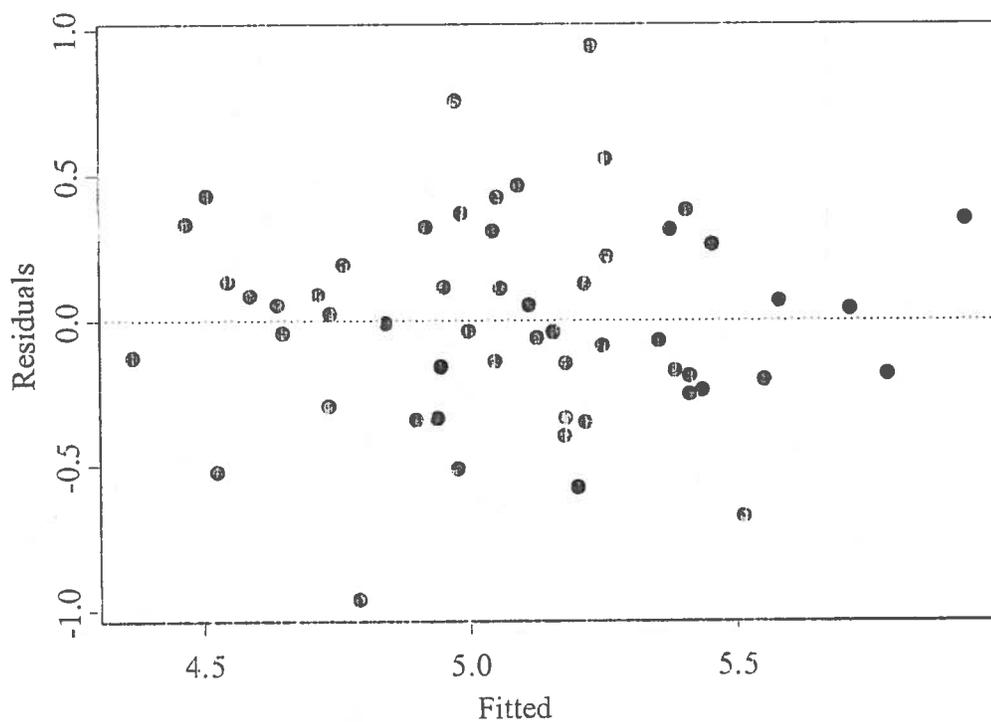
Appendix 8. Plot of studentized residuals by predicted value showing homogeneity of variance for the following regression model: $\text{Ln}(\text{Total Tree Density}) = 2.59 - 0.036 * \text{site exposure} + 0.0022 * \text{elevation}$.



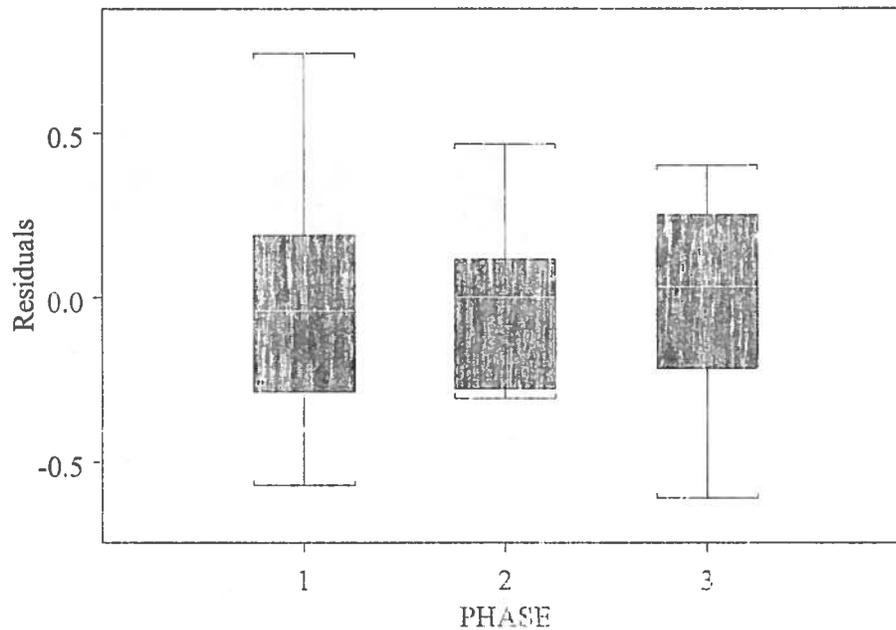
Appendix 9. Histogram of residuals showing adequate symmetry for the following regression model: $\text{Ln}(\text{Dominant Tree Density}) = 2.62 - 0.026 * \text{site exposure} + 0.001 * \text{elevation}$.



