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Article

Regional Assessment of Aspen Change and Spatial Variability on Decadal Time Scales

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Abstract: Quaking aspen (*Populus tremuloides*) is commonly believed to be declining throughout western North America. Using a historical vegetation map and Landsat TM5 imagery, this study detects changes in regional aspen cover over two different time periods of 85 and 18 years and examines aspen change patterns with biophysical variables in the Targhee National Forest of eastern Idaho, USA. A subpixel classification approach was successfully used to classify aspen. The results indicate greater spatial variability in regional aspen change patterns than indicated by local-scale studies. The observed spatial variability appears to be an inherent pattern in regional aspen dynamics, which interacts with biophysical variables, but persists over time.

Keywords: aspen abundance; change detection; Landsat TM; mixture tuned matched filtering; GIS

1. Introduction

Quaking aspen (*Populus tremuloides* Michx.) decline in western North America has garnered both scientific and public attention [1,2]. Many western states and counties now have local task forces dedicated to this important species as it provides unique habitat for many plant and bird species, food source for native ungulates such as elk and moose, and high aesthetic and recreational value for people. Restoration activities such as controlled burning and logging are commonly performed to address the concern over declining aspen cover [3,4]. Much of the current concern, however, is based on local-scale studies [5]. Recent landscape-scale studies suggest persistent or even increasing aspen stands at some locations [4,6–8]. Similarly, a regional-scale study in the Greater Yellowstone

Ecosystem of the western U.S. documents both aspen decline and aspen increase [9]. Furthermore, a recent geographic review of local-scale aspen studies throughout the western United States highlights spatial variability in aspen dynamics by demonstrating that all possible patterns of aspen change have been documented: (1) declining aspen; (2) persistent or stable aspen, and (3) increasing aspen [5]. Further information is needed on the spatial variability in aspen change at regional scales to guide policy and management.

Aspen is the most widely distributed deciduous tree in North America [2]. Aspen can reproduce both by seed or root suckering [10], although aspen establishment from seed is considered rare [11,12] and most stems are believed to establish from root suckers within pre-existing clones [2]. A clone can cover up to 90 hectares and live for thousands of years through repeated suckering [2]. Several biophysical factors including climate, fire, grazing, and clearcutting have been linked to various patterns of aspen change at local scales. Climate fluctuations and fire suppression have been proposed as factors associated with aspen decline [8,9]. In the absence of fire, apical dominance prevents suckering and aspen is replaced by grasses, forbs, shrubs, or conifers [10]. When suckering is successful, wild ungulate browsing can reduce sucker density and decrease successful regeneration [13–16]. Browsing by domestic livestock is also known to reduce aspen regeneration and recruitment. High-intensity cattle grazing [17–20] and sheep grazing can have strong negative effects on aspen suckers [21,22]. In contrast, aspen suckers establish in high density following disturbance such as fire or clearcutting in conifer forests [1,23]. Aspen can establish as an early successional species and aggressively compete with some species such as lodgepole pine [24], but some later seral species such as Douglas-fir can replace aspen over time [25]. Despite numerous local-scale studies that have documented aspen cover changes and contributing biophysical variables, the relative importance of the biophysical variables in regional-scale aspen changes is poorly documented. Particularly, the extent to which regional-scale aspen changes are related to biophysical variables is unknown.

Most evidence for aspen decline is provided by dendrochronological, demographic, or aerial photograph studies which cover relatively small spatial extents. Application of remote sensing techniques and satellite imagery might provide an optimum method to detect regional-scale aspen changes and their spatial variability due to the large spatial extent they cover. Satellite images have been successfully used to generate thematic classification of full-canopy aspen distribution [26–29], although aspen change detection, especially at longer time scales, has not been performed with satellite images due to the relatively short time period since the satellite sensors began operating. Landsat satellite imagery now spans approximately three decades. Landsat Thematic Mapper images used with subpixel classification techniques might reveal shorter-term (i.e., 1–3 decades) fine-scale aspen changes over large areas, while its combination with historical vegetation cover maps might be useful in detecting longer-term (i.e., >3 decades) aspen changes. The objective of this study is to test the utility of a subpixel classification technique in detecting aspen changes over large areas and in documenting the spatial variability in aspen change patterns as related to biophysical variables.

Pixels in Landsat imagery are 900 m^2 (30 m × 30 m) in size and thus frequently have a mix of vegetation cover types. This mixture within pixels poses a fundamental challenge in classifying pixels, because the spectral characteristics of the mixed pixels do not represent any single land cover type [30]. Spectral mixture analysis techniques have been developed to estimate the relative proportion of different land cover types within a pixel [31–33]. Spectral mixture analysis characterizes the spectral signatures in the imagery as a linear mix of the land cover types in each pixel [34]. Once "pure" pixels of each cover type are identified within imagery, the abundance of each cover type within each pixel can be estimated [34]. Spectral mixture analysis has previously been used with Landsat images to map other tree species and to estimate tree abundance within pixels [35–37], but this application has not been used to document aspen changes and spatial variability.

This study documented aspen changes across a ~301,000 ha area in the Targhee National Forest of eastern Idaho, USA over a 18-year period using spectral mixture analysis with recent and older Landsat images and over a 85-year period using a recent Landsat image with a 1920 vegetation cover map. Key questions to be answered were: (1) How has aspen distribution changed over both time periods? (2) Does aspen change over both time periods include varying patterns of declining, persistent, and increasing aspen? (3) If so, how does the spatial variability in aspen change relate to biophysical gradients? The specific objectives related to the third question were to determine if any of the previously documented variables were consistently associated with only: (a) aspen decline; (b) stable aspen communities, or (c) aspen increase leading to a particular change in aspen cover over time.

