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Estimating Juniper Cover From National Agriculture Imagery Program (NAIP) Imagery and Evaluating Relationships Between Potential Cover and Environmental Variables

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Abstract

Western juniper (*Juniperus occidentalis* subsp. *occidentalis* Hook.) woodlands are expanding from their historic range and causing significant declines of other plant communities. However, landscape-scale restoration projects are hindered by time-consuming and expensive methods to inventory juniper cover and prioritize landscapes based on developmental phase of juniper encroachment. We investigated the ability of feature-extraction software to estimate western juniper cover from color aerial photographs obtained from the National Agriculture Imagery Program (NAIP) and explored the relationships between juniper cover at stand closure (potential juniper cover) and environmental/site indices (heat load, site exposure, and integrated moisture index) and characteristics measured from commonly available geospatial data layers. Estimates of juniper cover derived from NAIP imagery and ground measurements were similar ($R^2 = 0.74$; $P < 0.01$). Neither method consistently estimated juniper cover higher or lower than the other method ($P = 0.79$). Environmental indices were either not correlated or weakly correlated with juniper cover at stand closure. However, the environmental/site characteristics (slope, aspect, and elevation) could be used to explain 40% of the variation in juniper cover at stand closure ($R^2 = 0.40$; $P < 0.01$). Thus, commonly available geospatial data layers can be used to assist in determining potential juniper cover. This information can then be compared to current juniper cover to determine juniper woodland developmental phase. Knowing the developmental phase is important because management strategies and effectiveness of restoration treatments differ among phases of juniper encroachment. Our results suggest that NAIP imagery can be a valuable tool to estimate juniper cover over large areas effectively to make landscape-scale restoration more feasible. The model of the relationship between environmental/site characteristics measured from commonly available geospatial data layers and potential juniper can be used to assist in restoration planning and prioritization, but could be improved with further refinement.

Resumen

Los montes de *Juniperus occidentalis* subsp. *occidentalis* Hook están expandiendo sus áreas históricas y están causando una disminución significativa de otras comunidades vegetales. Sin embargo, los proyectos de restauración a escala de paisaje están siendo impedidos por los métodos onerosos en términos de tiempo y dinero que se utilizan para relevar la cobertura de *Juniperus* y priorizar paisajes sobre la base de la fase de desarrollo de la invasión de *Juniperus*. Investigamos la habilidad de un software de extracción de rasgos para estimar la cobertura de *J. occidentalis* de fotografías aéreas a color obtenidas del Programa Agrícola Nacional de Imágenes (NAIP) y exploramos las relaciones entre cobertura de *Juniperus* en condiciones de dosel cerrado (cobertura potencial de *Juniperus*) e índices ambientales o de sitio (carga calórica, exposición del sitio, e índice integrado de humedad) y características medidas en capas de datos geo-espaciales comúnmente disponibles. Las estimaciones de cobertura de *Juniperus* derivadas de imágenes NAIP y mediciones sobre el terreno fueron similares ($R^2 = 0.74$; $P < 0.01$). Las estimaciones de ninguno de ambos métodos fue consistentemente superior o inferior a la estimación del otro método (P = 0.79). Las variables ambientales presentaron correlaciones débiles o ausencia de correlación con la cobertura de *Juniperus* en condiciones de dosel cerrado. Sin embargo, las características del ambiente/sitio (pendiente, exposición, y elevación) podrían ser utilizadas para explicar el 40% de la variación de cobertura de *Juniperus* en condiciones de dosel cerrado ($R^2 = 0.40$; $P < 0.01$). Por lo tanto, las capas de información geo-espacial comúnmente disponibles podrían utilizarse para asistir en la determinación de cobertura potencial de *Juniperus*. Esta información podría compararse con la cobertura actual de *Juniperus* para determinar la fase de desarrollo del monte. La identificación de la fase de desarrollo del monte es importante porque las estrategias de manejo y la efectividad de los tratamientos de restauración difieren entre fases de invasión de *Juniperus*. Nuestros resultados sugieren que las imágenes NADIP pueden ser una herramienta valiosa para realizar estimaciones efectivas de cobertura de *Juniperus* en áreas extensas a fin de facilitar acciones de restauración a escala de paisaje. El modelo de la relación entre características ambientales o de sito medidas a partir de capas de datos geo-espaciales comúnmente disponibles, y potencial de cobertura de *Juniperus*

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podría utilizarse para asistir en la planificación y priorización de acciones de restauración pero podría ser mejorado mediante refinamiento adicional.

