Assessment of Juniper Encroachment: An Approach Using Landsat Satellite Imagery and GIS datasets

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ABSTRACT

Juniper encroachment into otherwise treeless plant communities is one of the most pronounced environmental changes observed in rangelands of western North America in recent decades. Most studies on juniper change are conducted over small areas, although encroachment is occurring throughout regions. Whether changes in juniper cover can be assessed over large areas using long-term satellite data is an important methodological question. A fundamental challenge in using satellite imagery to determine tree abundance in rangelands is that a mix of trees, sagebrush, and herbaceous cover types can occur within a given image pixel. Our objective was to determine if spectral mixture analysis could be used to estimate changes in Rocky Mountain juniper (*Juniperus scopulorum* Sarg) and Utah juniper (*Juniperus osteosperma* [Torr.] Little) cover over 20 years and 20 000 ha in SE Idaho using Landsat imagery. We also examined the spatial patterns and variation of encroachment within our study area using GIS-based datasets of grazing use, land cover types, and topography. Juniper cover determined from 15-cm-resolution digital aerial ortho-photography was used to train and validate juniper presence/absence classification in 1985 and 2005 Landsat images. The two classified images were then compared to detect changes in juniper cover. The estimated rate of juniper encroachment over our study area was 22%-30% between 1985-2005, consistent with previous ground-based studies. Moran's *I* analysis indicated that juniper encroachment pattern was spatially random rather than clustered or uniform. Juniper encroachment was significantly greater in grazed areas ($p = 0.02$), and in particular in grazed shrubland cover type ($p = 0.06$), compared to ungrazed areas. Juniper encroachment was also greater on intermediate slopes (10%-35% slopes) compared to steeper or flatter terrain, and encroachment was somewhat less on north-facing ($p = 0.03$) and more on west-facing ($p = 0.02$) slopes compared to other aspects.

KEYWORDS: change detection, sub-pixel classification, spatial pattern, grazing, land cover

INTRODUCTION

Juniper encroachment is one of the most prominent changes occurring in the rangelands of western North America (Johnsen 1962; Blackburn and Tueller 1970; Burkhardt and Tisdale 1976; Miller and Rose 1995, 1999; Miller et al 2000; Wall et al 2001; Baker and Shinneman 2004). Juniper species are documented to have substantially increased in density and extent throughout their range in recent decades, although juniper cover fluctuated in the West during the Holocene and before the Euro-American settlement (Miller and Wigand 1994). As juniper trees mature and canopies close in encroached areas, understory herbaceous species and sagebrush cover can decrease, resulting in soil exposure and erosion (Miller et al 2000). Soil erosion and herbaceous and shrub cover decline can continue for substantial periods of time due to the longevity of junipers in the absence of fire (Waichler et al 2001). Intensive land treatments, such as prescribed burning, are now regularly performed to reduce juniper cover where the encroachment is perceived to decrease rangeland forage value or increase fire hazard.

Juniper encroachment has been attributed to climate variability and fire suppression (Miller and Wigand 1994), while variation in encroachment rates has been associated with differences in land cover types (Chamber et al 1999) and topographic positions (Miller et al 2000; Weisberg et al 2007). Interactions among these factors can lead to complex spatial patterns of encroachment, particularly when examined at small spatial scales and in the field (Weisberg et al 2007). Much of the previously documented juniper encroachment has occurred in shrub steppe communities (Miller and Wigand 1994; Weisberg et al 2007). Juniper seedlings often establish under sagebrush canopy as shrubs provide better soil moisture and protection from direct sunlight (Gottfried 1992; Miller and Rose 1995). It has been suggested that livestock grazing might promote juniper establishment by dispersing seeds, reducing competition from herbaceous forage species, and increasing shrub species that provide safe sites for juniper to establish (Gottfried 1992; Miller and Wigand 1994). However, we found no explicit statistical tests of the relationship between long-term grazing effects and increased juniper cover (Table 1).

