SINGLELEAF PIÑON AND UTAH JUNIPER CANOPY INTERCEPTION AND UNDERSTORY CHARACTERISTICS IN CENTRAL NEVADA

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ABSTRACT

Although piñon (*Pinus* spp.) and juniper (*Juniperus* spp.) occurred historically throughout the western United States, the infilling of woodlands and expansion into sagebrush steppe has caused a reduction in understory vegetation composition leading to impaired hydrologic function, increased surface runoff and soil erosion. We hypothesized that canopy interception by singleleaf piñon (*Pinus monophylla* Torr. & Frém.), and Utah juniper (*Juniperus osteosperma (Torr.) Little*) plays a significant role in reducing the amount of rainfall that reaches the soil beneath the tree canopy. Furthermore, we hypothesized that rainfall interception would be different between species, leading to differences in understory vegetation composition. This study was conducted on a piñon and juniper encroached sagebrush area in the Desatoya Mountains of central Nevada. A series of tree allometrics including height, diameter at breast height, stump diameter and live crown were measured and tree canopy area and volume (based on shape) were calculated. Simulated rainfall was used to quantify canopy interception and redistribution during 133 rainfall events ranging in size from 2.2 to 25.9 $\mathrm{mm} \cdot \mathrm{hr}^{-1}$ on 19 trees of each species, varying in size and morphology. Rainfall redistribution by the tree canopy is equal to the sum of stemflow plus throughfall. Interception, the inverse of redistribution, was calculated using total precipitation applied to the tree canopy minus redistribution. Our results indicated that interception reduced the rainfall reaching the soil beneath the tree canopy by an average of 44% however, we found no significant difference between the two tree species. Understory composition and soil surface characteristics were quantified to investigate vegetation differences under piñon and juniper canopies. Vegetation metrics determined to be significantly different between tree species were related to tree metrics and soil surface characteristics through regression analysis to elucidate associations. Our results indicate that there was 9%, 10% and 17% more herbaceous, shrub and total foliar cover respectively under piñon than under juniper canopies. No significant relationships were found between under canopy vegetation and tree metrics. However, herbaceous, shrub and total foliar cover under the tree canopy were found to be negatively related to average litter depth, yet litter depth was not significantly different between tree species.

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Chapter 1: GENERAL INTRODUCTION

Piñon (*Pinus spp.)* and juniper (*Juniperus spp.)* currently occupy approximately 19 million ha in the Intermountain West and as much as 90% of what is now woodland occurred as sagebrush plant communities prior to European settlement (Tausch et al. 1981; Miller et al. 2008; Davies et al. 2011; Miller et al. 2011) . Although these tree species occur naturally throughout much of the western U.S., their expansion into sagebrush steppe and infilling of woodlands is problematic for land managers throughout the west. This dramatic expansion into the sagebrush steppe has three probable causes: an altered fire return interval, heavy grazing by domestic livestock, and climate change (Miller and Rose 1999; Miller et al. 2000).

Historically, piñon and juniper in the Great Basin were confined to steep rocky ridges and occurred in the lower elevations as savannas due to periodic fire (West 1997). Historic fire return interval varies by ecological site. Miller and Rose (1999) state that mountain big sagebrush (*Artemisia tridentata* ssp. *vaseyana)* sites burned on average every 10 to 25 years and were 100% likely to burn within 45 years. This return interval would typically not allow trees to reach a height tall enough to avoid being killed by fire (Miller and Rose 1999). Today's altered fire regime of greater than 100 years between fires has facilitated the expansion of piñon and juniper into sagebrush dominated landscapes with increased tree density being linked to hotter, larger, more devastating canopy fires that promote invasion by non-native species in the aftermath (Miller and Tausch 2001).

Domestic livestock have contributed to altering the fire return interval by reducing the amount of fine fuels available for carrying fires (Miller et al. 2000). Heavy grazing by domestic livestock has often given woody plants an advantage by eliminating or reducing herbaceous plants thus increasing the opportunity for woody plant establishment (Miller and Wigand 1994).

Another mechanism thought to be responsible for piñon and juniper expansion is changing climate. For about 60 years, starting in the 1880s, climatic conditions in the Great Basin were favorable for woody species establishment thereby, setting the stage for rapid invasion (Bradley and Fleishman 2008). This 60 year period of high rates of establishment coincided with the highest number of domestic livestock throughout the west and implementation of active fire suppression by land management agencies (Bradley and Fleishman 2008). These three factors coupled with piñon and juniper's competitive ability to dominate site resources have each contributed to their dramatic expansion.

Piñon and Juniper Ecology

Piñon and juniper are perennial evergreen conifers that occur throughout the Intermountain West. In the Great Basin, piñon and juniper woodlands, are primarily composed of singleleaf piñon pine (*Pinus monophylla*) and two juniper species Utah and western juniper (*Juniperus osteosperma* and *J. occidentalis*) (Miller et al. 2008). Western juniper primarily dominates the northwestern portion of this region, while singleleaf piñon and Utah juniper generally occur throughout the remaining portions (Romme et al. 2009).

Singleleaf piñon typically occurs in the elevation range of 850 to 2700 m with average annual precipitation ranging from 28 to 50 cm, primarily occurring during winter and spring. Mature trees are round topped and reach heights of 12 m but the circumference of these trees is often hard to measure because of multiple stems starting at or near the soil surface. The common name “singleleaf” referrers to the one needle per fascicle, found only in this pine. The blue-gray needle-like leaves are cylindrical, 25 to 50 mm long, with a diameter of 0.8 to 1.7 mm. Cole et al. (2008) reported that needle anatomy is related to climate, and that the number of resin ducts and stomatal lines per needle can vary. Young trees have smooth grey bark which becomes furrowed and brownish with age. Piñon pines are monoecious and require two growing seasons to complete seed set. Seed production is varied and typically abundant production only occurs every 2-7 years. Singleleaf piñon will hybridize with two-needle piñon pine (*Pinus edulis*) where their distributions overlap (Lanner 1983; Cole et al. 2008). Two-needle piñon appears in limited numbers at the south east edge of the Great Basin. Its morphology and habitat are similar to singleleaf piñon in most respects with one major exception—two-needle occurs where the precipitation patterns shift to warm season occurrence (Lanner 1983).

Utah juniper typically occurs from 900 to 2400 m with annual precipitation ranging from 20 to 61cm, occurring as winter and spring precipitation. Mature height is usually less than 8 m and often occurs with multiple stems that can reach 10 to 30 cm in circumference. At maturity, the yellowish-green, appressed, scale-like leaves are 2-8 mm long occurring in alternating pairs along the twig

(Skau 1964). The shaggy bark is grayish brown and is easily shredded. Utah juniper is usually monoecious but sometimes dioecious and begins producing seed when it reaches 30 years old. Charlet (1996) observed that where singleleaf piñon and Utah juniper occur together, singleleaf will eventually outcompete Utah juniper and dominate the site

In areas where Utah and western juniper are sympatric, western juniper usually occurs only in the higher elevations above the range of the Utah juniper, but they can occur together at lower elevations along streams (Charlet 1996). Western juniper is typically found between 1260 to 2775 m in elevation, with precipitation ranging from 30 to 50 cm, mainly occurring in the winter and spring. Mature western juniper range from 4 to 10 m tall, usually with a single stem that can range from 35 to 70 cm in circumference. The gray-green scale-like leaves of a mature tree are from 1 to 3 mm long compressed to the stem in overlapping opposite pairs or in whorls of three. Each leaf contains a conspicuous resin gland on its dorsal surface that typically has a large drop of resin present (Miller et al. 2005). Bark is often reddish brown and shreds easily. Western juniper is both monoecious and dioecious and typically begins bearing seeds at 10-20 years of age but production is limited until they reach 50-70 years old (Miller and Rose 1995).

Piñon and juniper inhabit very similar ecological sites and occur in pure or mixed stands depending on environmental constraints such as elevation and the region where they are found (Romme et al. 2009). West (1997) reported that where piñon and juniper occur together, piñon tends to dominate middle elevations while juniper tends to be dominate in the higher and lower elevations because of its ability to tolerate drought and cold. Regional influence, much like elevation, is strongly tied to precipitation. Regions with higher precipitation, such as southeastern Oregon, favor western juniper while dryer areas, like central Nevada, favor Utah juniper. Due to reduced fire frequency, heavy grazing by domestic livestock and climate change piñon and juniper are present throughout sites that were historically sagebrush steppe and they are adapted to monopolize resources by outcompeting understory species.

Affects of Piñon and Juniper Encroachment

As piñon and juniper eliminate understory species there is a correlated degradation of primary ecological processes (Petersen 2004). This degradation results in the impairment of the spatial and temporal ability to capture energy, store nutrients and retain water within the system (Whisenant 1999). The impact of the degradation of these ecological processes is intensified in the arid-west where resources are especially limited. Historically piñon and juniper predominately occurred on rocky shallow soils but currently have expanded to nearly every soil type, including deep fertile soils where shrubs and grasses generally dominate (Miller et al. 2005). Piñon and juniper encroachment into sagebrush steppe has caused changes in soil chemistry and nutrient distribution (Tiedemann and Klemmedson 1995; Rau et al. 2005).

Trees and shrubs change the nutrient distribution within the soil profile by taking nutrients from deep soil pools and concentrating them on the surface (Rau et al. 2005). Piñon and juniper also concentrate more nutrients above ground than grasses or shrubs, which can result in loss of nutrients due to volatilization, wind redistribution and erosion after high intensity fire (Rau et al. 2005). Rau et al. (2005) reported that sodium concentrations were higher on piñon and juniper invaded soils but that zinc concentrations were higher under shrubs, however this study found no observed differences for potassium, manganese, or iron. A study in shrub steppe encroached by western juniper found little effect on soil available nitrogen but soil sulfur availability was dramatically increased (Tiedemann and Klemmedson 1995). Additionally, the authors found that phosphorus availability initially increased under tree canopies then declined significantly with stand age while potassium was relatively unchanged when comparing under trees to under shrubs (Tiedemann and Klemmedson 1995). Research has found that piñon and juniper change the carbon to nitrogen ratio and increase pH (Wall et al. 2001; Rau et al. 2009). Rau et al. (2009) reports that although it is thought that tree encroachment could be a substantial carbon sink, this may not be true for Great Basin systems. Although this may be true for above ground biomass, the loss of below ground carbon due to tree encroachment on sagebrush steppe may offset gains in carbon storage (Rau et al. 2009). The redistribution of nutrients and changes in mineral cycling have been found to enhance tree competitiveness with herbaceous species (Doescher et al. 1987).