Key Words: aerial photography, *Juniperus occidentalis*, landscape ecology, remote sensing, restoration, sagebrush, woodland encroachment

INTRODUCTION

Western juniper (*Juniperus occidentalis* subsp. *occidentalis* Hook.) woodlands have expanded from their historic range over the past 100–150 yr to occupy an estimated 3.6 million ha in eastern Oregon, southwestern Idaho, and northernmost portions of Nevada and eastern California (Miller et al. 2005). Prior to European American settlement, populations of western juniper occurred as open, sparse, savannah-like stands (Nichol 1937) or were confined to fire-safe areas (Cottman and Stewart 1940; Barney and Frischknecht 1974; West 1984). The postsettlement expansion of western juniper is considered unprecedented relative to prehistoric expansions (Miller and Wigand 1994). The encroachment of juniper woodlands into more productive communities and an increase in tree density is largely the consequence of a reduction in fire (Burkhart and Tisdale 1969, 1976; Miller and Wigand 1994; Miller and Rose 1999). Mountain big sagebrush (*Artemisia tridentata* subsp. *vaseyana* [RYBD.] Beetle), aspen (*Populus tremuloides* Michx.), and other woody species cover declines significantly as encroaching western juniper increases in dominance (Miller et al. 2000). Depending on site characteristics and the plant association being invaded, herbaceous cover and species diversity can decline and bare ground can increase with increasing juniper dominance (Miller et al. 2000).

Control of western juniper has been shown to increase understory productivity, cover, and diversity (Evans and Young 1984; Rose and Eddleman 1994; Bates et al. 1998, 2006). However, the structural attributes and developmental rates of juniper stands are heterogeneous across landscapes (Johnson 2005; Johnson and Miller 2006; Petersen et al. 2009); consequently the effectiveness of management actions also varies over landscapes. To obtain the most economic and ecologic benefit, selection of the most effective management actions and prioritization of juniper control across landscapes is paramount. Identifying a stand's developmental phase and current juniper cover are crucial to selecting effective management actions (Miller et al. 2005). Miller et al. (2000) reported that knowledge of stand-level cover of juniper, relative to potential cover, allows identification of the developmental phase of stands across landscapes.

Western juniper encroachment can be described with three developmental phases directly linked to the dominance of juniper over site ecological processes (Miller et al. 2005). In Phase I, juniper trees are present, but shrubs and herbaceous plants are the dominant vegetation exerting influence over ecological site process; Phase II, junipers are codominant with shrubs and herbaceous plants; and Phase III (stand closure), junipers are the dominant vegetation and exert the most influence over ecological site processes (Miller et al. 2000; Miller et al. 2005). The transition from Phase II to Phase III is especially concerning because treatment options become more limited in Phase III woodlands (Miller et al. 2000; Miller et al. 2005; Johnson and Miller 2006). The probability of a prescribed burn carrying through Phase III woodlands is greatly decreased because of the reduction in understory vegetation.

In order for land managers to prioritize juniper woodlands for treatment and select the most effective management action, information on current and potential juniper cover is needed across heterogeneous landscapes. However, there are two major constraints: 1) current forest and rangeland inventory methods are time consuming and expensive, and 2) landscape estimates of potential western juniper cover at stand closure are lacking. Remotely sensed images covering large areas may present managers an opportunity to monitor and inventory western juniper encroachment inexpensively relative to standard rangeland and forest inventory methods. If relationships between commonly available geospatial data layers and potential juniper cover can be determined, then estimates of potential juniper cover across landscapes may be feasible.