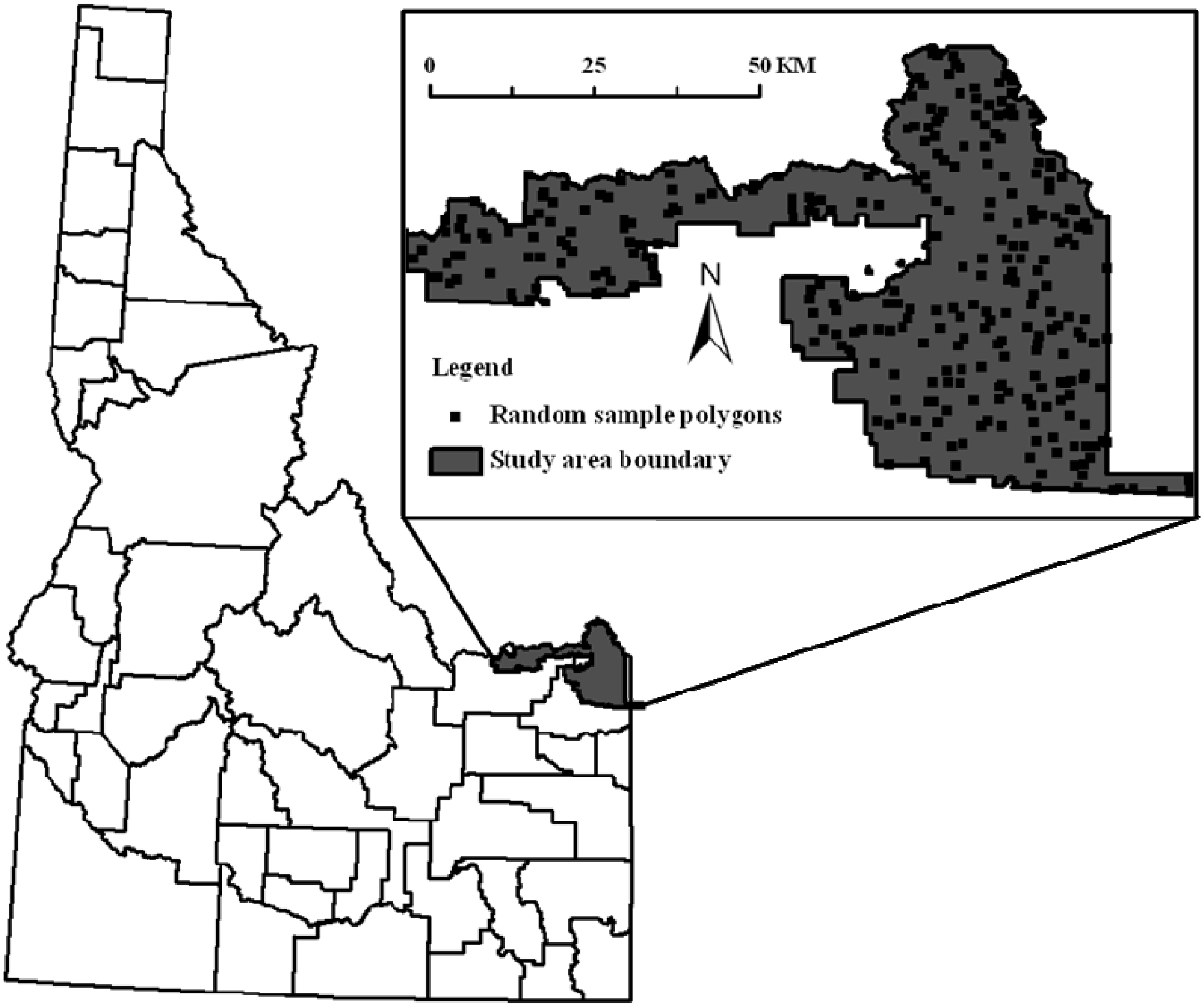
2. Methods

2.1. Study Site

This study examined a 301,332 ha area of the Targhee National Forest in eastern Idaho, USA (Figure 1). The Targhee National Forest is located within the Greater Yellowstone Ecosystem (GYE). It is managed by the United States Department of Agriculture (USDA) Forest Service. Within the Targhee National Forest, elevations span 1,660–4,000 m. Topography ranges from rolling foothills to rugged, glaciated mountain peaks. The Targhee National Forest experiences cold, moist winters and hot, dry summers. Annual precipitation ranges from 250–1,016 mm, much of which falls as snow. Temperatures range between −40 °C and 38 °C. The soils on mountainsides are most commonly Typic Haplocryepts, which are moderately deep, well-drained soils that form on a variety of geologic parent materials including rhyolitic tuff, gneiss, granite, or basalt. Soils on plains, level terraces, and floodplains can include Aeric Cryaquepts and Argic Cryaquolls [38].

The Targhee National Forest is dominated by coniferous forests interspersed with aspen patches and sagebrush-grasslands. In different subsections of the Targhee National Forest, up to 96 percent of the forests are Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and their mix. Aspen covers up to four percent of the forested areas [39]. Timber management activities have varied in different subsections of the forest resulting in varying distributions of stand age classes. In addition to wildlife browsing, much of the Targhee National Forest is grazed by livestock. Currently, 14 grazing allotments (total of 66,245 ha) within the study area are used by sheep at 0.01–0.3 Animal Unit Months per hectare (AUM/ha) grazing intensities and 33 allotments (total of 115,099 ha) are grazed by cattle at 0.01–0.66 AUM/ha grazing intensities (personal communication, Caribou-Targhee National Forest Range Management Specialists). The current grazing intensities have been relatively stable over the last ~25 years. Written records indicate that historic grazing intensities from 1910–1970 were approximately two times greater than current and that some of the current cattle-grazing allotments were historically grazed by sheep (personal communication, Caribou-Targhee National Forest Range Management Specialists).