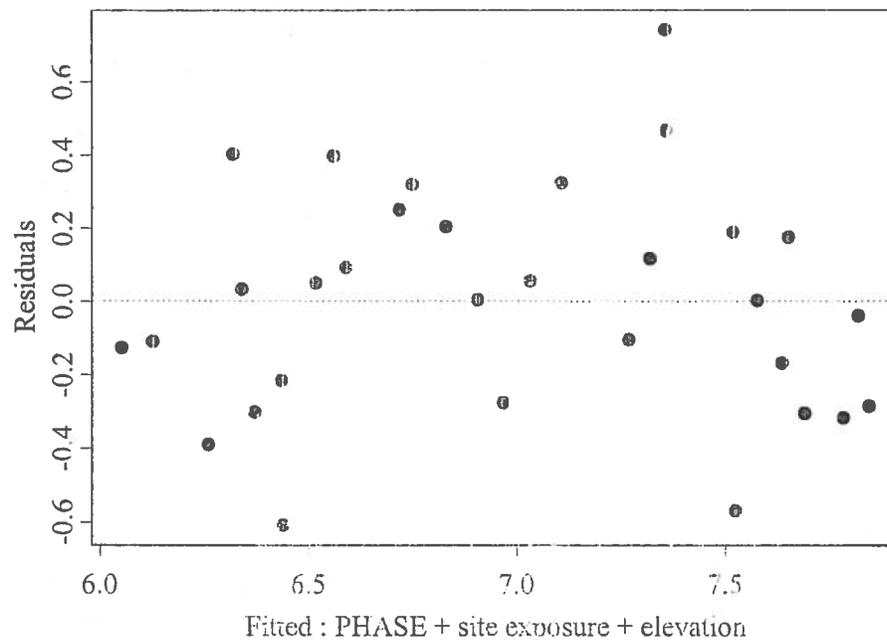
Appendix 10. Plot of studentized residuals by predicted value showing homogeneity of variance for the following regression model: $\text{Ln}(\text{Dominant Tree Density}) = 2.62 - 0.026 * \text{site exposure} + 0.001 * \text{elevation}$.



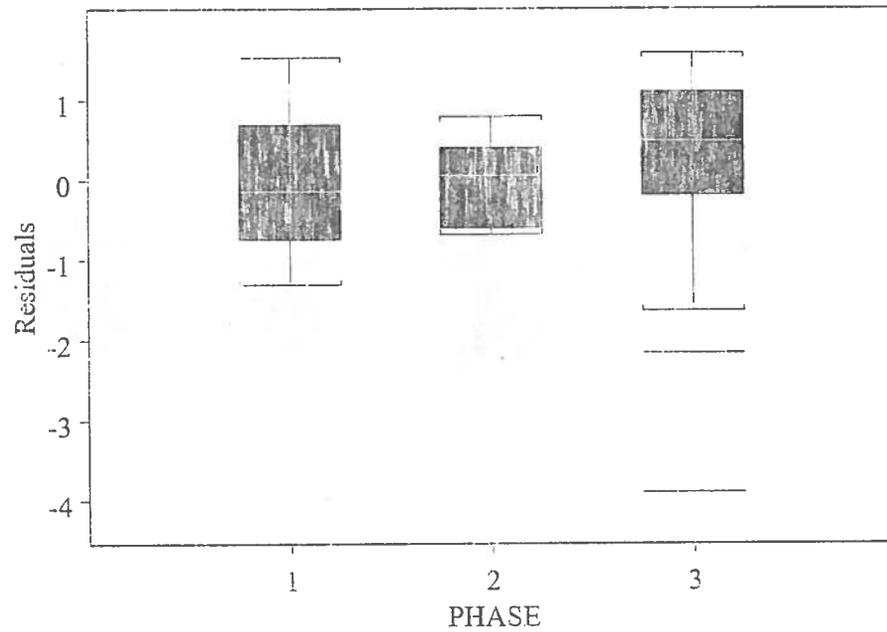
Appendix 11. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed herbaceous biomass as the response variable.