Once piñon and juniper invade a site they can quickly dominate resources and eliminate competition because of their morphological traits. These traits include tap and lateral roots and leaf structure which allows them to minimize evaporation losses (Miller et al. 2005). Western juniper has been found to invest nearly all of its energy in taproot development during its first ten years, after which it begins to invest in lateral roots (Krämer et al. 1996). Taproot development enhances the trees access to ground water and pools of soil nutrients deep in the soil profile that herbaceous plants may not be able to utilize. Miller et al. (2005) reported that by the time a western juniper tree is 30-35 years old, lateral roots will amount to 65% of the root biomass, and that lateral roots typically extend a distance equal to three times the height of the tree. The lateral root system of these trees allows them to capture large amounts of water and nutrients dominating even in the interspaces (Miller et al. 2005).

Closed canopy woodlands decrease the amount of water captured by soil by increasing bare ground in the interspaces which leads to greater raindrop impact, soil crusting, decreased infiltration, and increased erosion (Tausch et al. 2009). As piñon and juniper out-compete understory vegetation, one or more of the primary ecological processes can be negatively impacted resulting in decreased function on that site (Petersen 2004). One attribute used to measure hydrologic function is bare ground. As bare ground increases there is a correlated decline in hydrologic function (Whisenant 1999). Soil structure and vegetative cover aid infiltration, mitigate temperature fluctuations, and reduce wind and water erosion (Whisenant 1999). Peterson (2004) reported that intact sagebrush plant communities exhibited the highest rates of infiltration due to more herbaceous cover and greater surface litter whereas areas encroached with juniper had higher amounts of bare soil and a corresponding decrease in infiltration. The simplification of understory vegetation may cause a decline in the number of functional groups leading to a reduction in spatial and temporal energy capture and nutrient cycling.

Canopy interception

Effective precipitation refers to the amount of precipitation that enters the soil and is stored in the soil profile (Miller et al. 2005). Miller et al. (2005), reported that effective precipitation can differ from total precipitation because of western juniper canopy interception. Canopy interception is the amount of rainfall retained by the tree canopy (Horton 1919). Woodland precipitation interception and redistribution is divided into litter, canopy, stemflow and throughfall (Branson et al. 1981; Eddleman et al. 1994). Canopy redistribution is rainfall that comes through the canopy in the form of stemflow and throughfall. Stemflow is the precipitation that is funneled by stems to the trunk and is deposited at the base of the tree (Taucer 2006). Young et al. (1984) reported that following seasonal drought, stemflow in western juniper is enriched with nitrogen, thus stemflow enhances nitrification of tree litter, effectively fertilizing the fine roots at the base of the trunk. Throughfall is the portion of precipitation that falls directly through the canopy or that drips from leaves and stem to the ground (Branson et al. 1981). It may be that throughfall also fertilizes beneath trees by washing nutrients, accumulated through dry deposition, to the forest floor. A study of lodgepole pine and Engelmann spruce found that water loss due to snow interception was minimal (Hover and Leaf 1967 as sited in Larsen 1993). Eddleman (1994) reported that canopy interception in western juniper can exceed 12% of annual precipitation. The amount of precipitation lost to canopy interception depends on the amount and frequency of precipitation received, as well as storm intensity (Horton 1919; Branson et al. 1981). Although precipitation interception is varied, it directly affects the amount of effective precipitation that reaches the soil surface and understory; this affect can be ecologically important in semiarid areas like the Intermountain West where rainfall is limited.

Problem Statement

There is very little research available that has quantified canopy interception and rainfall redistribution by Utah juniper and singleleaf piñon. The purpose of this research was to quantify canopy rainfall redistribution by singleleaf piñon and Utah juniper and to model that redistribution based on tree allometrics. Once total rainfall redistribution, in the form of stemflow and throughfall, was quantified, rainfall interception was calculated. Models of interception and redistribution may be helpful for maximizing limited management resources across large landscapes and will aid in understanding piñon and juniper's hydrologic impacts at a multitude of scales. Additionally, we sought to quantify vegetation and soil surface characteristics under singleleaf piñon and Utah juniper canopies' and to investigate any differences. Vegetation metrics determined to be significantly different between tree species were related to tree metrics and soil surface characteristics through regression analysis to elucidate associations. These models may be useful in understanding the influences of singleleaf piñon and Utah juniper on understory species.

Hypotheses Tested

1. Singleleaf piñon differs from Utah juniper in total rainfall redistribution.
2. Singleleaf piñon differs from Utah juniper in total throughfall.
3. Singleleaf piñon differs from Utah juniper in total stemflow.
4. Rainfall redistribution can be related to tree metrics using regression analysis and these models can be used to predict rainfall redistribution.
5. Canopy interception reduces the amount of rainfall that reaches the soil under the most typical Nevada storm of less than 5 mm.
6. Vegetation under singleleaf piñon canopies is different from vegetation under Utah juniper canopies.
7. Vegetation under singleleaf piñon and Utah juniper canopies is related to tree metrics and/or soil surface characteristics.

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Chapter 2: Quantifying and Modeling Rainfall Interception and Redistribution by Singleleaf Piñon and Utah Juniper in Central Nevada

ABSTRACT

Although piñon (*Pinus* spp.) and juniper (*Juniperus* spp.) occurred historically throughout the western United States, the infilling of woodlands and expansion into sagebrush steppe has caused a reduction in understory vegetation composition leading to impaired hydrologic function, increased surface runoff and soil erosion. We hypothesized that canopy interception by singleleaf piñon (*Pinus monophylla* Torr. & Frém.), and Utah juniper (*Juniperus osteosperma (Torr.) Little*) plays a significant role in reducing the amount of rainfall that reaches the soil beneath the tree canopy. This study was conducted on a piñon and juniper encroached sagebrush area in the Desatoya Mountains of central Nevada. A series of tree allometrics including height, diameter at breast height, stump diameter and live crown were measured and tree canopy area and volume (based on shape) were calculated. Simulated rainfall was used to quantify canopy interception and redistribution during 133 rainfall events ranging in size from 2.2 to 25.9 $\mathrm{mm} \cdot \mathrm{hr}^{-1}$ on 19 trees of each species, varying in size and morphology. Rainfall redistribution by the tree canopy is equal to the sum of stemflow plus throughfall. Interception, the inverse of redistribution, was calculated using total precipitation applied to the tree canopy minus redistribution. Results indicated that an average of 44% of rainfall was intercepted across the range of storm intensities and that 68% of precipitation from storms of less than 5 mm was intercepted. A randomized block design was used to evaluate differences between singleleaf piñon and Utah juniper stemflow, throughfall and total redistribution of rainfall. Prior to analysis data was square root transformed to meet assumptions of normality (Zar 1999). A two-way analysis of variance (ANOVA) $\alpha = 0.05$ was used to detect differences between species, with storm size and tree canopy area held constant. No significant differences were found between piñon and juniper rainfall redistribution. The best fit predictive model of total redistribution was described by tree crown area, crown shape and storm size ($R^2 = 0.80$, $p < 0.\ 01$) with tree crown area and storm size accounting for 77% of the variability ($R^2 = 0.77$, $p < 0.01$). The storm size and tree canopy area model could be used by land managers to predict canopy redistribution and thereby canopy interception for large landscapes, utilizing remote sensing technology to estimate tree canopy area and historic storm sizes. Our results demonstrate that singleleaf piñon and Utah juniper impair hydrologic function through rainfall interception and contributes to piñon and juniper’s dominance of site resources.

INTRODUCTION

Piñon and juniper currently occupy approximately 19 million ha in the Intermountain West and prior to European settlement as much as 90% of what is now woodland occurred as sagebrush plant communities (Tausch et al. 1981; Miller et al. 2008; Davies et al. 2011; Miller et al. 2011) . Historically, piñon and juniper were confined to steep rocky ridges and occurred in the lower elevations as savannas due to periodic fire (West 1997; Romme et al. 2009). This dramatic expansion has three contributing factors: an altered fire return interval, heavy grazing by domestic livestock, and climate change (Miller and Rose 1999; Miller et al. 2000; Miller et al. 2011). Although the specific species of piñon or juniper varies depending on the region considered, many of the problems relating to their invasion are similar (Tausch et al. 2009). With increasing tree cover, shrubs and deep rooted bunchgrasses often decline resulting in increasing bare ground in intercanopy areas that leads to greater raindrop impact, soil crusting, decreased infiltration, and increased soil erosion (Petersen and Stringham 2008; Tausch et al. 2009). Petersen determined that as western juniper out-competes understory species there is a correlated degradation of primary ecological processes (Petersen 2004). This degradation results in the impairment of the spatial and temporal ability to capture energy, store nutrients and retain water within the system (Whisenant 1999). The impact of the degradation of these processes is intensified in the arid-west where resources are especially limited (Wilcox and Breshears 1994). One of the mechanisms thought to contribute to the loss of understory species and the degradation of primary processes is the interception of precipitation by the tree canopy (Larsen 1993; Miller et al. 2005).

Rainfall canopy interception is the amount of rainfall retained by the tree canopy and subsequently lost to evaporation (Horton 1919; Branson et al. 1981; Owens et al. 2006). Miller et al. (2005), reported that effective precipitation can differ from total precipitation because of western juniper canopy interception.

Rainfall not lost to interception is redistributed by the tree canopy as stemflow and throughfall. Stemflow is rainfall that is funneled by leaves and stems to the trunk and is deposited at the base of the tree (Taucer 2006). Young et al. (1984) reported that following seasonal drought, stemflow in western juniper is enriched with nitrogen, thus stemflow enhances nitrification of tree litter effectively fertilizing the fine roots at the base of the trunk. Throughfall is the portion of precipitation that falls directly through the canopy or that drips from leaves and stems to the ground (Collings 1966; Branson et al. 1981). Eddleman (1994) reported that canopy interception in western juniper can exceed 12% of annual precipitation. The amount of precipitation lost to canopy interception depends on the amount and frequency of precipitation received, and storm intensity (Horton 1919; Branson et al. 1981; Owens et al. 2006). Very little research has quantified canopy interception by singleleaf piñon and Utah juniper.