We propose that the National Agricultural Imagery Program (NAIP) digital orthophoto quarter quads (DOQQs) are an attractive candidate for measuring western juniper canopy cover, due to their wide availability and coverage of the United States, rigorous orthorectification procedures, and high spatial resolution (1×1 m pixel). Accurate estimation of potential juniper cover at stand closure is dependent on the efficacy of employing environmental factors to model potential stand-level juniper cover over heterogeneous landscapes.

We hypothesize that several recently developed indices of environmental gradients and/or basic site characteristics may have utility for estimating juniper cover at stand closure. An integrated moisture index (IMI; Iverson et al. 1997), a site exposure index (SEI; Balice et al. 2000), and a heat load index (HLI; McCune and Keon 2002) were selected for this study because of the relative ease of application to landscapes and potential biological significance. Iverson et al. (1997) used the IMI to predict composition and productivity of an Ohio forest. Johnson (2005) used the SEI to explain variation in rates of development and structure of western juniper stands. Davies et al. (2007) used the HLI to explain some of the variation in vegetation characteristics across the sagebrush steppe. The purposes of this study were to determine 1) the efficacy of using NAIP imagery to estimate western juniper cover, and 2) the relationship between environmental/site characteristics and juniper cover in closed western juniper stands across heterogeneous sites.

METHODS

Study Area

The 12 340-ha study area is located on Juniper Mountain in Owyhee County, Idaho, between the towns of Grand View, Idaho and Jordan Valley, Oregon. Mean annual precipitation ranges from 300 mm at lower elevations increasing to >560 mm at higher elevations and is primarily received in fall, winter, and early spring. Average minimum and maximum

temperatures vary from −6.6°C and 3.3°C in January to 13.3°C and 34.5°C in July, respectively. The growing season ranges from 90 d to 120 d across most of the study area, but is less than 60 d 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, which 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 (600–2 100 m).

The potential natural vegetation community at the study area was sagebrush–grassland. The current vegetation communities are predominantly of two types, sagebrush–grasslands and western juniper woodlands (Burkhardt and Tisdale 1976; Johnson and Miller 2006). The major potential plant associations across the valley slopes and bottoms are 1) mountain big sagebrush (*Artemisia tridentata* subsp. *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* subsp. *arbuscula* Nutt.) associated with bluebunch wheatgrass, Idaho fescue, or Sandberg bluegrass (*Poa sandbergii* Vasey) over restrictive layers of claypan or bedrock (Burkhardt and Tisdale 1976). These plant associations are common across the intermountain west (Miller and Eddleman 2000; Davies et al. 2006; Davies and Bates 2010). Sagebrush plant communities encroached by western juniper woodlands were the focus of this investigation.

Experimental Design

A completely random design was used to compare estimates of juniper cover derived from NAIP imagery to ground measurements. Forty points were randomly selected across the 12 340-ha study area. The nearest closed juniper stand to each randomly selected point was selected for sampling. Most closed stands were less than 700 m from the random points. Plant communities between random points and closed stands included Phase I and II juniper woodlands. Stand closure (Phase III) was determined with the use of the following criteria: 1) terminal and lateral leader growth of understory juniper trees located in mature tree interspaces were <10 and 6 cm, respectively (suppressed by intraspecific competition), and 2) live understory shrubs were completely absent and dead shrub skeletons were abundant (Miller et al. 2000). Juniper-cover values at the selected plots were estimated with ground measurements and from NAIP imagery.

These randomly selected, closed juniper plots were also used to determine correlations between juniper cover at stand closure and the environmental/site variables and indices. Environmental/site characteristics and indices were derived from USGS 10-m digital elevation model (US Geological Survey 2008), except soil characteristics were derived from NRCS Soil Survey Geographic Database (SSURGO) shape files (Natural Resource Conservation Service 2010).

Juniper Cover

Ground Measurements. One 30×50 m plot was used to sample each randomly selected stand. Juniper cover was measured with the use of the line intercept method (Canfield 1941) along three 50-m transects spaced at 15-m intervals. Juniper cover was measured in August 2007. The locations (UTM coordinates) of the four corners of the plots were recorded with global positioning system (GPS) units (GeoXT; Trimble Navigation Limited, Sunnyvale, CA). The Wide-Area Augmentation System was utilized for real-time deviation correction. To minimize projection errors associated with the collection of GPS data, all points were differentially corrected through GIS Pathfinder Office Program (Trimble Navigation Limited).