Figure 1. Study area and 300 randomly-generated sample polygon locations in the Targhee National Forest in Idaho, USA.

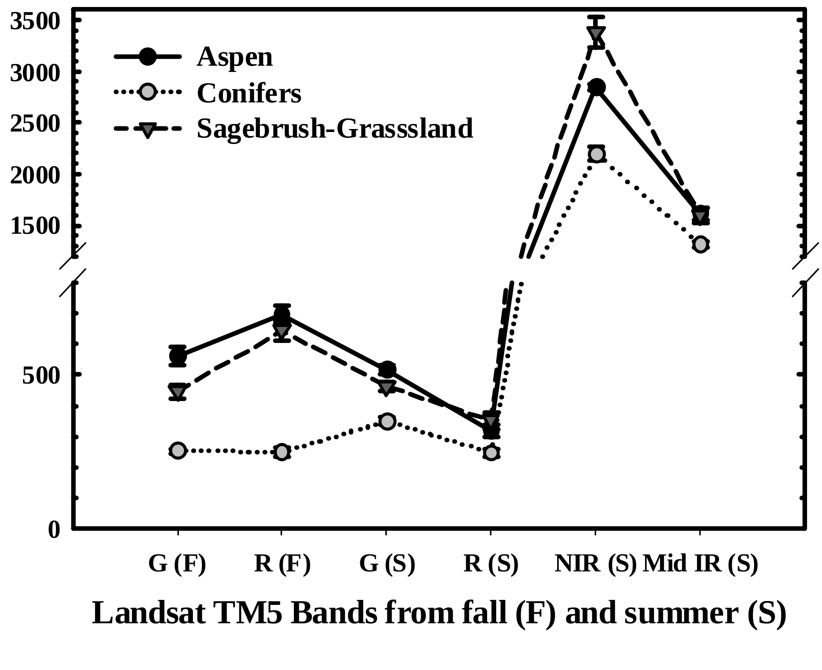


2.2. Aspen Maps and Image Classification

Digital aspen maps from three different years were used: 1920, 1987, and 2005. The 1920 aspen map was generated from a 1920 vegetation cover type map provided by the Forest Service in a digitized, georeferenced shapefile format projected in Universal Transverse Mercator Zone 12 North, North American Datum 1927 (UTM Zone 12 N, NAD 1927). This map included 2,094 polygons with a minimum mapping unit of 0.25 ha. Of these, 464 polygons had aspen mapped as a predominant species and were selected to generate the 1920 aspen map in a shapefile. The map was then converted into a raster format with 28.5 m × 28.5 m pixels to generate a 1920 aspen presence/absence map of the entire study area.

The 1987 and 2005 aspen maps were generated from two multitemporal composites of summer- and fall-season Landsat Thematic Mapper (TM) 5 satellite images (28.5 m × 28.5 m pixels). The two composites consisted of images acquired on 25 June 1987 and 27 September 1987, and 4 July 2005 and 11 September 2004, respectively. First, all four images (Path 39 and Row 29) were: (1) corrected for atmospheric effects using the FLAASH module in ENVI software (ENVI Version 4.5. ITT Industries Inc., 2008, Boulder, CO, USA); (2) projected in UTM Zone 12N, NAD 1927 projection and datum; (3) georectified (RSME <10 m), and 4) subset to the study area. Then, the summer image bands 2 (0.52–0.60 μm), 3 (0.63–0.69 μm), 4 (0.76–0.90 μm), and 5 (1.55–1.75 μm) were spectrally subset and saved with the respective fall bands 2 and 3 as a new image to generate the two multitemporal composite images. Multitemporal band combinations of summer and fall season Landsat images have been previously used by Wolter *et al.* [26] and Bergen and Dronova [40] to successfully classify aspen by taking advantage of the tree's unique phenology compared to the coexisting conifer trees. Aspen tree leaves are green and photosynthetically active in the summer and turn yellow during senescence before falling in the autumn. The yellowing of the aspen leaves caused by pigments of anthocyanins, carotenoids, tannins, and xanthophylls results in a major change in aspen spectral response leading to increased reflectance in the green (0.52–0.60 μm) and red (0.63–0.69 μm) portions of the visible electromagnetic spectrum during fall (Figure 2). This study takes advantage of the changes in these portions of the spectrum by combining the green and red bands (bands 2 and 3) of the fall image with the summer image bands 2, 3, 4 and 5.

Figure 2. Mean spectral reflectance of aspen and other dominant vegetation cover types within the study area in green (G = 0.52–0.60 μm), red (R = 0.63–0.69 μm), near infrared (NIR = 0.76–0.90 μm), and middle infrared (Mid IR = 1.55–1.75 μm) portions of the electromagnetic spectrum in the fall (F) and summer (S) seasons. Error bars are standard errors.



The resulting two multitemporal composite images were classified using the Mixture Tuned Matched Filtering (MTMF) technique [41] in ENVI software. MTMF is a spectral mixture analysis technique that estimates subpixel abundance of a target cover type as one of two or more possible cover types, known as endmembers (Equation 1):

$$R_i = \sum_{j=1}^{n} \mathrm{f}_j \, \mathrm{Re}_{ij} \text{ and } 0 \leq \sum_{k=0}^{n} \mathrm{f}_\mathrm{j} \leq 1 \tag{1}$$

where R_i is the reflectance of a mixed pixel, i is image band number, f_j is fraction of endmember, and j is endmember. MTMF is particularly suitable when only a single cover type is of interest. It optimizes the detection of a target cover type by suppressing the spectral signatures of unknown background and other land cover types of lesser importance. The target cover type in this study was aspen, while the nontarget cover type (i.e., no-aspen class) included conifers, sagebrush, grassland, and their mix. The target and nontarget cover types in this study were not examined for effects of shadow and topographic variation. The "pure" pixels selected from the imagery for aspen and other dominant cover spectra, therefore, include vegetative foliage as well as their shadow (Figure 2).