The purpose of this research was to quantify canopy rainfall redistribution by singleleaf piñon and Utah juniper and to model that redistribution based on tree allometrics. Once total rainfall redistribution, in the form of stemflow and throughfall, was quantified, rainfall interception was calculated. Models of interception and redistribution may be helpful for maximizing limited management resources across large landscapes and will aid in understanding piñon and juniper’s hydrologic impacts at a multitude of scales.

Site Description

This study was conducted in and around the Porter Canyon watershed in the Desatoya Mountains in Lander County, Nevada, where the elevation ranges from 1 800 m to 2 400 m. Precipitation predominantly occurs as winter snow and spring rain with a 30-year annual average of 25.6 cm. Average annual temperature ranges from -7.5°C to 17.3°C. Temperature and precipitation data are from the Big Creek *SNOTEL* weather station (lat 39°17' N, long 117°07' W, elevation 2630 m) (US Department of Agriculture, Natural Resource Conservation Service [USDA, NRCS] 2011).

Soil parent materials are primarily residuum weathered from conglomerate and/or shale and/or tuff (Soil Survey Staff 2012). Soils include Lithic/Typic/Aridic Argixerolls, Xeric Argidurid, Haploxeralfic Argidurids, and Xeric Haplargids. Rainfall simulations were primarily conducted on two ecological sites. The higher elevation site was a Loamy 10-12 PZ and the low elevation site was a Droughty Loam 8-10 PZ (USDA NRCS 2003). Potential native plant community for: the higher elevation site was described as being dominated by Thurber's needlegrass *(Achnatherum thurberianum* [Piper] Barkworth), bluebunch wheatgrass *(Pseudoroegneria spicata* [Pursh] Á. Löve) and mountain big sagebrush *(Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle): the lower elevation site would potentially have been dominated by Indian ricegrass *(Achnatherum hymenoides* [Roem. & Schult.] Barkworth), needle and thread *(Hesperostipa comata* [Trin. & Rupr.] Barkworth), spiny hopsage *(Grayia spinosa* [Hook.] Moq.) and Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp.

wyomingensis Beetle & Young). Both sites are currently encroached by Utah juniper and singleleaf piñon with intercanopy understory that is primarily composed of Sandberg's bluegrass *(Poa secunda* J. Presl) with mountain big sagebrush at the higher elevations and Wyoming big sagebrush at the lower elevations.

This study area is currently under public (Carson and Battle Mountain Districts, Bureau of Land Management) and private ownership. Porter canyon and the surrounding area have experienced a variety of disturbances including farming, tree harvest (both for mining and ranching purposes), sagebrush removal, homesteading and livestock grazing. The area is currently grazed by cattle with the season of use occurring as a rotation between spring use for two years and then fall use for two years.

METHODS

Experimental Design

A randomized block design was used to test for differences in canopy redistribution of simulated rainfall by singleleaf piñon and Utah juniper. Additionally, regression analysis was used to model canopy rainfall redistribution based on measured tree allometrics. Canopy rainfall redistribution was quantified on 19 piñon and 19 juniper trees with a total of 133 storms simulated over the 2010 and 2011 field seasons. Trees were selected to meet criteria based on species, size, form and accessibility. Ease of access was required for the rainfall simulation equipment, thus trees were chosen in flat areas close to roads. Each of the 38 trees received up to 5 rainfall events of varied intensity ranging from 2.2 mm · hr $^{-1}$ to 25.9 mm · hr $^{-1}$.

Allometric Assessment

Prior to simulated rainfall, a series of tree allometrics were measured including total tree height, live crown height, diameter at stump height, diameter at breast height, and crown diameter (Table 2.1). Total tree height was measured using a stadia rod. Diameter at stump height was measured 30 cm above ground level using a diameter tape. Diameter breast height was measured at approximately 1.4 meters above ground level using a diameter tape. Live crown was calculated by measuring total tree height minus the distance measured from first live foliage to the ground using a meter tape. Canopy area was calculated using the following equation: $\pi\,([\text{crown diameter}_1 + \text{crown diameter}_2] / 4)^2$ and canopy volume was calculated based on the most closely related canopy shape according to Table 2.2. Crown diameter was measured using a meter tape at the canopy's widest point (diameter$_1$) and perpendicular to that point (diameter$_2$).

Table 2.1 Average ± standard error values for metrics measured on 38 trees, 19 piñon and 19 juniper. *DBH is the diameter of the trunk at breast height.

Metric	Piñon average	Juniper average	Piñon range	Juniper range
Height (m)	4.8 ± 0.3	6.0 ± 0.3	3.1 – 7.6	4.7 – 8.3
DBH* (cm)	18.4 ± 2.2	26.3 ± 1.6	7.1 – 36.3	16.2 – 41.4
Stump diameter (cm)	25.5 ± 1.9	36.1 ± 2.0	10.7 – 38.9	20.1 – 49.8
Live crown height (m)	4.5 ± 0.3	5.4 ± 0.3	3.1 – 6.9	3.3 – 7.8
Canopy area (m^2)	16.4 ± 2.5	24.4 ± 2.8	4.4 – 45.1	8.9 – 53.5
Canopy volume (m^3)	47.4 ± 5.0	86.4 ± 5.4	8.4 – 194.6	18.5 – 172.7

Table 2.2 Formulas for calculating crown volume.

Shape formula	Shape name
$((\text{Crown diameter}_1 + \text{Crown diameter}_2)/2)^2 \times (\text{Live crown height}) \times (0.4909)$	Expanded Paraboloid
$((\text{Crown diameter}_1 + \text{Crown diameter}_2)/2)^2 \times (\text{Live crown height}) \times (0.2619)$	Cone

Rainfall Simulation

The thirty year rainstorm frequency for central Nevada was calculated from data derived from the Big Creek weather station located near Austin Nevada approximately 50 km east of Porter Canyon (Figure 2.1). The size and frequency of precipitation events was used to determine the range of simulated rainfall events. Simulated rainfall was applied during the pre-dawn period as this timeframe exhibited the calmest conditions ensuring minimal loss to evaporation and wind. The rainfall simulator was built using 1.9 cm diameter, galvanized pipe for the standpipe and adjusted in 1.5 m increments depending on tree height. The standpipe was placed to ensure rainfall from a single nozzle completely covered the canopy. Two 20-cm torpedo-levels were attached to the top of the standpipe along with four guy-ropes to level the simulator (Illustration 2.1). Water for simulations was supplied by a water truck and delivered to the simulator with a semi-trash pump. Four *Quick Fulljet®* nozzles, sizes 0.8, 1.7, 3.5, and 6.0, were used to generate storm intensities that ranged from 2.2 to 25.9 mm · hr $^{-1}$. Simulator output for each nozzle was measured using a known volume and pressure and simulated storm duration was one hour. Total liters applied for each storm was determined using a *GPI*® digital flow meter. Following simulation, trees were allowed to completely dry before additional storms were applied.

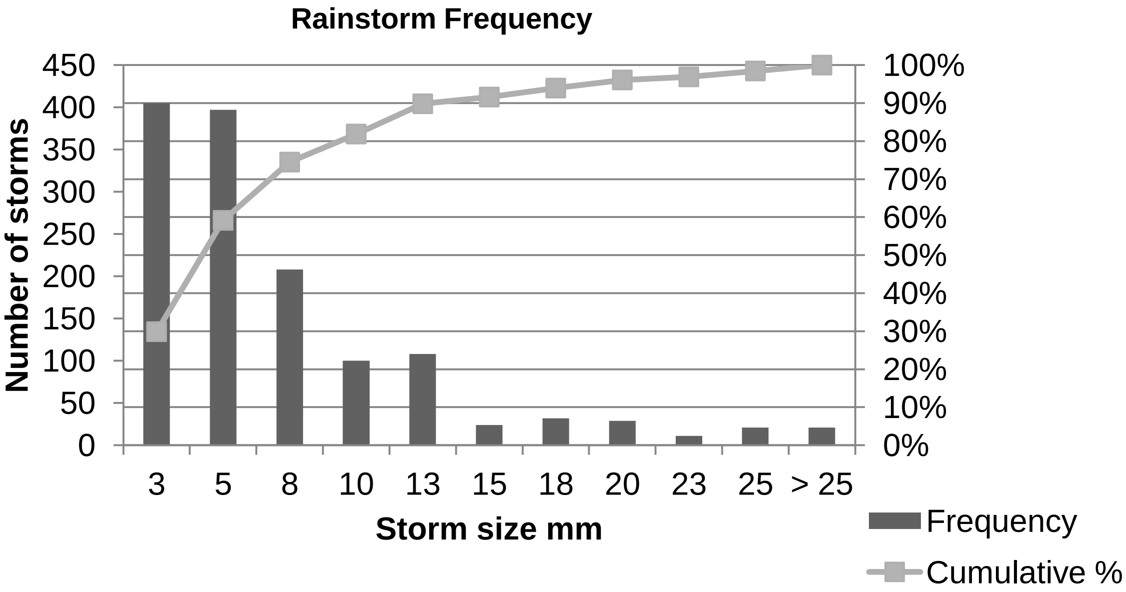

Figure 2.1 Thirty year rainstorm frequency for Big Creek weather station, located in central Nevada (USDA NRCS 2011).

Illustration 2.1a Rainfall simulator. Note: four guy ropes, levels, pressure gauge and nozzle.

Illustration 2.1b Rainfall simulator and pools beneath the tree canopy for throughfall capture.

Quantifying Rainfall Redistribution

Canopy rainfall interception is residual water that remains on vegetative surfaces after free drip has ceased and is represented by the equation *Canopy interception = total rainfall – (throughfall + stemflow)*. Total rainfall applied to the tree is calculated based on the proportion of the total wetted area occupied by the tree canopy. Wetted area was calculated using the following equation: $\pi \left([\text{diameter}_1 + \text{diameter}_2] / 4\right)^2$. Diameter$_1$ was measured at the wetted area's widest point and diameter$_2$ was measured perpendicular to diameter$_1$ using a meter tape.

Stemflow was captured using 2.54 cm plastic tubing which was attached to the tree's trunk using screws and silicone and then cut to create a gutter for collecting and transporting stemflow to a collection bucket (Illustration 2.2).

Illustration 2.2a Stemflow collar attached to trunk of tree.