NAIP Imagery. Digital orthophoto quarter quads (DOQQ) of the study area were obtained from the National Agriculture Imagery Program (US Department of Agriculture 2008). These DOQQs (1-m spatial resolution) were taken and postprocessed (orthorectified) in 2004. Polygons representing ground-measurement plots were created with the use of the location data collected during the field campaign. These polygons were then used as masks to clip NAIP imagery to the dimensions of the 40 ground reference sites. Juniper tree cover was classified within each of these subsets with the use of the Feature Analyst software extension (Visual Learning Systems Inc, Version 4.1), for ArcGIS® 9.3 (ESRI Corp, Redlands, CA). This program uses a combination of texture, reflectance, and spatial context information to classify land cover from high-resolution remotely sensed imagery. Training for the Feature Analyst classifier was performed by providing input in the form of digitized polygons that are representative of juniper tree cover, or nonjuniper features (e.g., bare ground, other vegetation, etc.). Training sets for these two classes were then combined into one multiclass input layer, and the software then extracts features representing input data. Prior to imagery classification, plots were grouped based on similarities in color characteristics, with group sizes ranging between three and five plots. For most plot groups 10 training sites were optimal for extraction of juniper cover from NAIP imagery; however, this number was doubled for groups where shading or other confounding features limited accuracy. Following training set construction, we initially experimented with a number of classification algorithms associated with Feature Analyst. We determined that a seven-cell bull's-eye search pattern, with a minimum aggregate of four pixels, is the most effective for extracting juniper. After classification, results were visually inspected and sites that overestimated or underestimated actual juniper cover were reclassified with the use of Feature Analyst hierarchical learning tools (i.e., clutter removal, add missed feature), until the output cover classification file was determined to be an accurate representation of juniper cover on site.

To verify the accuracy of the tree cover classification data derived from NAIP imagery an on-screen accuracy assessment was performed by randomly generating and assessing 75 points for each class (juniper cover or nonjuniper features), with sample size calculated directly from a binomial distribution, with a 95% confidence level and acceptable error of 5% (Jensen 2005).

Environmental Index and Characteristics

All environmental indices and characteristics were derived from National Elevation Dataset (NED), 1/3–arc second (10 m) coverages, acquired from the National Map Seamless Server (US

Geological Service 2008). For our study area, the resolution of the data was reported at 6.647 m. Calculations for all indices and environmental characteristics were performed with the use of ArcGIS® 9.3 (ESRI Corp, Redlands, CA). The NED data were merged and gaps (holes) in the data were filled, using the Fill tool in Spatial Analyst of ArcGIS 9.3, to remove artificial pits and peaks in the dataset. Slope in degrees and aspect raster-based datasets were created from the NED files with the use of Spatial Analyst, an extension of ArcGIS® 9.3.

Site Exposure Index (SEI). The SEI (Balice et al. 2000) was calculated using the slope and aspect raster data sets. The SEI rescales aspect to a north/south axis and weights it by steepness of the slope. The following equation was applied to the raster data sets to determine SEI:

$$\mathrm{SEI} = \mathrm{slope} \cdot \mathrm{cosine}\left(\pi \cdot \frac{\mathrm{aspect} - 180}{180}\right). \quad [1]$$

The SEI creates a data set of relative exposure ranging from − 100 to 100 from coolest to warmest locations (Balice et al. 2000).

Heat Load Index (HLI). The HLI was calculated from the slope, aspect, and latitude data layers (McCune and Keon 2002). The slope and aspect raster data sets were converted to radians. Aspect was further converted to folded aspect with the use of the following equation:

$$\text{Folded aspect} = \left|\pi - \left|\text{aspect} - \frac{5\pi}{4}\right|\right|. \quad [2]$$

The folded aspect, slope in radians, and latitude were then used to calculate the HLI with the use of the following equation:

$$\mathrm{HLI} = 0.039 + [0.808 \cdot \cos(l) \cdot \cos(s)] - [0.196 \cdot \sin(l) \cdot \sin(s)] - [0.482 \cdot \cos(a) \cdot \sin(s)], \quad [3]$$

where l = latitude, s = slope, and a = folded slope. HLI values range from 0 to 1, with 0 being the coolest and 1 being the hottest.