Table 1. Non-exhaustive summary of previous studies on historical juniper expansion in sagebrush steppe of Western North America. In most cases, values were estimated from figures or tables, and converted to the common S.I. units.

Authors, year	Species of Juniper	Type of evidence	Temporal extent	Spatial extent	Estimated encroachment rate
Blackburn & Tueller 1970	*J. osteosperma*	Tree-ring/tree density	1725-1960	1.4 ha	0.3-0.6 trees/ha/yr
Burkhardt & Tisdale 1975	*J. occidentalis*	Tree-ring/tree density	1830-1970	1 040 ha	Up to 31 trees/ha/yr
Young & Evans 1981	*J. occidentalis*	Tree-ring/tree density	1600-1978	1 000 ha	Up to ~2 trees/ha/yr
Miller & Rose 1995	*J. occidentalis*	Tree-ring/tree density	1878-1990	8.8 ha over 32 km	Up to 4 trees/ha/yr
Miller & Rose 1999		Tree-ring/tree density	1840-1995	5 000 ha	N.A.
Johnson & Miller 2006	*J. occidentalis*	Tree-ring/tree density	1850-2005	N.A.; <2 500 ha	Up to 6 trees/ha/yr
Strand et al 2006		Aerial photography	1939-1998	15 ha	4.5% increase in cover/yr
Weisberg et al, 2007	*J. osteosperma*	Aerial photography	1966-1995	2 500 ha	0.4-1.1% increase in cover/yr
This study	*J. osteosperma* *J. scopularum*	Satellite imagery	1985-2005	20 000 ha	0.7-1.5% increase in cover/yr

Most evidence for juniper encroachment is provided by dendrochronological, demographic, or aerial photography studies which cover relatively small spatial extent (Table 1). However, most land use decisions and management activities are impacted by regional-scale changes and the associated regional-level policies. Assessment of juniper change over large areas is needed to guide regional policy and land use management. An important research question is whether changes in juniper cover over large areas and their relationship to grazing, resident land cover types, and topography can be assessed using moderate-resolution Landsat satellite imagery and Geographic Information Systems (GIS) datasets. Pixels in Landsat imagery are 900 m^2 (30 m x 30 m) in size and thus frequently have a mix of vegetation cover types, especially in the hilly rangelands of SE Idaho where juniper trees are dispersed amongst herbaceous and sagebrush cover types during the encroachment process. This mix of cover types within pixels poses a fundamental challenge in classifying pixels, since the spectral characteristics of the mixed pixels do not represent any single land cover type (Lillesand and Kiefer 2000). Spectral mixture analysis techniques have been developed to allow estimates of how much of a pixel is comprised by different land cover types (Adams et al 1986; Small 2004; Xiao and Moody 2005). Spectral mixture analysis is most suited when there are a limited number of land cover types and when the spectral properties of these cover types can be assumed to be relatively constant. Spectral mixture analysis characterizes the spectral signatures in the imagery as a mix of the land cover types in each pixel, where each cover type is known as a separate "endmember" (Rencz 1999). Once "pure" endmembers (i.e., pure pixels of each cover type) are determined within imagery, endmember fractions or abundance of each cover type within each pixel can be estimated as a mixture (Rencz 1999). A mixture represents a linear combination of the endmembers, weighted by the areal coverage of each endmember in a pixel (Rencz 1999). The result is an estimate of how much of a given pixel is comprised of different cover types. Spectral unmixing of Landsat imagery has previously been used to map other tree species and to estimate tree fractions within pixels (Chen et al 2004; Small and Lu 2006), but has not been used to our knowledge for mapping juniper encroachment.