Illustration 2.2b Stemflow funneled to collection bucket.

The attachment height of the stem collar varied to permit placement below the lowest branch larger than 5 cm. Throughfall was captured using 16-cm diameter buckets or 106-cm diameter wading pools placed from trunk to canopy edge (Illustration 2.3). Buckets were used exclusively in 2010 but in 2011 a combination of pools and buckets were used to maximize the amount of throughfall captured. The number of buckets and pools under each canopy was calculated based on the sample size equation $n = \frac{(z_\alpha)^2 * (s)^2}{B}$ where the desired precision level was ± 10% and the standard normal coefficient was 1.96 (Elzinga et al. 1998).

Illustration 2.3a Pools used beneath tree canopy for capturing throughfall.

Illustration 2.3b Buckets placed under the canopy for capturing throughfall.

Data Analysis

The total rainfall applied to each tree was calculated by dividing the total liters of water applied by wetted area and then multiplying by the area of the tree canopy. Wetted area was directly measured during 80 storms of varying intensity and these measurements were used for generating species specific models to predict wetted area for the remaining 53 storms. Prior to regression analysis, eight storms of varying intensity were randomly removed from the dataset to test predicted wetted area values against actual wetted area values for these eight storms. Piñon variables were natural log transformed to meet assumptions of normality. Stepwise multiple linear regression was used to select best fit models for predicting wetted area. Explanatory factors that were not significant contributors, as determined using forward stepwise selection at ($p = 0.01$), were excluded from the final model. Predictor variables included in the stepwise regression were stand pipe height, maximum wind speed, average wind speed, total liters rainfall applied, total tree height, live crown height, stump diameter, diameter breast height, tree canopy area, tree canopy volume.

A randomized block design was used to evaluate differences between singleleaf piñon and Utah juniper stemflow, throughfall and total redistribution of rainfall. Prior to analysis data was square root transformed to meet assumptions of normality (Zar 1999). A two-way ANOVA ($\alpha = 0.05$) was used to detect differences between species stemflow, throughfall and total rainfall redistributed by the tree canopy. Stepwise multiple linear regression was used to select best fit models correlating tree metrics with the total rainfall redistributed by the tree canopy. Explanatory factors that were not significant contributors, as determined using forward stepwise selection at ($p = 0.01$), were excluded from the final model except for main effects that were included in significant interaction terms. JMP version 9.0 (SAS Institute 2010) was used for all statistical analyses.

RESULTS

Modeling Wetted Area

Analysis of piñon and juniper wetted area resulted in a significant regression ($p < 0.01$) producing a best fit model with $R^2 = 0.87$ for piñon and $R^2 = 0.88$ for juniper (Table 2.3). The betas preserved in the piñon model included standpipe height, maximum wind speed, total volume applied and stump diameter. The betas for the juniper model were maximum wind speed, total volume applied, live crown and tree canopy volume. The best fit model for each species was used to predict wetted area for 8 storms of varied intensity and the predicted values were tested against the actual wetted area. A students two-tailed t-test for piñon (p = 0.89) and for juniper (p = 0.82) failed to detect differences between mean modeled versus mean actual wetted area values. The best fit models were then used to generate wetted area values for fifty-three storms where wetted area values were not directly measured.

Table 2.3 Models used for predicting piñon and juniper wetted area.

	β_0	$\beta_1 x_1$	$\beta_2 x_2$	$\beta_3 x_3$	$\beta_4 x_4$	p – value	R^2
Juniper model	-25.55	1.656 Max wind $(km \cdot hr^{-1})$	0.030 Total liters applied	10.982 Live crown (m)	-1.761 Tree canopy volume (m^3)	< 0.01	0.88
Piñon model	0.138	0.267 Ln Max wind $(km \cdot hr^{-1})$	0.339 Ln Total liters applied	0.405 Ln Stump diameter (cm)	0.308 Ln* Stand pipe height (m)	< 0.01	0.87

Rainfall Redistribution

Results from analysis of variance (α = 0.05) performed on stemflow, throughfall and total rainfall redistributed (stemflow + throughfall) failed to detect a significant difference between piñon and juniper in stemflow ($F_{3, 132} = 0.25$ $p = 0.86$); throughfall ($F_{3, 132} = 0.45$ $p = 0.91$) or total redistribution ($F_{3, 132} = 0.46$ $p = 0.89$) after controlling for tree area and storm size by including them in the model (Figure 2.2). The average of total rainfall accounted for by each component of redistribution with all 133 storms was; stemflow 2%, throughfall 54% and total redistribution 56%.

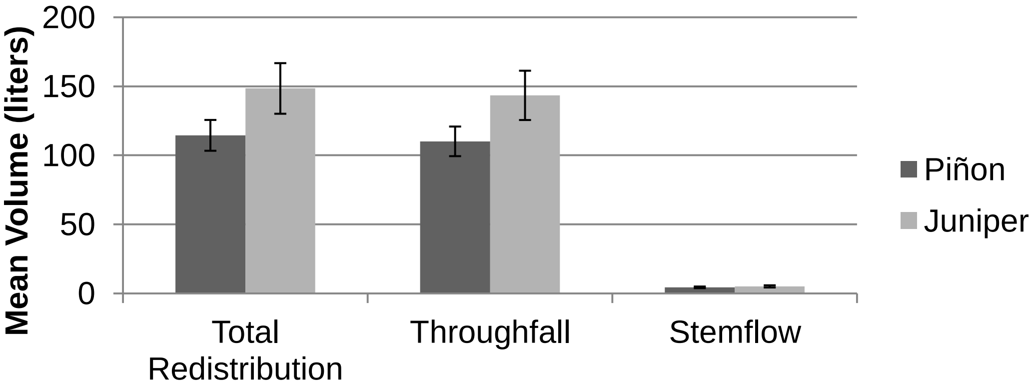

Figure 2.2 Total rainfall redistribution, throughfall and stemflow for singleleaf piñon and Utah juniper. No significance difference between tree species as determined using Analysis of Variance α = 0.05.

Modeling Rainfall Redistribution Using Tree Metrics

Regression of total rainfall redistribution resulted in a significant relationship ($p < 0.01$) between the square root transformed dependent variable and explanatory variables. The best fit model consisted of crown shape, canopy area, storm size and the interaction of storm size and tree canopy area $R^2 = 0.80$ (Figure 2.3, Table 2.4). The explanatory variables, in the order they were entered using stepwise regression, followed by the percent variation each accounted for, were: 1) the interaction of storm size and tree canopy area 68%, 2) storm size 7%, 3) crown shape 2%, 4) storm size squared 2% and 5) tree canopy area 1%. A reduced model including tree crown area, storm size and the interaction of these two resulted in $R^2 = 0.77$, $p < 0.01$ (Figure 2.4, Table 2.4). The explanatory variables followed by the percent variation explained by each variable were: 1) the interaction of storm size and tree canopy area 66%, 2) storm size 8%, 3) storm size squared 2% and 5) tree canopy area 1%.

Table 2.4 Regression equations for predicting rainfall canopy redistribution for singleleaf piñon and Utah juniper. The best fit model $\beta_5 x_5$ is based on whether the tree crown is approximalty cone or expanded paraboloid shaped. Cells with --- were intentionally left blank.

	β_0	$\beta_1 x_1$	$\beta_2 x_2$	$\beta_3 x_3$	$\beta_4 x_4$	$\beta_5 x_5$	p–value	R^2
Best fit model	0.421	0.875 Storm size (mm)	- 0.021 Tree area (m^2)	- 0.020 Storm size $(mm)^2$	$1.68e^{-6}$ Storm size (mm) * Tree area (m^2)	$\frac{\text{- 0.970 cone shaped crown or}}{\text{0.970 expanded paraboloid shaped crown}}$	< 0.01	0.80
Management model	0.034	0.814 Storm size (mm)	0.002 Tree area (m^2)	- 0.020 Storm size $(mm)^2$	$1.83e^{-6}$ Storm size (mm) * Tree area (m^2)	---	< 0.01	0.77

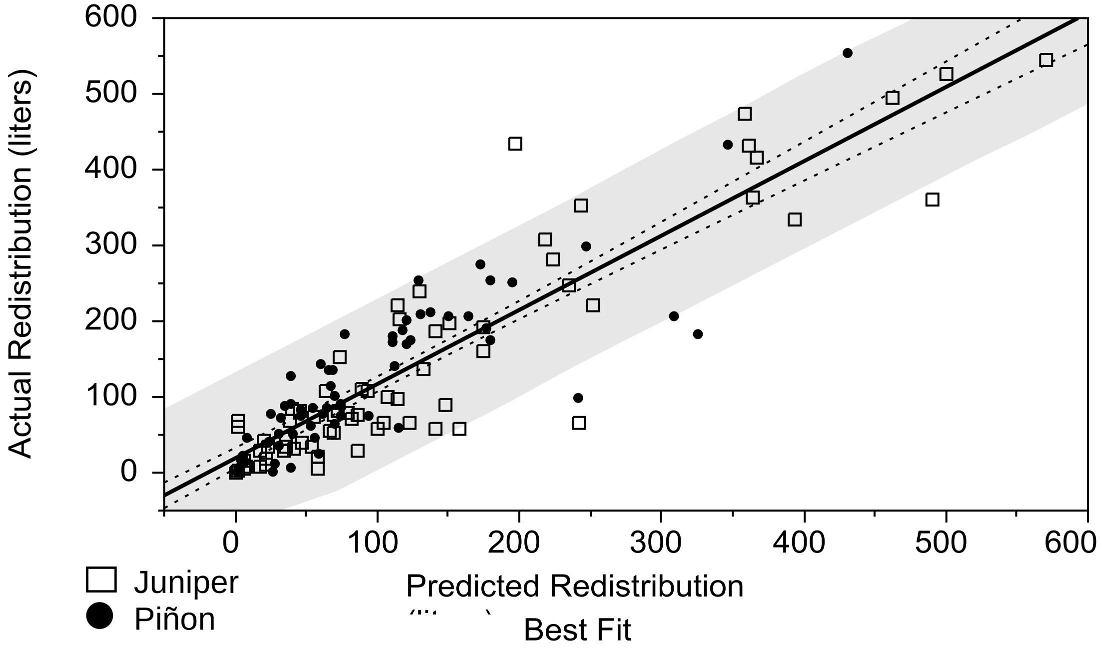

Figure 2.3 Plot of predicted vs. observed rainfall redistribution by singleleaf piñon and Utah juniper. Predicted values were generated by regression equation using tree canopy area, storm size and canopy shape. Dotted lines represent 95% confidence limits. Shaded area represents 95% prediction limits.