Integrated Moisture Index (IMI). The IMI was calculated from topography of the landscape to estimate soil moisture across heterogeneous landscapes (Iversen et al. 1997). Hill shade, flow accumulation, and curvature were each calculated with the use of NED data and Spatial Analyst tools in ArcGIS 9.3. The hill-shade data were calculated with the hill-shade tool, flow accumulation was determined with the use of flow direction and accumulation tools, and curvature was computed with the use of the curvature tool. The three data sets were then reclassified and normalized to a scale of 0–100. The curvature data were inversed to provide higher values for basins (sites of water collection) and lower values for hilltops. The following equation was used to determine IMI:

$$\mathrm{IMI} = (\text{hill shade} \cdot 0.5) + (\text{curvature} \cdot 0.15) + (\text{flow accumulation} \cdot 0.35). \quad [4]$$

The IMI values range from 0 to 100, where increasing values indicate increasing moisture accumulation and retention (Iversen et al. 1997).

Environmental/Site Characteristics. Slope, aspect, and elevation were calculated by averaging all pixels in each study plot for each variable. Because of its circular nature, aspect can be a poor explanatory factor for quantitative analysis. For example, although 1 and 360° represent the approximately the same aspect, the numbers are very different. Thus, aspect was converted to cos(aspect) to alleviate some of the difficulties in using aspect as an explanatory variable.

Soil surface and profile percent sand, silt, and clay, soil available water holding capacity, saturated hydraulic conductivity, and depth to a restrictive layer were determined from shape files from the SSURGO (Natural Resource Conservation Service 2010).

Statistical Analysis

From the on-screen accuracy assessment classification, error matrix tables were generated showing classification accuracy, species-level producers and user accuracy, and Kappa statistic. Linear regression (S-Plus V. 8.0; Insightful Corp, Seattle, WA) was employed to evaluate the relationship between juniper cover determined from the classification of NAIP imagery and ground-based juniper-cover measurements. Standard t tests (S-Plus V. 8.0) were used to determine if the differences in cover estimates between the two methods were significantly different, and if one method consistently estimated juniper cover higher or lower than the other method. To determine if there was a significant difference in juniper-cover estimates between the two methods, the larger estimate was subtracted from the smaller estimate at each plot. However, to determine if one method consistently estimated juniper cover higher or lower than the other method, ground measurements were always subtracted from the estimate derived from the NAIP imagery. Differences were considered significant at $P \leq 0.05$.

Relationships between environmental gradient indices and juniper cover were analyzed with linear regression with the use of S-Plus V. 8.0. Stepwise multiple linear regression was used to select models correlating juniper cover with environmental factors and indices. Explanatory factors that were not significant contributors (as determined using stepwise selection at $\alpha = 0.05$) were excluded from the final model. Reported R^2 values are adjusted R^2 values.

RESULTS

Tree cover classification showed an overall accuracy of 92%, and Kappa statistic of 0.84 (Table 1). User and producer accuracy were similar, indicating an equal number of omission and commission errors (Table 1).

Juniper-cover estimates from NAIP imagery and ground measurements were strongly correlated (Fig. 1). There was high agreement between the ground measurements and estimates from NAIP imagery ($R^2 = 0.74$, $P < 0.01$). The intercept was not significantly different from zero ($P = 0.43$). Minimum juniper cover recorded was 26.8% and 24.7% with the use of the aerial images and ground-measuring methods, respectively.

Table 1. Error matrix showing number of sample points stratified between juniper and nonjuniper locations, and the classification accuracy and Kappa statistic.