We studied juniper (*Juniperus scopulorum* Sarg and *J. osteosperma* [Torr.] Little) encroachment of the last 20 years in SE Idaho using Landsat satellite imagery and spectral mixture analysis. Our objectives were: 1) to determine if spectral mixture analysis could be used with Landsat imagery to detect and quantify changes in juniper cover over 20 years and across 20 000 ha and 2) to examine how juniper changes vary due to livestock grazing, resident land cover types, and topographic positions by combining maps of juniper change derived from Landsat imagery with GIS datasets. Juniper encroachment rates could be further complicated by issues such as distance to nearest juniper stand or dispersal limitation, and so we also determined whether juniper encroachment patterns were clustered, random, or uniform. Our choice of Landsat imagery was based on its accessibility, moderate resolution (30 m x 30 m) compared to other types of satellite data (e.g., MODIS and AVHRR), and its availability for all earth surfaces for every 16-day-period in seven spectral bands. We chose two Landsat image scenes for juniper change detection: one from August 1985 and another from August 2005. Annual seasonal drought tends to prevail in August in SE Idaho. In addition, the greenness of sagebrush communities is lowest at this time of the year following sagebrush ephemeral leaf drop and herbaceous species senescence (Bilbrough and Richards 1993; Kremer and Running 1993). We expected this time period to allow more prominent detection of evergreen juniper in the sagebrush-steppe rangeland ecosystem.

METHODS

Study Site Description

Two regions of interest across a total area of ~200 km^2 (42º53´18"N, 112º28´37"E) were selected for this study, one south of Pocatello and the other west of Pocatello (Figure 1). The western region (Region 1) included Chinese Peak and Camelback Mountain, while the southern region (Region 2) included Kinport Peak and Gibson Mountain. Both regions consist of hilly and mountainous topography ranging in elevation from 1 400 m to 1 850 m. Slope largely ranged between 0-45 degrees (in percent) in both regions, while aspect varied between 140 (southwest) and 310 (northwest) degrees in Region 1 and 280 (northwest) through north to 170 degrees (southeast) in Region 2. A majority of the area is public land managed by the Bureau of Land Management (BLM) and US Forest Service (USFS) (approximately 40% and 50%, respectively), while the rest includes private land (~10%). The soils are coarse-silty, mixed, frigid Calcic Haploxerolls (Ririe series; USDA, NRCS 1997). Average annual precipitation in Pocatello is 325 mm.

Common plant species are Rocky Mountain juniper (*Juniperus scopulorum* Sarg), Utah juniper (*Juniperus osteosperma* [Torr.] Little), big sagebrush (*Artemisia tridentata* Nutt. spp.), "three-tip" sagebrush (*Artemisia tripartita* Rydb), grey rabbitbrush (*Chrysothamnus nauseosus* [Pall.] Britt.), green rabbitbrush (*Chrysothamnus viscidoflorus* [Hook.] Nutt.), bulbous bluegrass (*Poa bulbosa* L.), thickspike wheatgrass (*Elymus lanceolatus*), needle-and-thread grass (*Stipa comata* Trin. & Rupr.), cheatgrass (*Bromus tectorum* L.), and tapertip hawksbeard (*Crepis acuminata* Nutt.) (Ratzlaff and Anderson 1995).

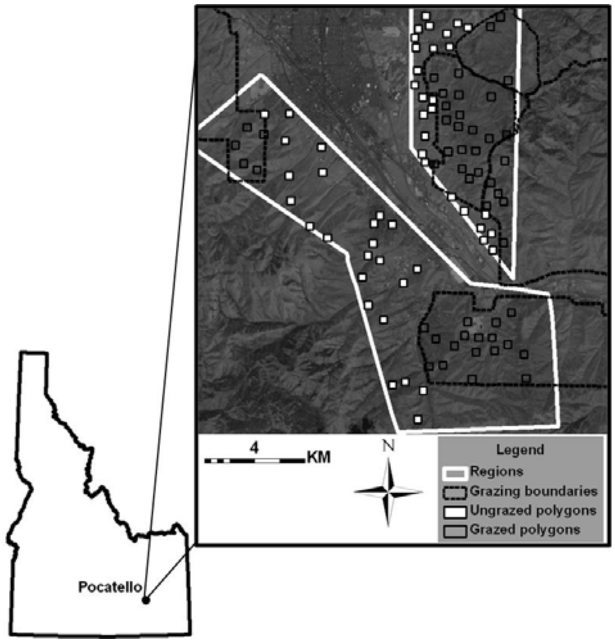

Figure 1. The study regions, grazing boundaries, and the 100 randomly generated sample polygons in the Pocatello area of southeastern Idaho.