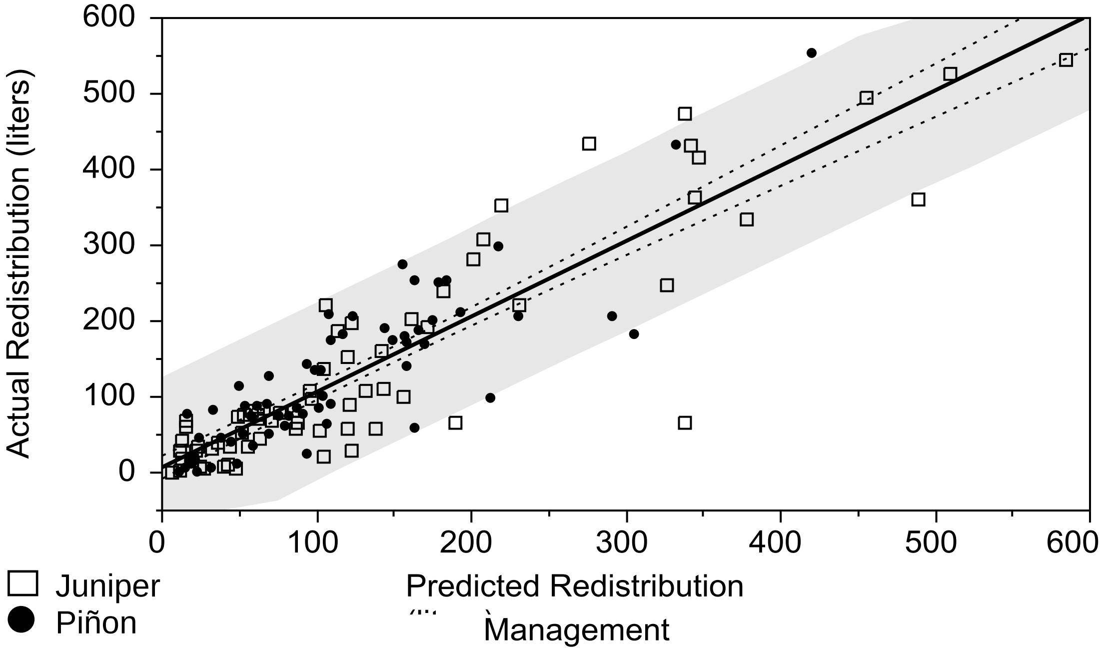

Figure 2.4 Plot of predicted vs. observed rainfall redistribution by singleleaf piñon and Utah juniper. Predicted values were generated based on regression equation using tree canopy area and storm size. Dotted lines represent 95% confidence limits. Shaded area represents 95% prediction limits.

Interception predictions

Our results demonstrate that in central Nevada, where the majority of rainfall events are 5 mm or less (Figure 2.1), singleleaf piñon and Utah juniper interception reduced the rainfall reaching the soil by 68% under the tree canopy. Average interception across the entire range of storm sizes from 2.2 to 25.9 mm was 44%. Based on the model using storm size and tree canopy area to predict interception, a tree with 10 m^2 canopy will intercept 60% of rainfall in a 13 mm · hr^{-1} storm. Interception increases to 75% with a storm of 5 mm · hr^{-1}. As tree canopy area increases from 10 m^2 to 20 m^2 interception in the 5 mm · hr^{-1} storm increases to about 88% and in the 13 mm · hr^{-1} storm about 80% of rainfall is intercepted by the tree canopy. The striking increase in interception with initially small increases in tree area has tremendous implications for management of piñon and juniper encroached landscapes in regards to potential rate of impact on understory production, sagebrush obligate wildlife habitat, soil erosion and aquifer recharge (Figure 2.5).

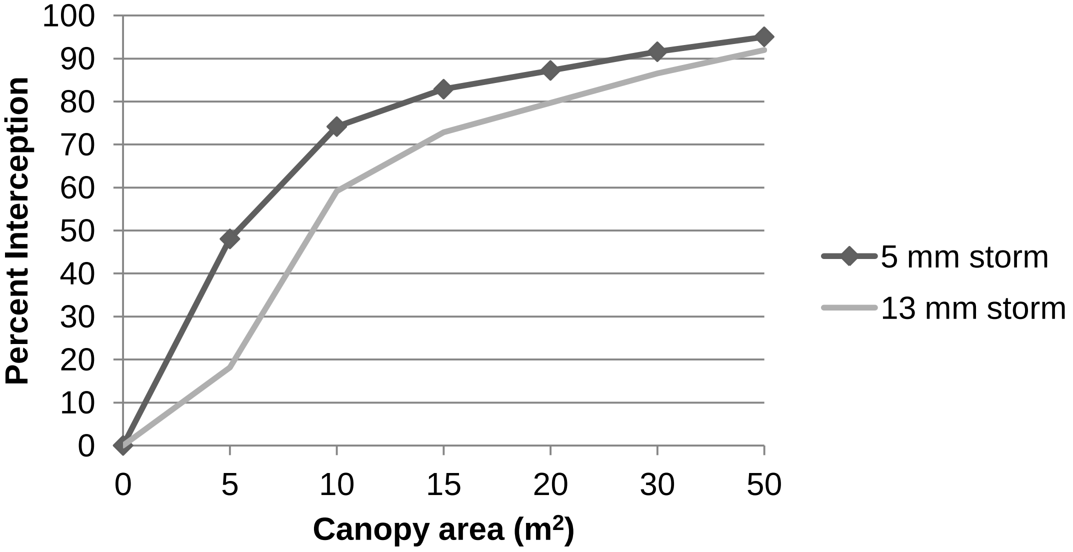

Figure 2.5 Percent intercepted as tree canopy area increases under two different storm sizes. Percent interception values were generated using model based on storm size and tree area.

DISCUSSION

The majority of rainfall redistribution occurred as throughfall rather than stemflow likely because of the horizontal branching structure of singleleaf piñon and Utah juniper. Similar to our study, research on alligator and Utah juniper in north-central Arizona reported that rainfall redistribution occurred mostly as throughfall due to drooping branches and small storms that failed to generate stemflow (Skau 1964). A study in Arizona conducted in two needle piñon (*Pinus edulis*

Engelm.) and Utah juniper reported no significant difference between the two species in terms of throughfall (Collings 1966). This coincides with our results showing no difference between singleleaf piñon and Utah juniper. These similar results could allow for broad application of the redistribution and interception predictive models developed in this study to a large range of piñon and juniper affected areas.

Water deposited at the base of the tree due to stemflow averaged 2% of total rainfall, which is a minor component of total rainfall redistribution. The amount of stemflow was largely dependent on the size of storm with smaller storms generating little if any stemflow. These highly variable and relatively small amounts of stemflow are similar to studies in western, Utah, ashe (*Juniperus ashei J.* Buchholz), and alligator (*J. deppeana* Steud.) juniper (Skau 1964; Young et al. 1984; Larsen 1993; Owens et al. 2006). Young et al. (1984) found that despite its small quantity, stemflow is important for depositing nutrients, accumulated during dry seasons, which could enhance nitrification of litter, thereby fertilizing the fine roots at the base of the tree. This possible fertilization coupled with the additional water, although small, could be a mechanism for enhancing the tree’s ability to compete with understory plants.

Eddleman et al. (1994) reported that in western juniper systems canopy interception can exceed 12% of annual precipitation. Similarly, in Arizona a one year study of Utah and alligator juniper found that interception was 17.2% (Skau 1964 as cited in Branson et al. 1981). In a three year study with over 2 700 storms ashe juniper was found to intercept nearly all moisture received in 2.5 mm rainfall events (Owens et al. 2006). Similarly a study on redberry (*Juniperus pinchotii* Sudw.) and ashe juniper found that rainfall events less than 5 mm do not reach the litter layer beneath the tree canopy due to interception (Thurow and Hester 1997).Our study coupled with similar findings indicate that piñon and juniper canopy interception significantly reduces the amount of water reaching the soil and in areas where the majority of rainfall occurs as small storms the potential detrimental implications for understory production and composition, sagebrush obligate habitat quality, restoration activities, aquifer recharge and potential soil erosion are heightened.

Future research is needed to quantify the effects of canopy interception on snowfall in piñon and juniper. In central Nevada 76% of yearly precipitation occurs as snowfall (USDA NRCS 2011) and in systems dominated by winter precipitation the consequences of this interception could be tremendous..

MANAGEMENT IMPLICATIONS

The results of this study demonstrate that total tree redistribution of rainfall for singleleaf piñon and Utah juniper can be modeled with reasonable accuracy based on storm size and tree canopy area. When canopy shape is added the model becomes somewhat more powerful. Based on similar findings for interception percentages and rainfall redistribution in ashe, western, Utah, alligator juniper and two needle piñon, these models may be useful in much of the area currently occupied by piñon and juniper species (Skau 1964; Collings

1966; Young et al. 1984; Larsen 1993; Owens et al. 2006). Estimates from this model can be used to inform land managers of the effects of piñon and juniper on actual versus effective rainfall, that is, the amount of water that reaches the soil surface.

The ability to predict interception, based on tree area and storm size, when coupled with tools currently available will facilitate landscape-scale management decisions. A few of the tools available to managers include; USDA-NRCS soil maps and ecological site descriptions, precipitation and climate records, and digital elevation models. Combining the existing data layers with remotely sensed tree cover data and the associated modeled interception values will provide management with a powerful landscape scale tool for predicting the potential impact of tree encroachment on understory plant communities, associated soils and ecological processes. Land managers could utilize this information to project the ecological impact of encroachment on critical wildlife management areas, high risk locations for soil erosion, watershed hydrology, groundwater recharge and other ecosystem services. This knowledge would aid in pinpointing specific areas for land management planning and restoration efforts.