MTMF technique produces two images which are used together to determine target cover abundance: 1) an image of matched filtering scores that estimates the abundance of target cover within each pixel, and 2) an image of infeasibility values that indicates the relative accuracy of the matched filtering score. In the first image, a matched filtering (MF) score around 0 indicates background signal or noise, while a score of 1 corresponds to 100 percent target cover within a pixel. In the second image, high infeasibility values (e.g., values of 10–130) indicate greater likelihood that pixels are false positives. Therefore, a correctly classified pure aspen pixel with 100 percent aspen cover, for example, would have a matched filtering score of 1 and a low infeasibility value such as 0 or 1.

The two images resulting from MTMF classification present different information and have to be combined to produce a final map of the target cover. There is, however, no automated approach to combining the two images. A user-defined approach is, therefore, required to produce a final map of the target cover type [42]. To determine a suitable approach to combining the two images, the relationship between the two bands of each image was examined in different areas of the study region using scatter plots. An exponential relationship was observed between the MF scores and infeasibility values in all areas of both images. A subset of approximately 100,000 pixels was then extracted from each image. An exponential model was fit to the two bands and the model parameters were estimated in a statistical software (SPSS 15.0 for Windows). The following regression models (Equations 2 and 3) were produced for the 1987 and 2005 images, respectively:

$$y = 1.408^{e1.696x} \tag{2}$$

$$y = 0.737^{e0.007x} \tag{3}$$

where the infeasibility values were the response variable and the matched filtering scores were the predictor variable. The regression models were then applied to the rest of the images to produce a final aspen presence/absence map from each image in ESRI® ArcMapTM 9.2 software (ESRI Inc, 1999–2006). The pixels that fell under the regression curve that had matched filtering scores of 0.3–1 and 0.5–1 with infeasibility values of <2 and <5 were classified as aspen presence in 1987 and 2005, respectively, while all other pixels were classified as aspen absence (Figures 3 and 4). The selected ranges of matched filtering scores were determined by iteratively testing for a spectral threshold between 0–1 to decide on aspen presence and absence and thereby optimize classification accuracy. To determine the appropriate threshold, the accuracy of multiple classification models were assessed 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 same process was used to determine the threshold in the infeasibility values for each image.

Figure 3. Aspen presence and absence classification of 2005 Landsat TM5 multitemporal composite using Mixture Tuned Matched Filtering (MTMF) technique with a regression approach. The exponential regression model was fitted to the MTMF-produced matched filtering scores and infeasibility values (R^2 = 0.57, p < 0.0001). Pixels that fell under the regression curve (solid grey line) that had matched filtering scores of 0.5–1 (dashed grey lines) and infeasibility values of <5 (dotted grey line) were classified as aspen presence. All other pixels were classified as aspen absence.

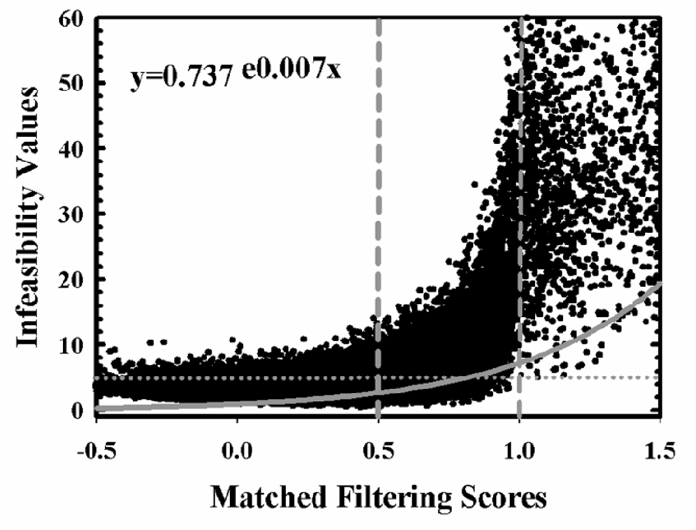
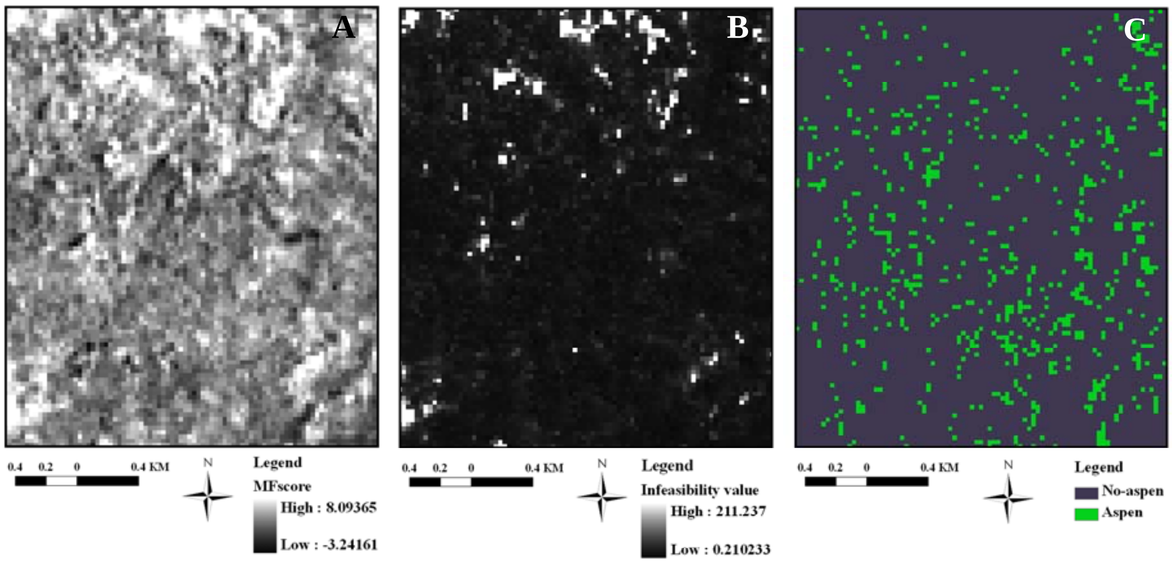


Figure 4. The Mixture Tuned Matched Filtering (MTMF) classification images and final aspen map for 2005. The image of matched filtering scores (a) estimates the abundance of target cover within each pixel, while the image of infeasibility values (b) indicates the relative accuracy of the matched filtering score in each pixel. Aspen presence and absence map (c) is produced after the regression integration of the two images.