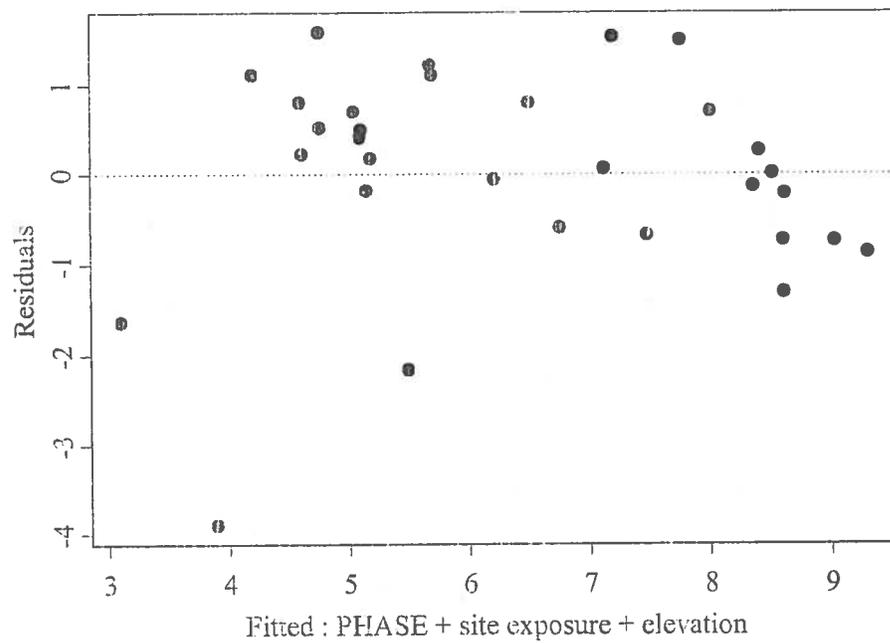
Appendix 12. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with log transformed herbaceous biomass as the response variable.



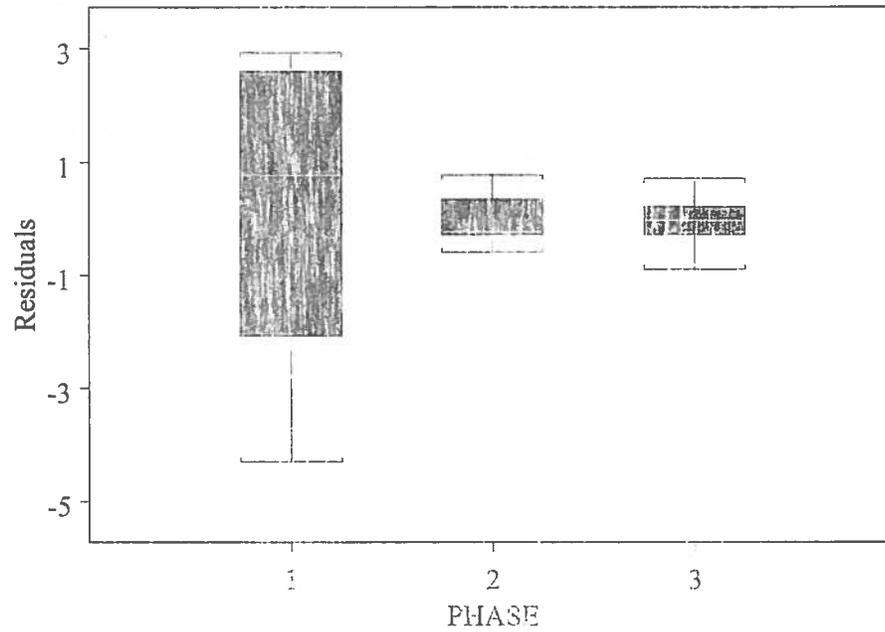
Appendix 13. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed shrub biomass as the response variable.