The two regions included grazed areas dispersed throughout ungrazed areas. The grazed areas (five allotments) are managed by the BLM (Figure 1) and have been used in spring-summer seasons over the last 20 years. Our review of the BLM grazing records and discussions with BLM Range Conservationists revealed that grazing regimes in these areas have been relatively constant during the study time period. The grazed areas vary between 1 466-5 321 ha in size and 0.01-0.24 Animal Unit Months per hectare in grazing intensity.

Landsat Imagery and Juniper Classification

We used one Landsat5 Thematic Mapper satellite image subset from August 02, 1985 and one Landsat5 Thematic Mapper satellite image subset from August 13, 2005. Both images (Path 039, Row 030) were atmospherically and geometrically corrected and projected in UTM Zone 12 North, NAD 1983 projection and datum. Digital color aerial ortho-photograph with a 15-cm resolution from August 2004 (USDA National Agricultural Imagery Program) was used for training and validation of Landsat image classification. The 1985 Landsat image was co-registered to the 2005 Landsat image using 30 ground control points (root mean squared error = 0.07).

The Matched Filtering Spectral Unmixing technique was used to classify juniper in the Landsat imagery (ENVI Version 4.3, ITT Industries Inc, 2006, Boulder, CO). The Matched Filtering Spectral Unmixing approach detects a user-defined target cover type in the imagery, while suppressing the spectral signatures of other cover types. The classification training requires identification of pure pixels of the cover class of interest as well as pure pixels that do not have the cover class of interest (i.e., pixels of other cover types). In our case, the target cover type of interest was juniper. The other cover types to be suppressed largely included sagebrush and herbaceous cover as well as their mix. Using the 15-cm-resolution aerial photograph, we selected in each Landsat imagery 10 pure juniper pixels and 10 other pure pixels that clearly had no juniper, but sagebrush and herbaceous cover and their mix. The two Landsat images were trained and classified separately and fractions of juniper endmember were estimated in both images. The spectral separation of the pure pixels was successful in both Landsat images (Figure 2) and remarkably similar between the images.

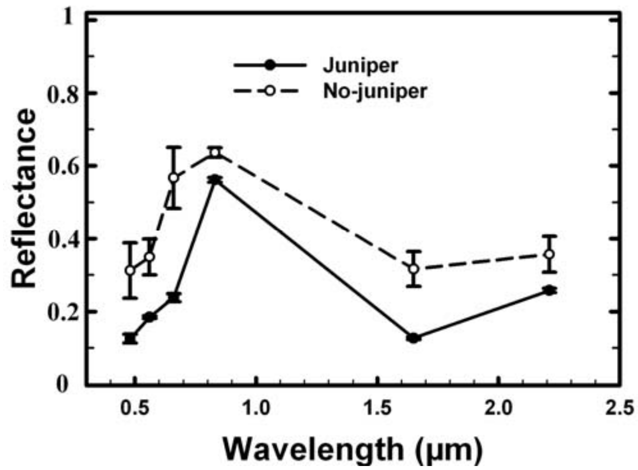

Figure 2. Mean (+/- SE) spectral reflectance of the "pure" pixels with 100% juniper cover (N = 10) and 0% juniper cover (N = 10) in the Landsat images.