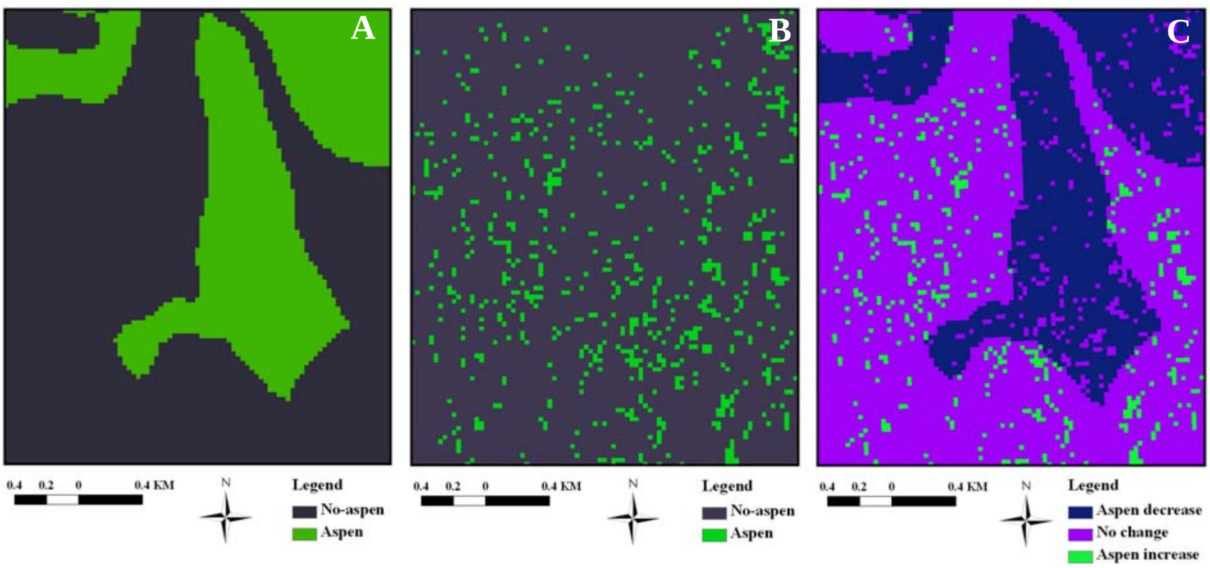


Accuracy assessment of the 2005 and 1987 image classification was performed using a total of 355 and 375 square polygons (28.5 m × 28.5 m), respectively, which were randomly generated using Hawth's tool in ArcMap 9.2. Accuracy assessment was performed using digital aerial photographs from September, 2005 in 3-band (Red, Green, Blue), 8-bit Digital Orthorectified Quadrangles (DOQ) format with 1m resolution (USDA Farm Service Agency Aerial Photography Field Office and USDA Forest Service). Square polygons having aspen at any abundance in the digital aerial photography was checked against the pixels that were classified as aspen, while all other polygons were checked against the pixels classified as no-aspen. There were no high resolution aerial photographs available for 1987, so the 28.5 m × 28.5 m polygons having full aspen cover in the 2005 photographs were assumed to have aspen presence in 1987. Similarly, polygons with no aspen in 2005 and with no history of aspen-excluding events (e.g., fire, clearcut) between 1987–2005 were assumed to have aspen absence in 1987. The polygons for the 1987 image accuracy assessment, therefore, only included areas with approximately 100% aspen cover and 0% aspen cover, while the polygons for the 2005 image included varying amount of aspen cover.

2.3. Aspen Change Detection

Two separate change detections were performed. First, the 1920 aspen map was compared to the 2005 aspen map to estimate longer-term aspen changes. Second, the 1987 and 2005 aspen maps were compared to estimate shorter-term aspen changes. Both comparisons used simple image differencing, which is a pixel-by-pixel comparison method that resulted in three different classes: aspen decrease, no-change, and aspen increase. Using these classes, total areas of aspen decrease, no-change, and aspen increase within the entire study region were estimated (Figure 5).

Figure 5. Examples of local-scale aspen changes between 1920 and 2005. Simple image differencing was performed using 1920 (a) and 2005 (b) aspen presence and absence maps, which resulted in three different classes: aspen decrease, no-change, and aspen increase.



In addition, statistical samples of all pixels were taken using 300 square polygons which were randomly generated throughout the study region using Hawth's tool in ArcMap 9.2. Each square polygon included 100 pixels (10 pixels × 10 pixels in dimension, 8.12 ha area) (Figure 1). The number of pixels, which is also the percent estimate, of aspen decrease, aspen increase, and no-change from both periods was then estimated within each polygon. The estimates of aspen decrease and aspen increase were used for statistical analysis with other variables to further analyze patterns of aspen changes.