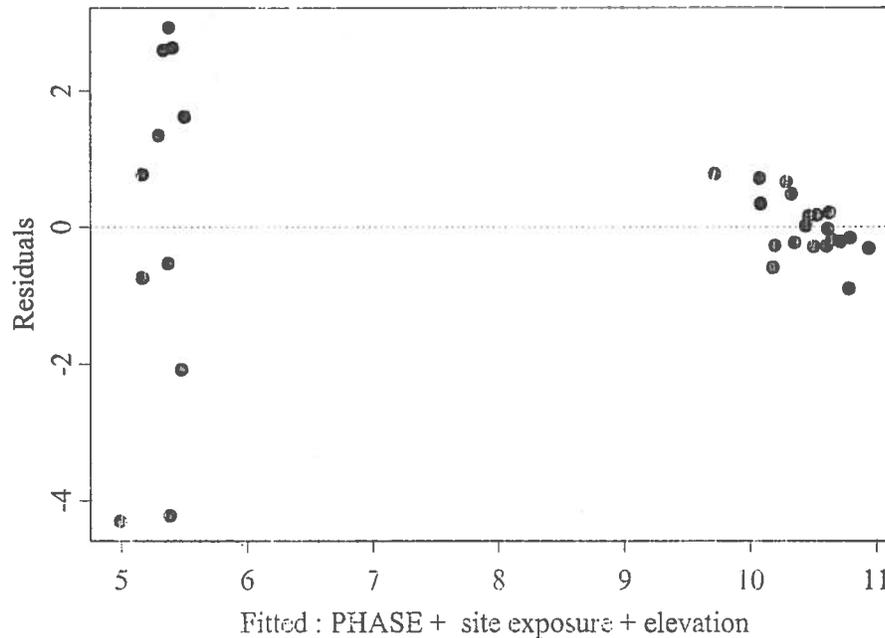
Appendix 14. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with log transformed shrub biomass as the response variable.



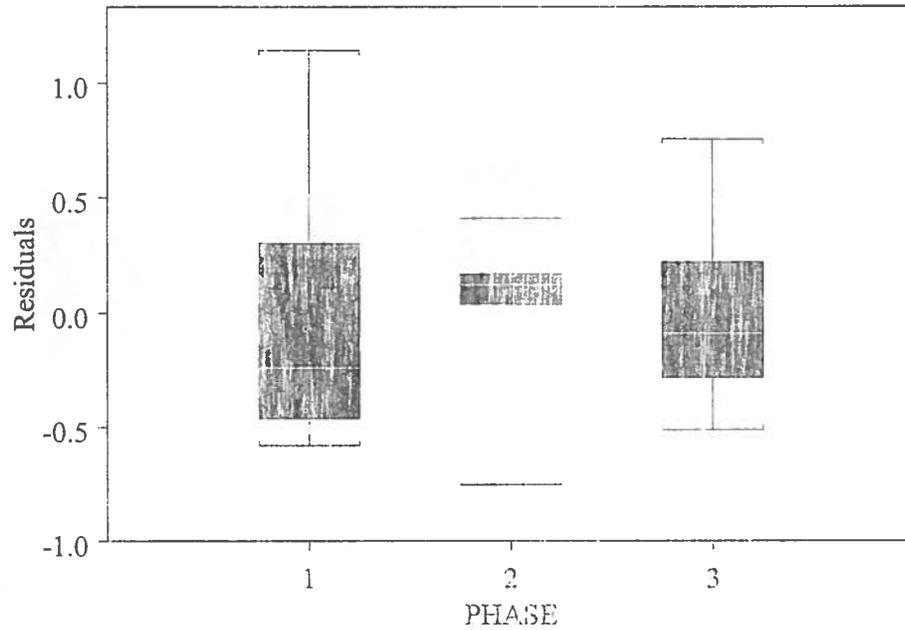
Appendix 15. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed tree biomass as the response variable.