Using the estimated juniper fractions in each image, juniper presence and absence was classified in each pixel to produce a binary map of juniper presence and absence for each image date. During this process, a spectral threshold was set between 0-1 to decide on juniper absence and presence and thereby optimize the classification accuracy. To determine the appropriate threshold, we assessed the accuracy of multiple classification models beginning with a nominal threshold value of 0.0 and incrementally increasing the threshold by 0.05 units until increases in threshold no longer improved accuracy. The resulting threshold value was 0.3. The accuracy of each 2005 juniper classification model was assessed with 65 randomly selected pixels (random points generated by Hawth's tools, ESRI® ArcMap™ 9.1 software (ESRI Inc, 1999-2006)) having a range of juniper cover of 0%-100% which were visually estimated in the aerial photograph in 30 m x 30 m windows to correspond with the 2005 Landsat pixels. The accuracy of each 1985 juniper classification model was assessed with 65 randomly selected pixels having either 0% or >50% cover of large juniper trees (>2 m in canopy diameter). There were no high resolution aerial photographs available for 1985, so we assumed that 30 m x 30 m windows having high values of juniper percent cover in the 2004 photographs likely had juniper presence in 1985. Similarly, windows with no juniper in 2004 nor trunk skeletons or history of juniper-excluding events between 1985-2005 were assumed to have juniper absence in 1985. Our assumptions were supported by local familiarity with this region and the slow growth rates of juniper.

Change Detection
A post-classification image differencing method (Lillesand and Kiefer 2000) was used to compare the 1985 and 2005 binary maps and to detect pixels with newly established junipers, where junipers were absent in the earlier date. This allowed us to examine the overall juniper cover increase both in the extent and density across the study area over the 20-year period. In addition, we compared the estimated abundances of juniper within each pixel between the two unmixed Landsat images using a paired *t*-test (n = 60 246) to provide additional information on pixel-level juniper density changes from 1985 to 2005. However, pixel-level juniper fraction estimates were not quantitatively assessed for classification accuracy and were, therefore, not used in further analysis. Only the juniper change map resulting from the comparison of the two binary maps was used in the statistical analysis.

GIS Datasets
We created GIS-derived independent variables of grazing, land cover types, and topography using ArcMap 9.1 software. Digital maps of fires and grazed area boundaries were acquired from the BLM (Weber and BLM Pocatello field office 2006). A thematic map of land cover types generated by the Idaho GAP Analysis project for the Pocatello area was used. This map included 15 different land cover

types in our study area (70% overall accuracy) and had a spatial resolution of 30 m and minimum mapping unit of 2 ha. We performed an independent accuracy assessment of our own within our study area and considered the accuracy of this map acceptable (75% overall accuracy). To further improve the accuracy, we combined the 15 land cover types into four classes at the next coarser level of thematic classification. For example, all shrub cover types (i.e., big sagebrush, low sagebrush, and bitterbrush) were grouped into a single cover type of shrubland. The resulting four land cover types included grassland, shrubland, riparian, and urban land (very small area of housing development outside of the city of Pocatello as the city was intentionally excluded from our study area). A USGS digital elevation model (DEM) of 26.8 m resolution was used to derive topographic aspect (in degrees) and slope (in percent).

Statistical Analyses

We examined the spatial pattern of juniper encroachment within each region using Moran's *I* to determine if juniper encroachment was clustered, random, or uniform across the landscape. Moran's *I* index was estimated using the juniper change map and Euclidian distance method with inverse distance relationship in ArcMap 9.1 software. A z-score was also estimated to determine the statistical significance of the estimated *I*. Moran's *I* values close to -1 indicates a uniform pattern, while values close to 1 indicates a clustered pattern. Moran's *I* values close to 0 indicates a random pattern (O'Sullivan and Unwin 2003).

The relationship of juniper change and landscape factors was examined using analysis of variance (ANOVA) (SPSS 14.0 for Windows, 2005). The units of replication were randomly located polygons that each had 100 pixels (a square area of 90 000 m^2). There were 100 replicate polygons, and they were distributed evenly between grazed and ungrazed areas (Figure 1), with 85 polygons in shrubland, eight in grassland, and the remaining seven in riparian and urban areas. The response variable was the number and percent of pixels in the random polygons classified as having new juniper presence in 2005 compared to the 1985 classified image. Data were square-root transformed to meet assumptions of normality. A one-way ANOVA was used to compare juniper increase in grazed and ungrazed polygons. A separate two-factor ANOVA was used to assess whether the grazing effect varied among shrubland and grassland (these were two levels of the second factor, resident land cover), with pair-wise post-hoc comparisons to examine the interactive effects of grazing and land cover types.