2.4. GIS-Derived Variables

Current GIS layers of vegetation cover types, forest harvest, forest stand age, livestock grazing, and fire were acquired from the Forest Service. All shapefiles were: (1) projected in UTM Zone 12N, NAD 1927 projection and datum; (2) subset to the study area, and (3) converted into a raster format with 28.5 m × 28.5 m pixels. Then the pixels corresponding to the 300 randomly-generated, square polygons were extracted for statistical analysis (Figure 1). This random sampling included five vegetation cover type classes: (1) grass and brush; (2) tall sage and grass mix; (3) Douglas-fir; (4) lodgepole pine, and (5) mixed conifer. The sampled grazing classes were: (1) no-grazing; (2) cattle-grazing; (3) sheep-grazing, and (4) combined grazing units (i.e., allotments grazed both by cattle and sheep). The forest harvest samples included three classes: (1) nonforested land; (2) recently clearcut forests that only have seedlings 2.5 cm in diameter or <30 cm in height, and (3) no recent cut which included saplings 2.5–7.5 cm in diameter, poles 7.5–17.5 cm in diameter, and mature trees >17.5 cm in diameter. The forest stand age samples included four classes: (1) 0–50 years; (2) 50–100 years; (3) 100–200 years, and (4) 200–300 years.

2.5. Statistical Analysis

Changes from the two time periods were analyzed separately. For each time period, a multivariate analysis of variance (MANOVA) model was constructed with aspen decrease and aspen increase as response variables. Grazing, forest harvest, stand age, and vegetation cover types were used as predictor (categorical) variables with all possible interaction terms. Fire was added into this model as a covariate due to the limited sample size distribution in the burned polygons (n = 15 burned polygons). When a predictor variable was statistically significant, all pair-wise post hoc comparisons were performed using Tamhane's test with Bonferroni corrections to determine where significant differences were found.

3. Results

3.1. Aspen Maps and Image Classification

Spectral separation of aspen from the dominant vegetation cover types of conifer and sagebrush-grassland in the Landsat image subset was successful (Figure 2). MTMF classification performed well with aspen spectra. The 1987 aspen presence/absence classification had 93% overall accuracy. Its user's accuracy was 85% and 95% for aspen and no-aspen classes, respectively, while producer's accuracy was 83% and 95% for aspen and no-aspen classes, respectively (Table 1). The 2005 aspen presence/absence classification had 92% overall accuracy. User's accuracy was 80% and 96% for aspen and no-aspen classes, respectively, while producer's accuracy was 87% and 93% for aspen and no-aspen classes, respectively (Table 2).

Table 1. 1987 Landsat image classification accuracy assessment.

Observed/Classified	Aspen	No-aspen	Row Total
Aspen	73	13	86
No-aspen	15	274	289
Column total	88	287	
Producer's accuracy	83%	95%	
User's accuracy	85%	95%	
Overall accuracy	93%		

Table 2. 2005 Landsat image classification accuracy assessment.

Observed/Classified	Aspen	No-aspen	Row Total
Aspen	80	20	100
No-aspen	12	263	275
Column total	92	283	
Producer's accuracy	87%	93%	
User's accuracy	80%	96%	
Overall accuracy	92%		

3.2. Aspen Change: 1920–2005

Aspen classification models indicated that 5.8% of the study area had aspen in 1920, while 6.6% was aspen in 2005. Aspen change detection indicated that 5.5% of the study area experienced aspen decline, while 6.2% experienced aspen increase resulting in 0.8% net increase in aspen cover over the 85-year period. Pixel-by-pixel comparison indicated that 94.5% of the 17,479 ha classified as aspen in 1920 experienced aspen decline, while 18,831 ha in other areas of the Targhee National Forest experienced aspen increase.

The MANOVA model results indicated that all predictor variables were statistically significant in aspen changes over this time period (Table 3), although none of the interaction terms was significant. Grazing, forest harvest, and vegetation cover types were significant in both aspen increase and aspen decline (all p-values <0.05), while stand age was significant in aspen decrease only ($p = 0.05$). Specifically, cattle-grazed areas had significantly greater aspen increase, while sheep-grazed areas had significantly greater aspen decrease compared to ungrazed areas ($p = 0.041$ and 0.016, respectively) (Figure 6a). Compared to nonclearcut forests, clearcut forests had significantly greater aspen increase and decrease (both p-values <0.001) (Figure 6b). Douglas-fir forests had significantly greater aspen decrease than lodgepole pine forests ($p < 0.001$) (Figure 6c), while Lodgepole pine forests had significantly greater aspen increase compared to sagebrush-grassland ($p < 0.001$) and Douglas-fir forests ($p < 0.001$) (Figure 6c). Stand age class of 0–50 years had significantly greater aspen decrease compared to stand age class of 200–300 years ($p < 0.001$) (Figure 6d).

Figure 6. Aspen change patterns in the 1920–2005 time period. Aspen increase (positive grey bars) and aspen decrease (negative black bars) were simultaneously analyzed as two response variables in a MANOVA model. Grazing, forest harvest, and vegetation cover types were significant predictor variables in aspen increase ($p < 0.05$), while all predictor variables were significant in aspen decrease ($p < 0.05$). (a) Aspen changes patterns and grazing; (b) Aspen change patterns and forest harvest; (c) Aspen change patterns and vegetation cover type (LP pine = Lodgepole pine); (d) Aspen change patterns and forest stand age.