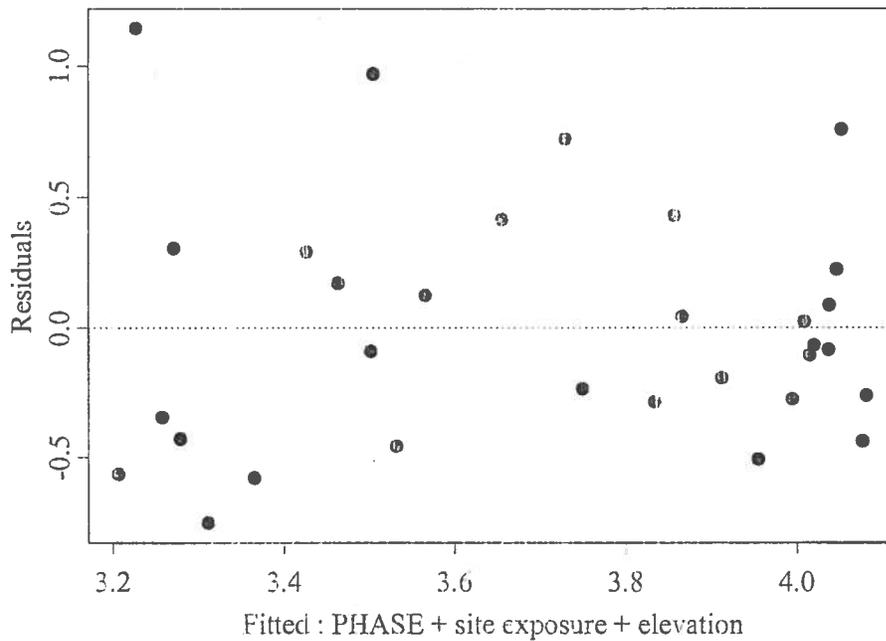
Appendix 16. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with tree biomass as the response variable.



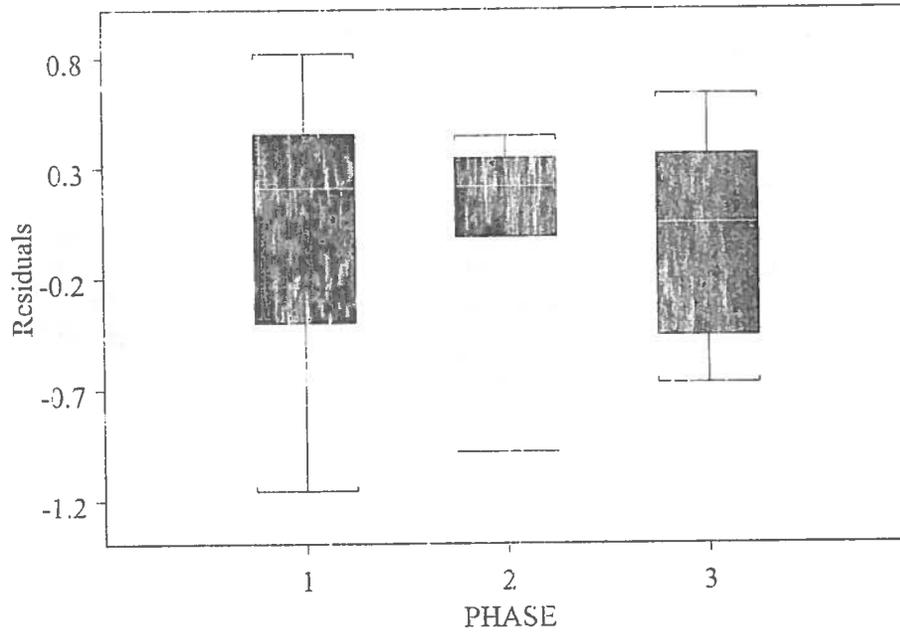
Appendix 19. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed one hour fuels biomass as the response variable.