Multiple regression was used to assess the interactive effects of topography and grazing on juniper increase. The topographic aspect and slope associated with each pixel within each random polygon were extracted from the DEM and grouped into four categorical classes of aspect (315º-45º, 45º-135º, 135º-225º, and 225º-315º) and three categories of slope (0%-10%, 10%-35%, and >35%) within each polygon. The number of pixels showing new juniper presence from 1985 to 2005 in each polygon was modeled as a response to grazing (grazed or ungrazed), aspect (4 classes), and slope (3 classes).

RESULTS

The spectral properties associated with juniper were distinct compared to other cover types, with the most differences in spectral properties between juniper and the surrounding land cover types being particularly evident at wavelengths longer than 0.6 µM (Figure 2). The overall accuracy was 92% in the 2005 Landsat imagery and 79% in the 1985 Landsat imagery. The 2005 image classification had greater user's and producer's accuracies than the 1985 image classification (Table 2), though the spectral signatures of endmembers were remarkably similar between the two images.

Over the study period, the number of pixels with new juniper presence from 1985 to 2005 increased 29.7% in Region 1 and 21.6% in Region 2. Juniper cover per pixel increased 16.6% in Region 1 (p = 0.0001) and 14.2% in Region 2 (p = 0.0002). The estimated Moran's *I* was 0.04 with a z score of 772.3 for Region 1 (p = 0.01) and 0.03 with a z score of 1 160 for Region 2 (p = 0.03), indicating that juniper encroachment occurred in a random pattern, but not in a localized clustering or in an even distribution of trees in both regions.

Table 2. Classification accuracy of juniper presence and absence in 1985 and 2005 Landsat images.

Year of image	Class	User's accuracy	Producer's accuracy	Overall accuracy
2005	Juniper presence	91%	94%	
	Juniper absence	94%	91%	92%
1985	Juniper presence	80%	95%	
	Juniper absence	86%	62%	79%

The percentage increase between 1985-2005 in pixels of the random polygons having new juniper presence was significantly greater in grazed compared to ungrazed areas, over all land cover and topographic variation (28.2% ± 17.9 SD and 22.5% ± 13.6 SD, respectively, $F_{1,99} = 5.31$, $p = 0.02$). There was a marginally significant interaction of grazing and land cover types ($F_{2,99} = 2.8$, $p = 0.06$; Figure 3). Post-hoc comparisons indicated that ungrazed grassland had 11.1% greater juniper increase than ungrazed shrubland ($p < 0.0001$), and grazed shrubland had 9.5% greater juniper increase compared to ungrazed shrubland ($p = 0.06$) (Figure 3).

The regression model indicated grazing and topography significantly affected juniper change between 1985-2005 ($p < 0.000$ and adjusted $R^2 = 0.81$). Grazing, medium slope class (10%-35 %), and northerly and westerly aspects were significant predictor variables ($p = 0.04$; 0.001; 0.03, and 0.02, respectively). Medium slope class had 5.6% and 4.4% greater juniper increase compared to the flatter and steeper slope classes, respectively (Figure 4a). Northerly aspects had a somewhat lower rate of juniper increase than other aspects, while westerly slopes had a slightly greater rate of juniper increase (Figure 4b).