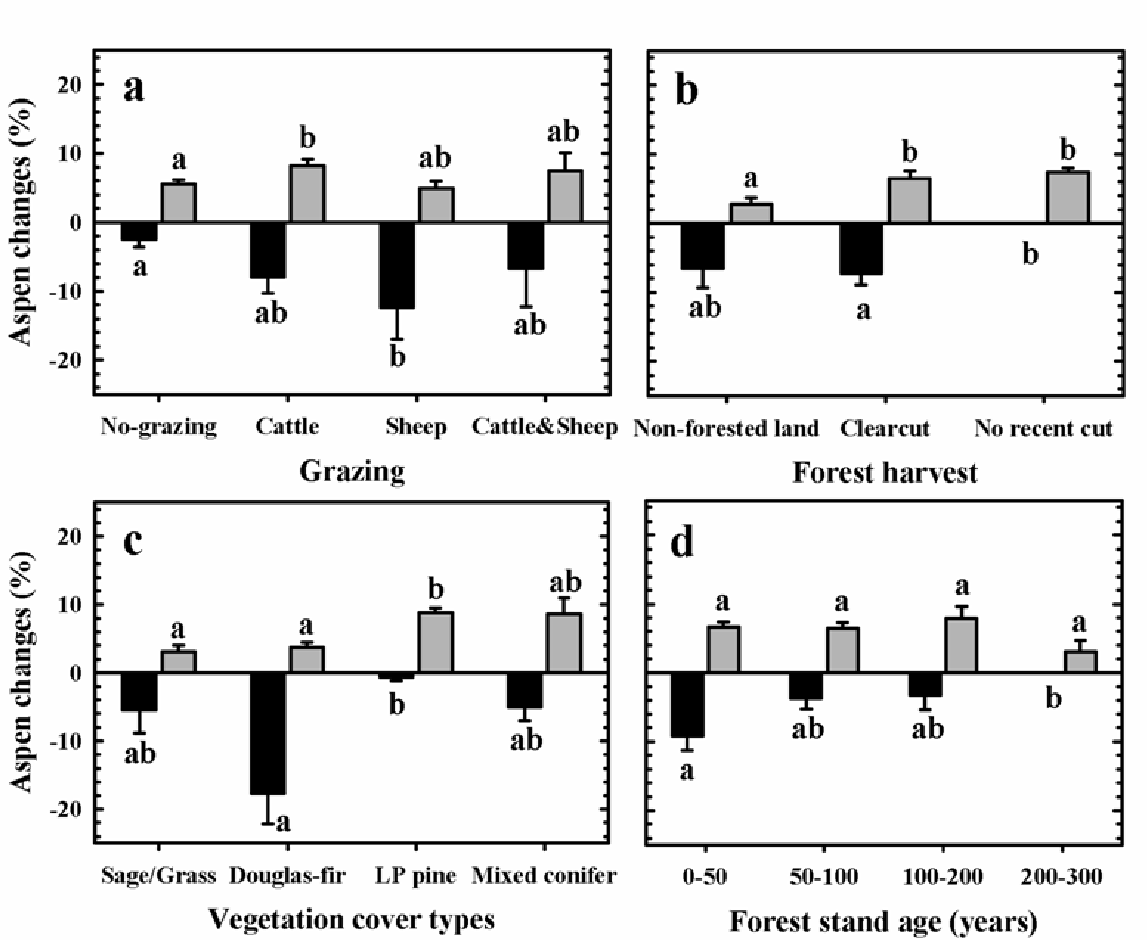


Table 3. Predictor variables examined with aspen change patterns over the two time periods.

Predictor variables	Aspen change patterns	MANOVA test p-values
1920–2005 period		
Grazing	Increase	0.002
	Decrease	< 0.001
Forest harvest	Increase	< 0.001
	Decrease	0.011
Stand age	Increase	0.081
	Decrease	0.05
Vegetation cover	Increase	0.001
	Decrease	0.019

Table 3. Cont.

1987–2005 period		
Grazing	Increase	0.152
	Decrease	0.006
Forest harvest	Increase	< 0.001
	Decrease	0.216
Stand age	Increase	0.187
	Decrease	0.05
Vegetation cover	Increase	< 0.001
	Decrease	0.674