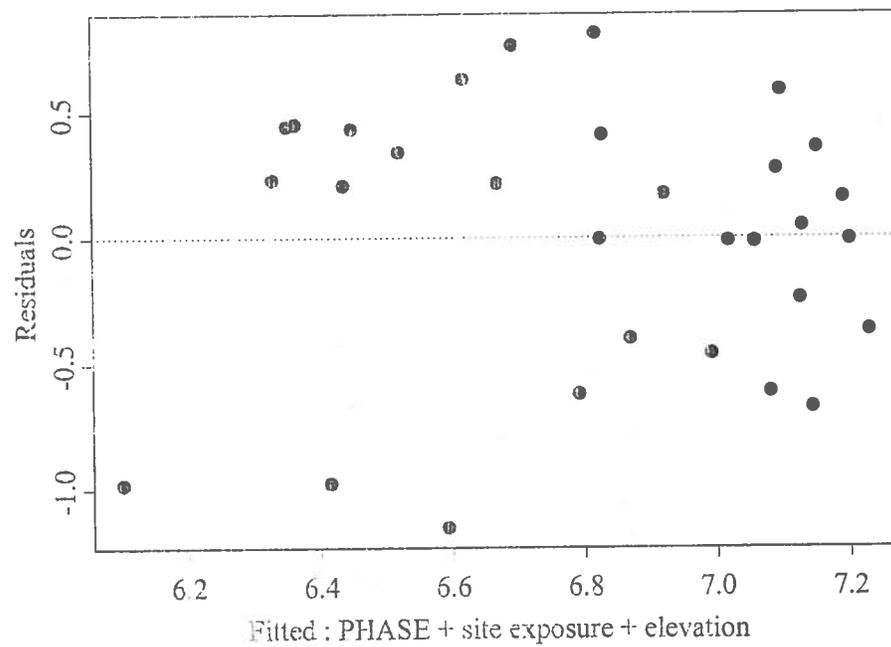
Appendix 20. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with log transformed one hour fuels biomass as the response variable.



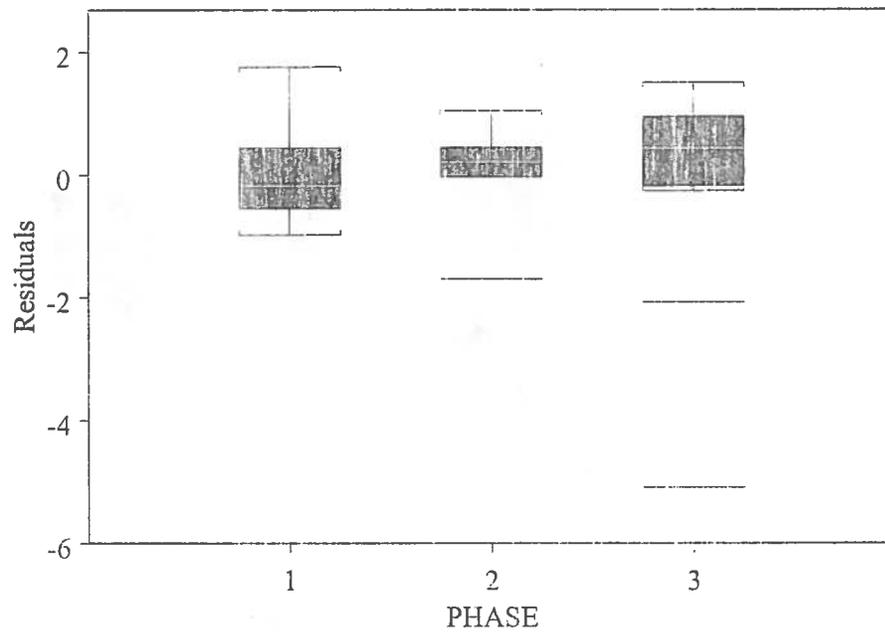
Appendix 21. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed ten hour fuels biomass as the response variable.