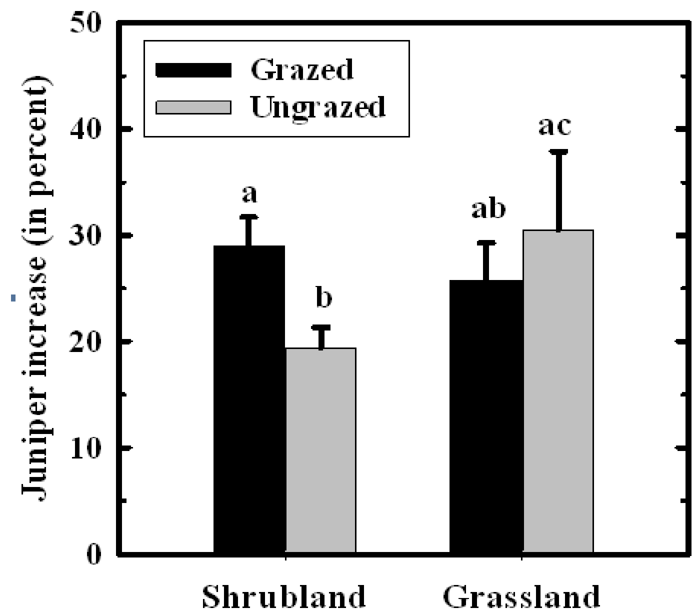

Figure 3. Mean (+/- SE) increase in the percent of pixels with new juniper presence in grazed and ungrazed shrubland and grassland cover types between 1985-2005. Letters indicate significant differences at α =0.1.

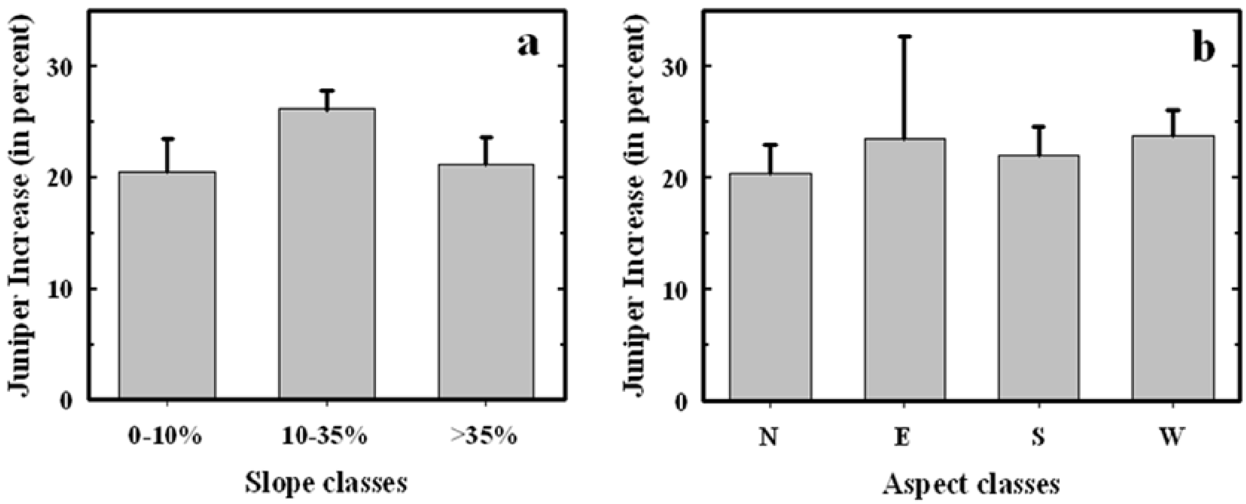

Figure 4. Mean (+/- SE) increase in the percent of pixels with new juniper presence in categorical classes of slope (panel a) and aspect (panel b).

DISCUSSION

The application of moderate-resolution Landsat imagery in classifying and detecting changes in sparsely distributed juniper cover was successful. The spectral mixture analysis allowed accurate detection of juniper presence and absence, which then generated realistic temporal change detection over the past 20 years for a large region of semi-arid rangelands. The distinct spectral characteristics of pixels that had juniper, compared to pixels without juniper, were probably due to the dark greenness and relatively high leaf area of juniper compared to the surrounding light-colored vegetation. These non-juniper cover types had less foliage and chlorophyll during the dry end-of-growing season days from which we selected our imagery.