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Chapter 3: Quantifying vegetation and soil surface characteristics under singleleaf piñon and Utah juniper canopies in central Nevada

ABSTRACT

Although piñon and juniper occurred historically throughout the western United States, the infilling of woodlands and expansion into sagebrush steppe has caused a reduction in understory vegetation composition leading to impaired hydrologic function, increased surface runoff and soil erosion. As piñon and juniper eliminate understory species there is a correlated degradation of primary ecological processes (Petersen 2004). This degradation results in the impairment of the spatial and temporal ability to capture energy, store nutrients and retain water within the system (Whisenant 1999). The elimination of understory species and the associated degradation of ecological function in tree encroached sagebrush ecosystems is largely due to their ability to compete for nutrients, light and water (Jameson 1967; Doescher et al. 1987; Breshears et al. 1998; Yager and Smeins 1999). We hypothesized that vegetation under the singleleaf piñon (*Pinus monophylla* Torr. & Frém.), and Utah juniper (*Juniperus osteosperma (Torr.) Little*) is different between species and that it is related to individual tree metrics and soil surface characteristics. This study was conducted on a piñon and juniper encroached sagebrush area in the Desatoya Mountains of central Nevada. Vegetation and soil surface characteristics were quantified using line intercept, canopy and basal gap. The metrics measured included average litter depth, total foliar cover, shrub foliar cover, herbaceous foliar cover, litter cover, percent bare soil, herbaceous basal cover, dead and live shrub canopy cover. A series of tree allometrics including height, diameter at breast height, stump diameter, distance to first live branch and live crown were measured and tree canopy area and volume (based on shape) were calculated. Our results indicate that there was 9%, 10% and 17% more herbaceous, shrub and total foliar cover respectively under piñon than under juniper canopies. Regression analysis was used to test for relationships between measured tree metrics and/or soil surface characteristics. No significant relationships were found between under canopy vegetation and tree metrics. However, herbaceous, shrub and total foliar cover under the tree canopy were found to be negatively related to average litter depth, yet litter depth was not significantly different between tree species.

INTRODUCTION

Piñon and juniper ecosystems currently occupy approximately 19 million ha in the Intermountain West and as much as 90% of what is now woodland occurred as sagebrush plant communities prior to European settlement (Tausch et al. 1981; Miller et al. 2008; Davies et al. 2011; Miller et al. 2011) . Historically, piñon and juniper were confined to steep rocky ridges and occurred in the lower elevations as savannas due to periodic fire (West 1997; Romme et al. 2009). This dramatic expansion has three contributing factors: an altered fire return interval, heavy grazing by domestic livestock, and climate change (Miller and Rose 1999; Miller et al. 2000; Miller et al. 2011). Although the specific species of piñon and juniper is varied depending on the region considered, many of the problems relating to their invasion are similar (Tausch et al. 2009). With increasing tree cover, shrubs and deep rooted bunchgrasses often decline resulting in increasing bare ground in intercanopy areas that leads to greater raindrop impact, soil crusting, decreased infiltration, and increased erosion (Pierson et al. 2007; Petersen and Stringham 2008; Tausch et al. 2009). Peterson determined that as western juniper out-competes understory species there is a correlated degradation of primary ecological processes (Petersen 2004). This degradation results in the impairment of the spatial and temporal ability to capture energy, store nutrients and retain water within the system (Whisenant 1999). The impact of the degradation of these processes is intensified in the arid-west where resources are especially limited (Wilcox and Breshears 1994).

The elimination of understory species and the associated degradation of ecological function in tree encroached sagebrush ecosystems is largely due to the tree’s ability to compete for nutrients, light and water (Jameson 1967; Doescher et al. 1987; Breshears et al. 1998; Yager and Smeins 1999). By the time western juniper is 30-35 years old, lateral roots will amount to 65% of the root biomass and typically extend a distance equal to three times the height of the tree, allowing access to water and nutrients even in the interspaces (Miller et al. 2005). Miller et al. (2005) also reported that woodland encroachment into sage steppe alters the spatial distribution of soil organic matter, carbon and nutrients. The redistribution of nutrients under western juniper has been found to enhance its competition with herbaceous vegetation (Doescher et al. 1987). Yager and Smeins (1999) report that Ashe juniper (*Juniperus ashei J. Buchholz*) adversely effected the recruitment of understory species due in part to shade but principally because of the interaction of the physical factors of litter and moisture regime (Yager and Smeins 1999). In addition to competition for light and nutrients, piñon and juniper significantly reduce the amount of rainfall reaching the soil through canopy and litter interception (Collings 1966; Larsen 1993; Owens et al. 2006; Lossing 2012). There has been no research to ascertain if there are significant differences in understory vegetation beneath singleleaf piñon and Utah juniper canopies.

The purpose of this research was to quantify vegetation and soil surface characteristics under singleleaf piñon and Utah juniper canopies' and to investigate any differences. Vegetation metrics determined to be significantly different between tree species were related to tree metrics and soil surface characteristics through regression analysis to elucidate associations.

Site Description

This study was conducted in and around the Porter Canyon watershed in the Desatoya Mountains in Lander County, Nevada, where the elevation ranges from 1 800 m to 2 400 m. Precipitation predominantly occurs as winter snow and spring rain with a 30-year annual average of 25.6 cm. Average annual temperature ranges from -7.5°C to 17.3°C. Temperature and precipitation data are from the Big Creek *SNOTEL* weather station (lat 39°17' N, long 117°07' W, elevation 2630 m) (US Department of Agriculture, Natural Resource Conservation Service [USDA, NRCS] 2011).

Soil parent materials are primarily residuum weathered from conglomerate and/or shale and/or tuff (Soil Survey Staff 2012). Soils include Lithic/Typic/Aridic Argixerolls, Xeric Argidurid, Haploxeralfic Argidurids, and Xeric Haplargids. Rainfall simulations were primarily conducted on two ecological sites. The higher elevation site was a Loamy 10-12 PZ and the low elevation site was a Droughty Loam 8-10 PZ (USDA NRCS 2003). Potential native plant community for: the higher elevation site was described as being dominated by Thurber's needlegrass *(Achnatherum thurberianum* [Piper] Barkworth), bluebunch wheatgrass *(Pseudoroegneria spicata* [Pursh] Á. Löve) and mountain big sagebrush *(Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle): the lower elevation site would potentially have been dominated by Indian ricegrass *(Achnatherum hymenoides* [Roem. & Schult.] Barkworth), needle and thread *(Hesperostipa comata* [Trin. & Rupr.] Barkworth), spiny hopsage *(Grayia spinosa* [Hook.] Moq.) and Wyoming big sagebrush (*Artemisia tridentata* Nutt. subsp. *wyomingensis* Beetle & Young). Both sites are currently encroached by Utah juniper and singleleaf piñon with intercanopy understory that is primarily composed of Sandberg's bluegrass *(Poa secunda* J. Presl) with mountain big sagebrush at the higher elevations and Wyoming big sagebrush at the lower elevations.

This study area is currently under public (Carson and Battle Mountain Districts, Bureau of Land Management) and private ownership. Porter canyon and the surrounding area have experienced a variety of disturbances including farming, tree harvest (both for mining and ranching purposes), sagebrush removal, homesteading and livestock grazing. The area is currently grazed by cattle with the season of use occurring as a rotation between spring use for two years and then fall use for two years.

METHODS

Experimental Design

Trees were selected to meet a randomized block design for rainfall simulation experiment based on species, size, form and accessibility (Lossing 2012). Vegetation and soil surface characteristics were quantified under 17 piñon and 19 juniper trees during the 2010 and 2011 field seasons. A student's two-tailed t-test was used to detect significant differences in vegetation under piñon and juniper canopies. Regression analysis was used to model vegetation under the tree canopy based on tree allometrics and average litter depth.

Vegetation Assessment

Cardinal directions were used to locate four transects along which vegetation was quantified. Each transect originated at the tree's trunk and ended at the edge of the canopy. Vegetation and soil surface characteristics measured include, average litter depth, total foliar cover, herbaceous foliar cover, total shrub foliar cover, litter cover, bare soil, herbaceous basal cover, dead and live shrub canopy cover (Table 3.1). Herbaceous measurements included grass and shrubs exclusively. The shrub component was parsed into live and dead categories. Line intercept was utilized to estimate canopy gaps of 5 cm or more for living and dead shrubs and basal gaps of 2 cm or more for both grasses and forbs (Elzinga et al. 1998). Point intercept, recorded every 10 cm, was used to estimate foliar cover by species (Elzinga et al. 1998). Tree litter depth was measured every 10 cm along each transect, from the top of the litter to the organic soil layer.

Table 3.1 Average ± standard error and the range of values for vegetation and soil surface characteristics. Total foliar cover refers to total foliar cover of grasses, forbs and shrubs. Total herbaceous includes grasses and forbs.

Percent cover	Piñon	Juniper	Piñon Range	Juniper Range
Total foliar	34.8 ± 0.04	18.3 ± 0.02	6.8 – 60.6	1.9 – 37.2
Total herbaceous	20.6 ± 0.03	11.6 ± 0.02	6.8 – 40.2	1.0 – 23.4
Shrub cover	18.4 ± 0.04	8.4 ± 0.02	0 – 56.5	0 – 23.9
Litter	81.5 ± 0.03	73.2 ± 0.05	46.1 – 96.5	26.3 – 97.6
Bare soil	15.5 ± 0.03	22.2 ± 0.05	2.4 – 53.9	1.5 – 67.8
Dead shrub canopy	7.0 ± 0.02 [a]	2.3 ± 0.01[b]	0 – 22.6	0 – 10.0
Live shrub canopy	11.1 ± 0.02	5.8 ± 0.01	0 – 42.0	0 – 20.5
Herbaceous basal	3.8 ± 0.01	2.8 ± 0.00	0 – 11.8	0 – 6.2
Average litter depth (cm)	3.3 ± 0.45	3.4 ± 0.39	1 – 6.9	1 – 6.4

Allometric Assessment

A series of tree allometrics were measured including total tree height, live crown height, diameter at stump height, diameter breast height, distance to first live branch and crown diameter (Table 3.2). Total tree height was measured using a stadia rod. Diameter at stump height was measured 30 cm above ground level using a diameter tape. Diameter breast height was measured at approximately

1.4 meters above ground level using a diameter tape. Live crown was calculated by measuring total tree height minus the distance measured from first live foliage to the ground using a meter tape. The distance from the soil surface to the first live branch was measured using a meter tape. Canopy area was calculated using the following equation: π ([crown diameter$_1$ + crown diameter$_2$] / 4)^2 and canopy volume was calculated based on the most closely related canopy shape. Crown diameter was measured using a meter tape at the canopy's widest point (diameter$_{1)}$ and perpendicular to that point (diameter$_2$).