Classified category	Juniper	Nonjuniper	Total	User's accuracy
Juniper	68	7	75	91%
Nonjuniper	5	70	75	93%
Total	73	77	150	
Producer's accuracy	93%	91%		
Overall accuracy				92%
Kappa statistic				0.84

Maximum juniper cover recorded was 82.2% and 78.7% with the use of the NAIP imagery and ground-measuring methods, respectively. Mean difference between NAIP imagery and ground-measured juniper cover was $6.6 \pm 0.61\%$ ($P < 0.01$). Minimum and maximum difference between NAIP imagery and ground measurements was 0.04% and 13.5%, respectively. However, juniper-cover estimates derived from NAIP imagery compared to ground measurements were not consistently higher or lower ($P = 0.79$).

Correlations between environmental gradient indices and juniper cover at stand closure were either not significant or only explained a limited amount of variation in juniper cover. The IMI and juniper cover in closed stands were not correlated ($P = 0.68$). Similarly, the HLI was not correlated with juniper cover at stand closure ($P = 0.74$). The juniper cover at stand closure was correlated negatively with SEI ($P = 0.04$). The SEI explained 10% of the variation in juniper cover at stand closure ($R^2 = 0.10$).

Environmental variables were correlated to juniper cover in closed woodlands. Juniper cover at stand closure correlated positively with aspect, slope, and elevation and correlated negatively with the interaction between slope and aspect. Juniper cover was correlated with all the measured soil characteristics ($P < 0.05$), except soil surface texture ($P > 0.05$). These soil characteristics explained some of the variation in juniper cover ($R^2 = 0.11$ to 0.17), but the stepwise linear regression excluded all of them from the final model ($P > 0.05$). The linear regression model best describing the relationship between juniper cover at stand closure and environmental characteristics was (standard errors in parentheses below parameter estimates):

$$\begin{aligned}\text{Juniper cover} = &-\underset{(44.17)}{49.62} + \underset{(6.27)}{1.69}\,(\cos(\text{aspect})) \\ &+ \underset{(0.45)}{0.90}\,(\text{slope}) + \underset{(0.02)}{0.05}\,(\text{elevation}) \\ &- \underset{(0.71)}{1.32}\,(\text{slope}\cdot\cos(\text{aspect})). \qquad [5]\end{aligned}$$

This equation explained 40% of the variation in juniper cover at stand closure ($R^2 = 0.40$; $P < 0.01$; residual standard error = 12.16). None of the environmental indices were included in the final model because they were excluded by the stepwise selection procedure.

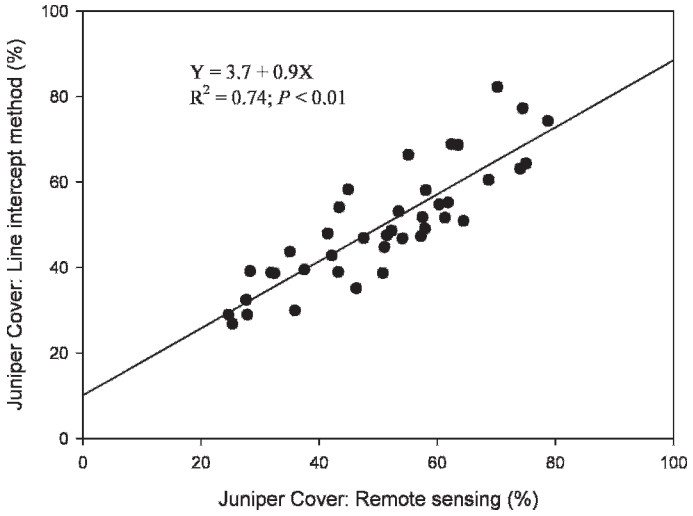

Figure 1. Correlations between ground and remote-sensed estimates of western juniper cover at Juniper Mountain, Idaho, USA.

DISCUSSION

The results of this study demonstrate that reasonably accurate estimates of western juniper cover can be obtained from NAIP imagery as shown by similar estimates of juniper cover between ground measurements and analysis of NAIP imagery. This suggests that aerial images, in conjunction with feature extraction software, can be used to estimate western juniper cover over large landscapes reliably. These results are advantageous because western juniper control programs are often constrained by finite resources and thus, being able to estimate juniper cover over large landscapes accurately will make these projects more affordable. Accurate estimates of western juniper cover are essential to prioritizing management and selecting the appropriate treatments in juniper control programs to restore sagebrush steppe plant communities (Miller et al. 2005).