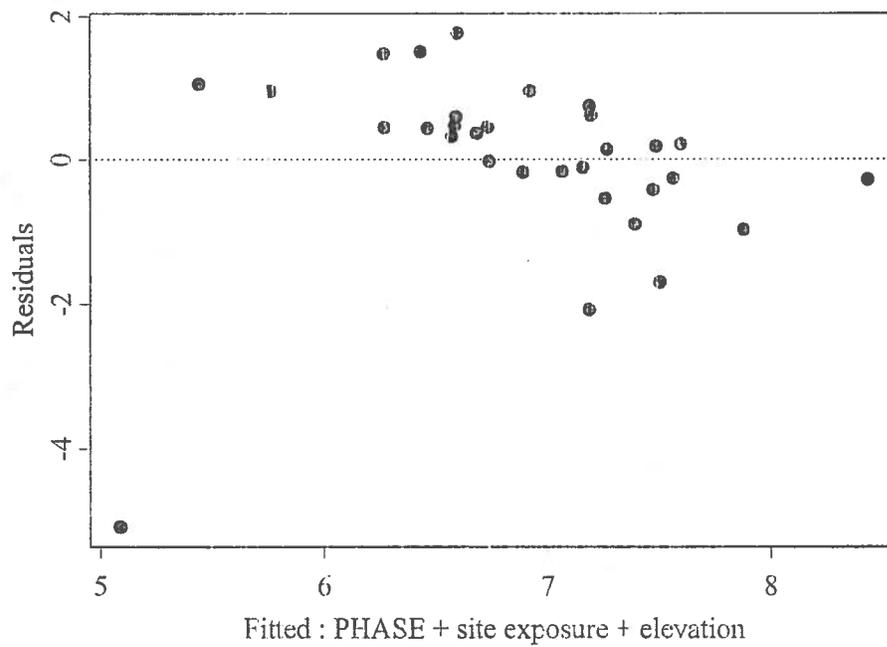
Appendix 22. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with log transformed ten hour fuels biomass as the response variable.



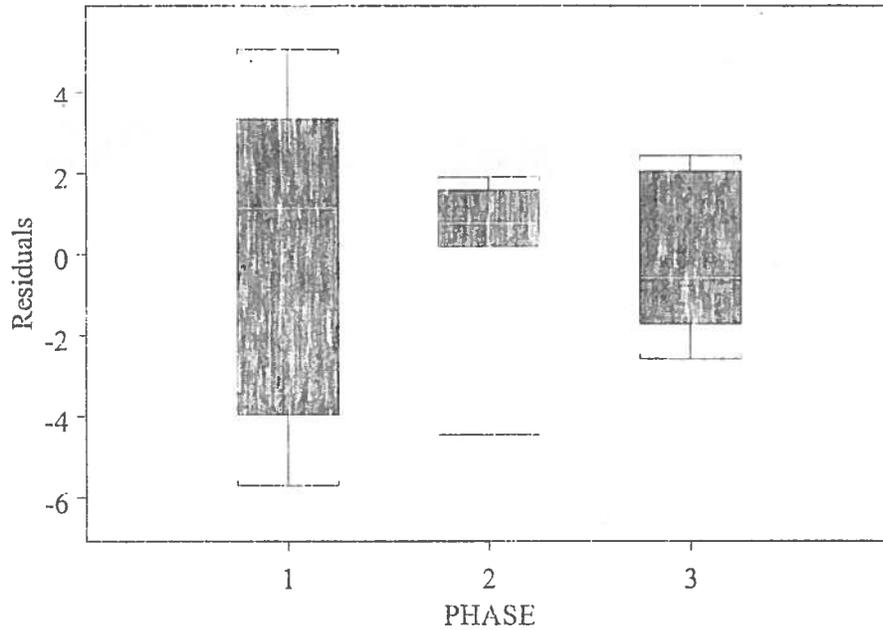
Appendix 23. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed hundred hour fuels biomass as the response variable.



Appendix 24. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with log transformed hundred hour fuels biomass as the response variable.



Appendix 25. Histogram of residuals showing adequate symmetry for the ANCOVA model with log transformed thousand hour fuels biomass as the response variable.



Appendix 26. Plot of studentized residuals by predicted value showing homogeneity of variance for the ANCOVA model with log transformed thousand hour fuels biomass as the response variable.