Table 3.2 Average ± standard error values for metrics measured on 36 trees, 17 piñon and 19 juniper. *DBH is the diameter of the trunk at breast height.

Metric	Piñon average	Juniper average	Piñon Range	Juniper Range
Height (m)	4.8 ± 0.3	6.0 ± 0.3	3.1 – 7.6	4.7 – 8.3
DBH* (cm)	18.4 ± 2.2	26.3 ± 1.6	7.1 – 36.3	16.2 – 41.4
Stump diameter (cm)	25.5 ± 1.9	36.1 ± 2.0	10.7 – 38.9	20.1 – 49.8
Live crown height (m)	4.5 ± 0.3	5.4 ± 0.3	3.1 – 6.9	3.3 – 7.8
Canopy area (m^2)	16.4 ± 2.5	24.4 ± 2.8	4.4 – 45.1	8.9 – 53.5
Canopy volume (m^3)	47.4 ± 5.0	86.4 ± 5.4	8.4 – 194.6	18.5 – 172.7
Distance to first live branch (cm)	29.2 ± 6.4	68.0 ± 9.2	0 – 100	17 – 140

Data Analysis

Prior to analysis the arcsine square root transformation was used for percent data to meet assumptions of normality (Zar 1999). A student's two-tailed t-test ($\alpha = 0.05$) was used to detect vegetation differences between piñon and juniper. Stepwise multiple linear regression was used to select models correlating tree metrics with vegetation under the tree canopy. Explanatory factors that were not significant contributors, as determined using forward stepwise selection ($p = 0.01$), were excluded from the final model. Predictor variables included in the stepwise regression were average litter depth and the following tree metrics; height, diameter at breast height, stump diameter, live crown height, distance to first live branch, tree canopy area and volume. JMP version 9.0 (SAS Institute 2010) was used for all statistical analyses.

RESULTS

Results from student's two-tailed t-test's ($\alpha = 0.05$) found a significant difference under the canopy of singleleaf piñon and Utah juniper in total foliar cover ($p = 0.001$), herbaceous foliar cover ($p = 0.005$), total shrub foliar cover ($p = 0.035$) and dead shrub canopy cover ($p = 0.044$) (Figure 3.1). Although not significant at $\alpha = 0.05$ it is highly suggestive that live shrub canopy cover is different under the canopy of piñon and juniper ($p = 0.083$). A student's two-tailed t-test failed to detect any significant difference in herbaceous basal cover, litter cover, bare soil and average litter depth between the two tree species (Table 3.1).

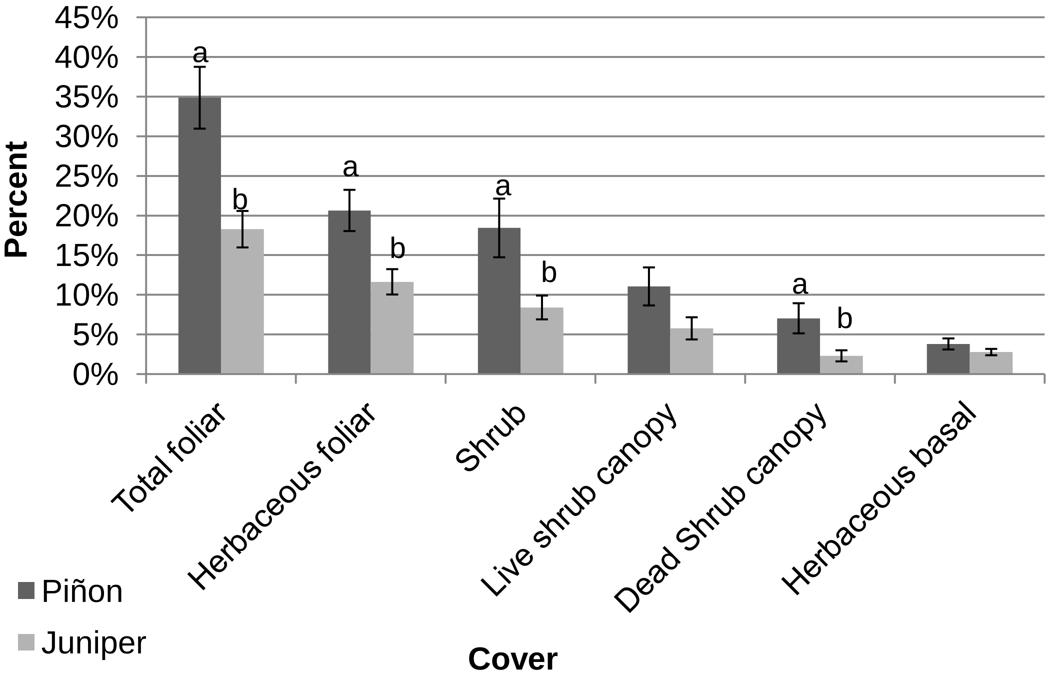

Figure 3.1 Differences between piñon and juniper understory vegetative cover. Different letters indicate significant difference between species. Significance determined using student's two-tailed t-test $\alpha = 0.05$.

Regression of the arcsine square root of total foliar cover resulted in a significant relationship ($p < 0.001$) with average litter depth and tree species ($R^2 = 0.371$, $p = 0.0005$) (Table 3.3, Figure 3.2). Regression of the arcsine square root of herbaceous foliar cover resulted in a significant relationship ($p < 0.001$) with average litter depth and tree species ($R^2 = 0.366$, $p = 0.0005$) (Table 3.3, Figure 3.3). Stepwise multiple linear regression found no significant relationship for total shrub canopy cover or dead shrub canopy cover and the associated tree and soil surface metrics. Average litter depth was most frequently between 2 and 3 cm deep under piñon and juniper canopies (Figure 3.4).

Table 3.3 Regression equations predicting total foliar cover and herbaceous foliar cover by the square root of average litter depth.

	β_0	$\beta_1 x_1$	$\beta_2 x_2$	p – value	R^2
Total foliar cover	0.632	JUOS = -0.101 PIMO = 0.101	-0.034 * average litter depth	< 0.001	0.371
Herbaceous foliar cover	0.496	JUOS = -0.067 PIMO = 0.067	-0.031 * average litter depth	< 0.001	0.366

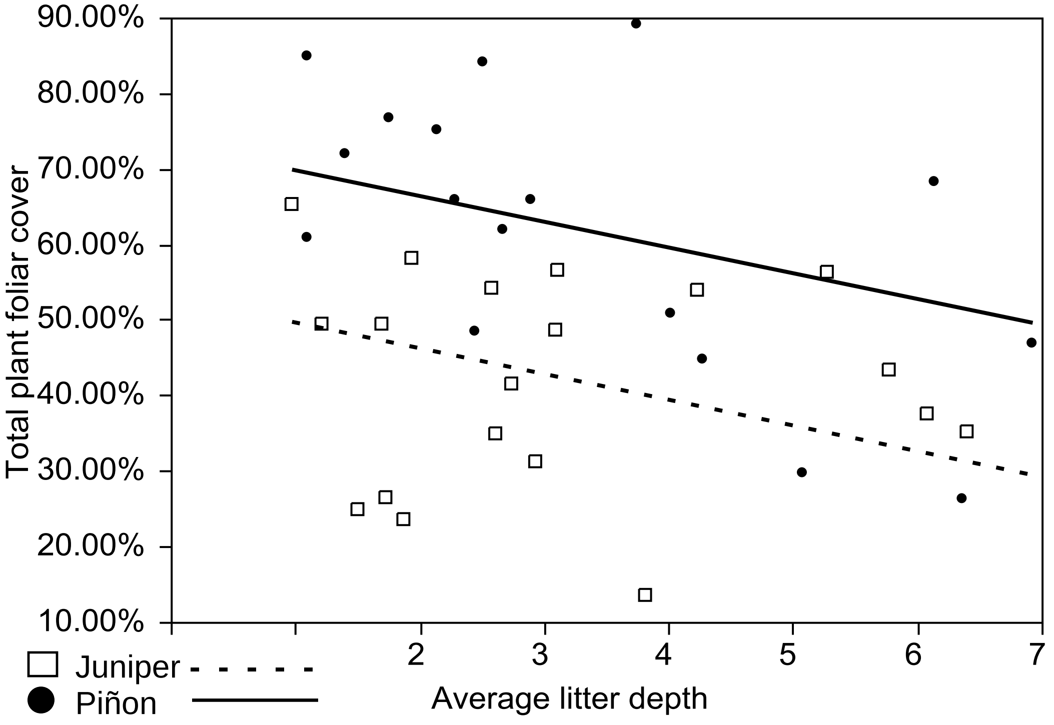

Figure 3.2 Regression of total foliar cover by average litter depth (cm) under the canopy of singleleaf piñon and Utah juniper.

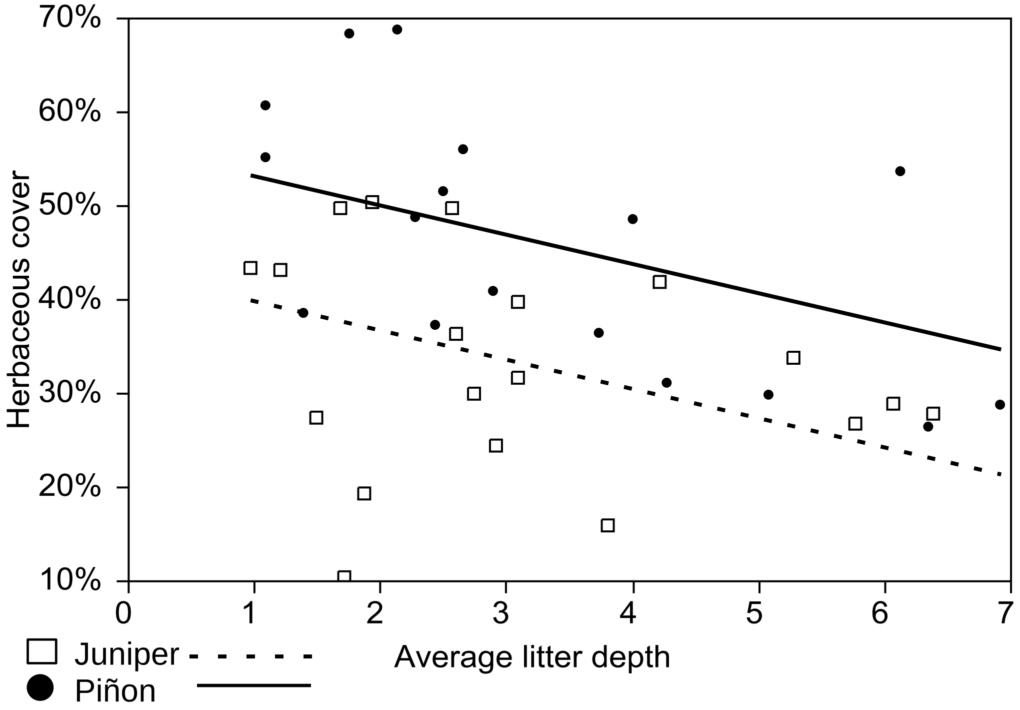

Figure 3.3 Regression of herbaceous foliar cover which includes grasses and forbs by average litter depth (cm) under the canopy of singleleaf piñon and Utah juniper.