There were some differences between estimates of western juniper cover depending on sampling method; however, neither method produced consistently higher or lower estimates. Thus, some NAIP imagery estimates would be greater than ground-measurement estimates and vice versa. With respect to NAIP, imagery error associated with this estimate can occur as a result of variable image quality from such factors as motion blur, time the imagery was taken (e.g., sun angle influences the degree of shadow in the imagery), color aberrations, cloud contamination and atmospheric variability, and incorrect orthorectification of the image (Chen et al. 2004; Wulder et al. 2004; Booth and Cox 2006; Booth et al. 2008; Moffet 2009). Another potential source of differences between the NAIP imagery estimates and ground measurements is that the images were acquired in 2004 and the ground measurements performed in 2007. During this period of time juniper cover could have constricted or expanded as a result of climatic conditions, infilling, mortality, or other factors. Considering that neither of the estimates were constantly greater than the other estimate, the time between when the estimates were acquired probably had limited influence. Other vegetation with reflectance similar

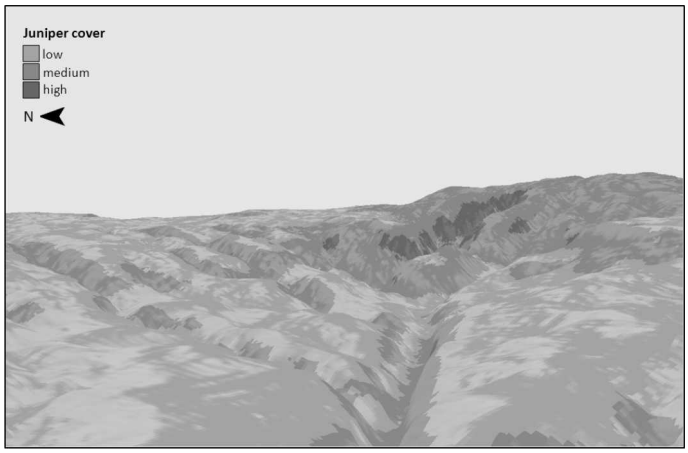

Figure 2. Model of the relationship between juniper cover at stand closure and topography characteristics applied across the study area on Juniper Mountain, Idaho, USA. Model equation is as follows: juniper cover = − 49.62 + 1.69 (cos(aspect)) + 0.90 (slope) + 0.05 (elevation) – 1.32 (slope · cos(aspect)).

to juniper being classified as western juniper may also be a source of error, particularly where western juniper and other vegetation are highly intermingled.

Differences between estimates could simply be caused by line-intercept measurements not adequately representing the entire plot. The line-intercept method measures cover along transect lines, whereas the extraction of tree cover with the use of the NAIP imagery estimates cover across the entire plot. Regardless, western juniper-cover estimates were not vastly different between methods. We suggest that the differences were minor enough to consider estimates of juniper cover from NAIP imagery acceptable for management purposes.

Estimating juniper cover at stand closure based on selected environmental gradient indices proved to be ineffective. The indices of environmental characteristics were especially limited in their correlation to juniper cover in closed stands. Neither the IMI nor HLI were correlated with juniper cover at stand closure ($P = 0.68$ and 0.74, respectively). In contrast, Davies et al. (2007) reported that the HLI explained some of the variation in vegetation cover in several plant functional groups in sagebrush plant communities; however, their study did not include western juniper. Similar to the correlation between SEI and juniper density reported by Johnson and Miller (2006), we found that the SEI was correlated with juniper cover ($P = 0.044$), but explained only 10% of its variation. Thus, environmental indices tested were limited in their usefulness at explaining variation in potential juniper cover for management purposes.

However, the correlation between environmental factors and potential juniper cover was stronger. The moderate correlation between environmental characteristics and western juniper cover at stand closure ($R^2 = 0.40$; $P < 0.01$) is similar to other attempts to correlate environmental characteristics with vegetation characteristics across landscapes in the Intermountain West (Jensen et al. 1990; Johnson and Miller 2006; Davies et al. 2007). Johnson and Miller (2006) found moderate to strong correlations between juniper (total and dominant tree) density and environmental characteristics. Davies et al. (2007) reported weak to moderate correlations between most vegetation structural characteristics and environmental variables. Dissimilarly, Petersen and Stringham (2008) found strong relationships between sagebrush structural characteristics and explanatory variables. However, they were working in a relatively small watershed, included biotic variables, and included varying phases of juniper encroachment. Petersen and Stringham (2008) recognized that the correlations found between vegetation structure and explanatory variables in their study would probably be weaker if applied at large landscapes.