The results of this application have important implications for the monitoring and assessment of rapidly expanding juniper woodlands which is an issue for over 24 million hectares in the western United States (Miller and Wigand 1994). Field-based approaches for detecting juniper cover changes provide highly accurate and valuable results, but they can be labor intensive, time consuming, and limited in the spatial extent they can cover. In comparison, the application of remote sensing methods can be more cost-effective and timely due to the large areal extent they cover. Digital satellite imagery also provides opportunities for more robust and comprehensive analysis of change, as the imagery can be easily integrated with other sources of digital data, such as terrain models and digital maps of grazing boundaries or land cover types. Moreover, data from satellite platforms, such as Landsat, can be acquired in retrospect to examine past changes, in this case over 20 years.

Our results indicated up to 30% increase in pixels having juniper over the past 20 years in the Pocatello area of SE Idaho. The estimated rates of increase in juniper cover in this study were in approximate agreement with the estimates of juniper increase in other areas based on different methods (Table 1). Notably, there appears to be more convergence of juniper change estimates from the large-scale studies. The estimated rate of juniper increase appeared different in our two regions, which might be due to the difference in the initial juniper cover between the two regions. Region 1 with relatively greater increase in juniper cover had greater initial juniper cover of approximately 25%. Weisberg et al. (2007) indicate that juniper expansion rate can be density-dependent and the process might be dominated by infilling. Compared to other areas, they suggest that expansion rate might be greater in areas where the initial juniper cover is >10%. Our spatial pattern analysis indicated that juniper encroachment was randomly distributed in each region, and not locally clustered or uniform. The random spatial pattern might be associated with juniper dispersal systems that are facilitated by multiple factors including gravity, birds,

frugivorous mammals, and some livestock which pass germinable seeds (Chambers et al 1999). Padien and Lajtha (1992) also found juniper encroachment patterns to be random at regional scales.
Greater juniper encroachment in grazed compared to ungrazed areas in our study was consistent with the expected, but not often explicitly tested, positive effects of grazing on juniper increase suggested by previous studies (Miller and Wigand 1994; Miller and Rose 1995, 1999). Livestock grazing can decrease the competitive effects of palatable herbaceous species on new and establishing juniper trees (Evans 1988). The reduction in competition might accelerate juniper establishment (Johnsen 1962) by making plant communities more susceptible for juniper encroachment (Miller and Wigand 1994). Our findings of marginally greater juniper encroachment in grazed shrubland compared to ungrazed shrubland are also consistent with conclusions in previous literature. Livestock grazing can increase shrub species that help facilitate juniper encroachment (Gottfried 1992), and there are several ground-based reports affirming the encroachment of juniper into shrub steppe (Miller and Wigand 1994; Miller et al 2000; Weisberg et al 2007). Shrubs provide better soil moisture and protection from direct sunlight (Gottfried 1992; Miller and Rose 1995). Litter accumulation beneath shrub canopies further improves soil moisture and temperature, and provides nutrients to the developing juniper seedlings (Evans 1988).

Our results indicated that grazing and topographic positions were important predictor variables of juniper encroachment. Indeed, this model explained much of the variability in juniper encroachment without including land cover types as a predictor variable. This might indicate that topographic heterogeneity can be a more important factor than land cover types. Little is known regarding topographic effects on juniper encroachment (Johnson and Miller 2006; Weisberg 2007). However, Johnson and Miller (2006) suggest that once a threshold is crossed in the juniper encroachment process, disturbances such as fire are no longer important and instead topography might become the important factor that explains much of the variability in juniper woodland expansion.

CONCLUSIONS

Management Implications

This study demonstrated a successful application of Landsat imagery and classification methods in detecting juniper cover increase. Juniper cover appears to be increasing in a random spatial pattern and at varying rates across the landscape due to differences in grazing use, land cover types, and topography. If further inquiry can demonstrate causality between juniper encroachment and these variables, land management can be adjusted to abate further unwanted increases in juniper. The approach described here could enable a more rapid assessment of juniper woodland changes across large areas and inform management decisions.

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