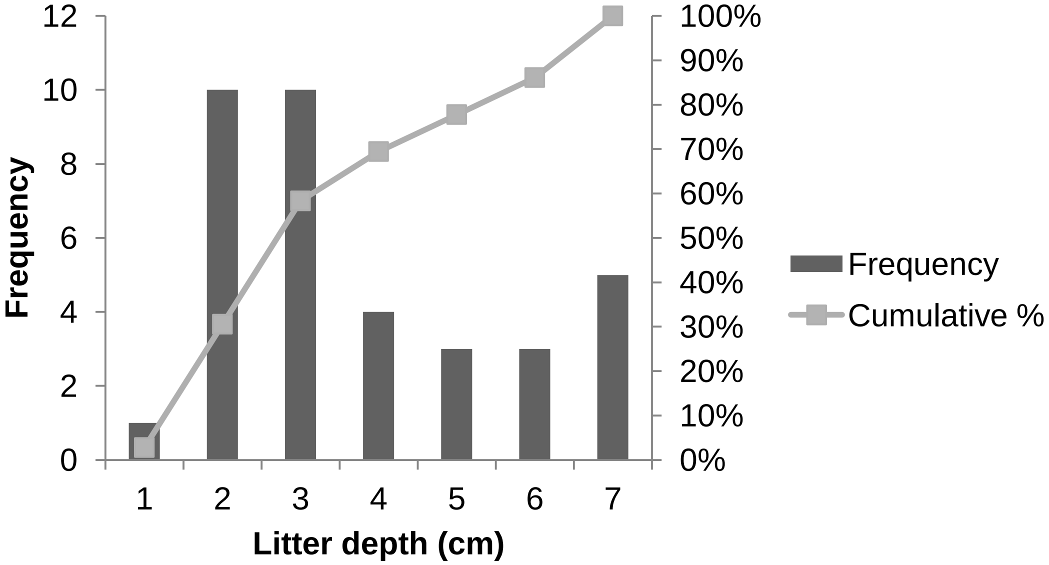

Figure 3.4 Frequency distribution and cumulative percentage of average litter depth beneath singleleaf piñon and Utah juniper canopies.

DISCUSSION

We hypothesized that tree metrics, such as the height to the lowest branch, thought to be related to shade would have a negative relationship on under canopy vegetation but no significant relationships were found. Rather than a shade surrogate, the most significant predictor of total foliar cover and herbaceous foliar cover was average litter depth. As average litter depth increased there was a corresponding decrease in each category of vegetative cover. These findings are similar to research conducted on oneseed juniper (*Juniperus monosperma* (Engelm.) Sarg.), Utah juniper and two needle piñon (*Pinus edulis* Engelm.) where litter was primarily responsible for the suppression of blue grama (*Bouteloua gracilis* (Willd. ex Kunth) Lag. ex Griffiths) (Jameson 1966). A greenhouse study investigating seedling emergence as it relates to increasing Utah juniper litter depth, reported that bluebunch wheatgrass, bottlebrush squirreltail (*Elymus elymoides* (Raf.) Swezey), cheatgrass (*Bromus tectorum* L.), 'Paiute' orchardgrass (*Dactylis glomerata* L.), Lewis flax (*Linum lewisii* Pursh), small burnet (*Sanguisorba minor* Scop.), antelope bitterbrush (*Purshia tridentata* (Pursh) DC.), and mountain big sagebrush seedling emergence decreased significantly with increasing litter depth (Horman and Anderson 2003). Also, Yager and Smeins (1999) found that ashe juniper (*Juniperus ashei J. Buchholz*) adversely effected the recruitment of understory species due in part to shade but principally because of the interaction of the physical factors of litter and moisture regime.

In addition to the physical factors of litter inhibiting herbaceous species access to sunlight and soil, litter also reduces the soil water available under the tree canopy through interception. Studies of rainfall canopy and litter interception in western, redberry (*Juniperus pinchotii* Sudw.) and ashe juniper and found that interception of precipitation from litter may be higher than losses to canopy interception (Larsen 1993; Thurow and Hester 1997). Our results indicated that litter depth was the primary factor influencing total foliar cover and herbaceous foliar cover under the tree canopy. Increased litter depth under the tree canopy corresponds to limited access to soil, sunlight and water for understory species.

The suppression of understory species with increasing litter depth has pertinent implications for land managers throughout the areas encroached by piñon and juniper. We found that once litter depth exceeded 4 to 5 cm the vegetation under the tree canopy declined rapidly (Figure 3.2 and 3.3). Similarly, a greenhouse study of singleleaf piñon and Utah juniper wood chips found that chip depths greater than 5 cm reduced seedling emergence (Benson 2006). These results indicate that land managers should consider, when applying piñon and juniper treatments such as mastication, that litter depths greater than 4 to 5 cm may suppress understory reintroduction.

Our results indicate that there was significantly more vegetative cover in the understory of piñon when compared to juniper. There were however no significant relationships between understory vegetation metrics and measured tree variables that would explain these results. The vegetation difference under the canopy of singleleaf piñon and Utah juniper is not a result of rainfall canopy redistribution since these species do not differ in rainfall redistribution (Lossing 2012). However, the Utah juniper included in this study appear to be older than the piñon therefore, the reduced vegetative cover under juniper may be a consequence of long-term competition. Over time piñon and juniper can dominate resources both below and above ground. Miller (2000) reported that by the time western juniper is 30-35 years old, lateral roots will amount to 65% of the root biomass and typically extend a distance equal to three times the height of the tree, allowing access to water and nutrients even in the interspaces (Miller et al. 2005).

Future Research

Further research is needed to elucidate the biological variables driving vegetation differences under piñon and juniper. Litter interception of precipitation should be compared under piñon and juniper to investigate any species difference. The influence of juniper roots into the intercanopy zone has been shown to extend up to three times the height of the tree (Miller et al. 2005). Therefore, soil moisture under the tree canopy should be investigated along with soil chemistry components. Future investigations should include measurement of both the under canopy vegetation and intercanopy vegetation to elucidate potential differences in understory vegetation. Additionally, the sharp needle-like leaves of the piñon tree may deter livestock and wildlife use therefore leading to greater vegetation cover under piñon trees. Within grazed landscapes, livestock use should be considered as a potential causal mechanism.

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Chapter 4: General Conclusions

Canopy rainfall interception

The results of this study demonstrate that piñon and juniper rainfall redistribution, and its inverse interception, can be modeled based on storm size and tree canopy area. Land managers could combine this information with existing data layers to project the ecological impact of encroachment on critical wildlife management areas, high risk locations for soil erosion, watershed hydrology, groundwater recharge and other ecosystem services. Additionally, our results indicated a difference in foliar vegetation under the canopies of piñon and juniper but this is likely due to our study site having older juniper than piñon. Foliar vegetation under the tree canopy was most significantly related to average litter depth rather than tree metrics.

Our findings indicate that there may be long-term ecological consequences of tree litter accumulation, even after tree removal, due to litter's detrimental effects on understory species reestablishment. Our study coupled with similar findings indicate that piñon and juniper canopy interception significantly reduces the amount of water reaching the soil under the tree canopy and in areas where the majority of rainfall occurs as small storms the potential detrimental implications for understory production, sagebrush obligate habitat quality, restoration activities, aquifer recharge and potential soil erosion are heightened.

In addition to quantifying rainfall redistribution under singleleaf piñon and Utah juniper, we also collected samples of stemflow and throughfall. These samples were analyzed for nutrient content by Dr. Robert Blank. For more information about the results of this analysis contact the Great Basin Rangeland Research Unit USDA Agriculture Research Service.

Future Research

Future investigations should include measurement of both the under canopy vegetation and intercanopy vegetation to elucidate potential differences in understory vegetation by tree species and the biological variables driving vegetation differences. The effects of canopy interception on snowfall in piñon and juniper have not been quantified and in systems dominated by winter precipitation the consequences of this interception could be tremendous.

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Appendix. Percent occurrence of understory species under all 17 singleleaf piñon and 19 Utah juniper trees.

Latin Name	Common Name	Percent Occurrence Under Piñon	Percent Occurrence Under Juniper
Grasses			
Bromus tectorum	Cheatgrass	12%	16%
Carex douglasii	Douglas' sedge	0	11%
Elymus elymoides	Squirreltail	47%	42%
Poa secunda	Sandberg bluegrass	100%	100%
Live Shrubs			
Artemisia tridentata ssp. *wyomingensis*	Wyoming big sagebrush	0	16%
Artemisia tridentata ssp. *vaseyana*	Mountain big sagebrush	71%	53%
Chrysothamnus viscidiflorus	Yellow rabbitbrush	24%	12%
Ribes velutinum	Desert gooseberry	0	11%
Symphoricarpos albus	Snowberry	35%	5%
Dead Shrubs			
Artemisia tridentata ssp. *vaseyana*	Mountain big sagebrush	65%	47%
Artemisia tridentata ssp. *wyomingensis*	Wyoming big sagebrush	0	16%
Chrysothamnus viscidiflorus	Yellow rabbitbrush	12%	0
Forbs			
Astragalus purshii	Woollypod milkvetch	6%	5%
Lupinus sp.	Lupine	29%	26%
Phlox hoodii	Carpet phlox	59%	32%