The relationship between environmental factors and juniper cover suggest that we should expect greater western juniper cover at stand closure at higher elevations, on steeper slopes, and in more northerly facing aspects (Fig. 2). These factors probably influence juniper cover by their influence on the availability of water to juniper trees. Less exposed sites would have reduced evaporation; thus more water would be available for transpiration. Similarly, Davies et al. (2007) reported that relationships between herbaceous cover and environmental characteristics were probably due to the influence of the environmental characteristics on availability of water for plant growth. Johnson and Miller (2006) also reported the influence of environmental/site characteristics on juniper stand characteristics was probably due to environmental/site characteristics' affect on soil water availability.

Combining the information acquired from remotely measured juniper cover and environmental/site variables has potential to be especially useful in directing management. Estimates of juniper cover from NAIP imagery compared to potential stand closure cover values can be used to determine the developmental phase of juniper encroachment (Miller et al. 2000). Knowing current juniper cover compared to potential stand closure juniper cover can help to determine the juniper encroachment developmental phase (Miller et al. 2000). Identifying the developmental phase of western juniper encroachment is crucial to selecting effective management actions (Miller et al. 2005) and to prioritizing management to prevent transitions to development phases that are more costly and risky to restore. Management options become more limited and expensive as Phase II woodlands transition into Phase III woodlands because a reduction in understory fuel decreases the likelihood of prescribed fire carrying through the stand (Miller et al. 2000; Miller et al. 2005; Johnson and Miller 2006). Phase III compared to earlier-phase woodlands may also be at a greater risk of exotic plant invasion following juniper control treatments because of a reduced herbaceous understory (J. D. Bates, unpublished data, 2010). Estimating juniper cover from NAIP imagery and potential juniper cover from commonly available geospatial data layers to direct management makes landscape-scale restoration projects more feasible. This method has potential to be used in other plant communities to facilitate more effective and efficient landscape-scale restoration. Though our model is a good starting point, estimates of developmental phase could be improved with a more refined model to estimate potential juniper cover. Models estimating potential juniper cover may also need to be developed within ecoregions to increase their accuracy and reduce the potential confounding effects of regional climatic differences.

MANAGEMENT IMPLICATIONS

Estimating western juniper cover across large areas with NAIP imagery is an efficient and effective tool for landscape restoration projects. Thus, some of the constraints in implementing landscape-scale restoration projects can be alleviated by using aerial images. These images can also be used to prioritize management by level of juniper cover. Environmental/site variables explained a significant amount of the variation in juniper cover at stand closure and this information can be used to help prioritize and direct management. This information can be especially useful when compared to current levels of juniper encroachment. Thus, comparing the potential juniper cover at stand closure to current levels of juniper cover derived from NAIP imagery can be used to estimate the juniper encroachment phase. Our study demonstrates that using remote-sensing technology to determine juniper cover and environmental/site variables can be an effective tool to direct landscape-scale restoration projects that would otherwise be prohibitively expensive to implement. However, further exploration of the relationships between juniper cover and environmental/site factors could improve the ability to indentify developmental phases and detect transitions from one developmental phase to another. Additionally, the applicability of using these techniques in juniper stands with less juniper cover needs to be tested. Further research is needed to determine if juniper-cover estimates derived from NAIP imagery in Phase I and II juniper woodlands are as accurate as measurements in Phase III woodlands. Co-occurring vegetation in earlier developmental phases may decrease the accuracy of juniper-cover estimates derived from NAIP imagery. Our results suggest that NAIP imagery and environmental/site characteristics measured from commonly available geospatial data layers have the potential to be useful in landscape-scale restoration projects and land management in the Intermountain West and other ecosystems.

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