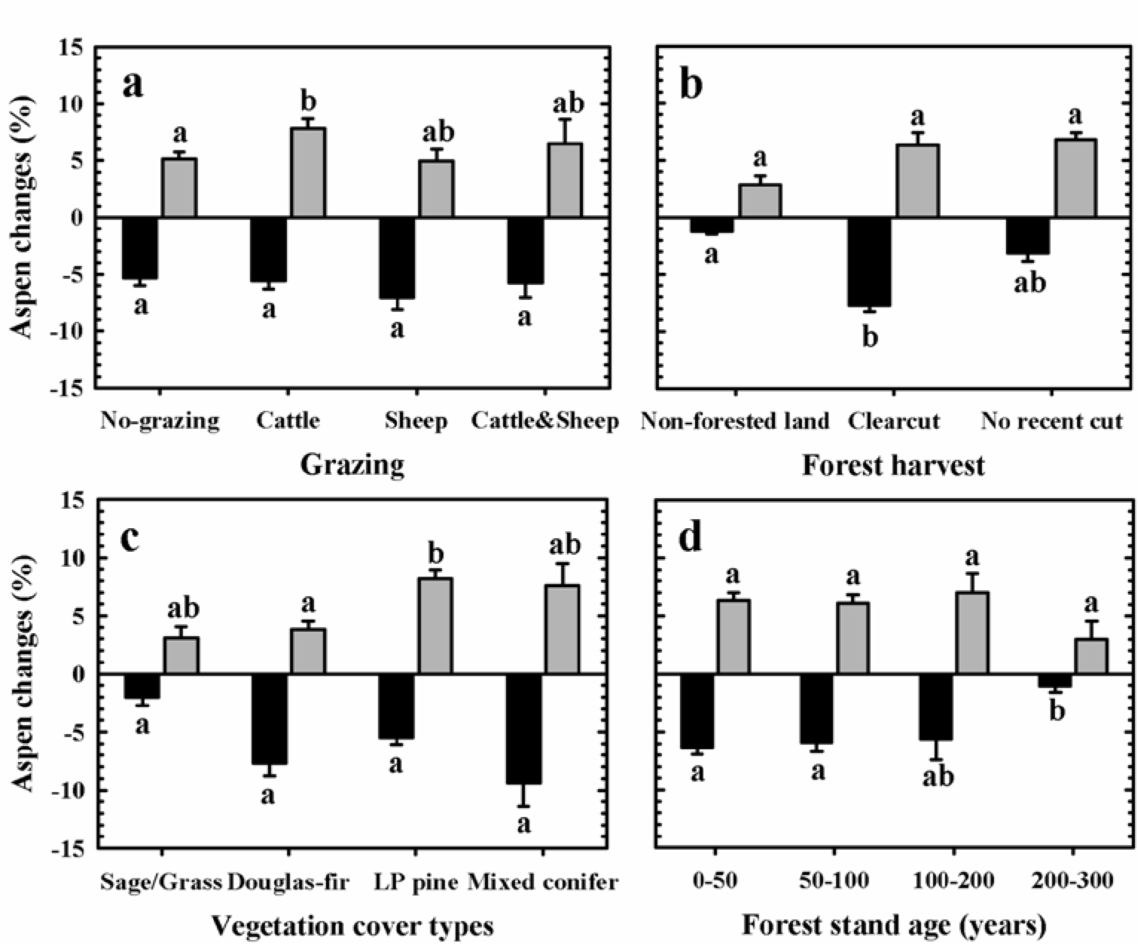
3.3. Aspen Change: 1987–2005

In 1987, 6.3% of the study area was classified as aspen, while 6.6% of the area was classified as aspen in 2005 indicating a 0.3% net increase in aspen cover over this period. Change detection indicated that 5.6% of the study area experienced aspen decline, while 5.9% experienced aspen increase. Pixel-by-pixel comparison indicated 89.5% (17,000 ha) of the 19,000 ha classified as aspen in 1987 experienced aspen decline by 2005, while 17,800 ha in other parts of the study area were classified as new aspen in 2005.

The MANOVA model results indicated that all of the predictor variables were statistically significant in aspen changes over this time period (Table 3). Grazing and vegetation cover types were significant in aspen increase only ($p = 0.006$ and < 0.001, respectively), while forest harvest and stand age were significant in aspen decrease only ($p < 0.001$ and 0.05, respectively). Specifically, cattle-grazed areas had significantly greater aspen increase compared to ungrazed areas ($p = 0.025$) (Figure 7a). Aspen decrease was significantly greater in clearcut forests compared to nonclearcut forests ($p < 0.001$) (Figure 7b). Lodgepole pine forests had significantly greater aspen increase than Douglas-fir forests ($p = 0.005$) (Figure 7c). Stand age classes of 0–50 years and 50–100 years had significantly greater aspen decrease compared to stand age class of 200–300 years ($p = 0.003$ and $p = 0.008$, respectively) (Figure 7d).

Only one of the interaction terms was significant. Grazing and vegetation cover type interaction was significant in aspen decrease ($p = 0.016$), but not in increase ($p = 0.265$). Specifically, aspen decline was significantly greater in ungrazed and cattle-grazed mixed conifer forests than ungrazed and cattle-grazed lodgepole pine forests, respectively ($p = 0.0006$ and $p < 0.0001$). Furthermore, aspen decline was significantly lower in sheep-grazed mixed conifer forests than sheep-grazed lodgepole pine forests ($p < 0.0001$). Aspen decline was significantly greater in cattle-grazed mixed conifer forests than ungrazed and sheep-grazed mixed conifer forests ($p < 0.0001$ and $p < 0.0001$). Aspen decline was significantly greater in sheep-grazed lodgepole pine forests than in cattle-grazed and ungrazed lodgepole pine forests ($p < 0.0001$ and $p < 0.0001$, respectively).

Figure 7. Aspen change patterns in the 1987–2005 time period. Aspen increase (positive grey bars) and aspen decrease (negative black bars) were simultaneously analyzed as two response variables in a MANOVA model. Grazing and vegetation cover types were statistically significant predictor variables in aspen increase ($p < 0.05$), while forest harvest and stand age were significant in aspen decrease ($p < 0.05$). (a) Aspen changes patterns and grazing; (b) Aspen change patterns and forest harvest; (c) Aspen change patterns and vegetation cover type (LP pine = Lodgepole pine); (d) Aspen change patterns and forest stand age.



4. Discussion

4.1. Aspen Classification

Landsat image spectral separation of aspen from the other dominant vegetation cover types of conifer and sagebrush-grassland was successful. As expected, the difference in spectral reflectance of aspen and conifer trees was greater in the fall image bands 2 and 3 compared to the summer bands 2 and 3. The difference in aspen and sagebrush-grassland spectral reflectance, however, was not large in most bands (Figure 2) possibly due to the similar phenology and timing of senescence of aspen and herbaceous vegetation. This might indicate that confusion of aspen with grassland vegetation is more common in the resulting map than with conifer vegetation cover type. MTMF unmixing technique performed well. MTMF appeared particularly sensitive to the aspen spectra and successfully detected aspen presence at any abundance. The MTMF bands were then successfully combined via the regression approach. Both the regression approach and the thresholds in the MTMF bands can be adapted and further tuned for site-specific or target-specific studies to make the MTMF classification more sensitive to a target cover type within a given area.

Overall, aspen presence/absence classification was successful and accuracies were similarly high in the 1987 and 2005 Landsat composites (Tables 1 and 2). There was no quantitative accuracy assessment available for the 1920 vegetation cover map, from which the 1920 aspen map was generated. The original map was made by the Forest Service and was likely assessed in the field at least qualitatively. It is currently considered reasonably accurate by the Forest Service. Similar to previous studies [43,44], this study only has quantitative accuracy assessment for the current aspen map, but not for the historic aspen map. Uncertainty, therefore, exists in the 1920–2005 change detection estimates.

4.2. Aspen Change Detection

Both the longer- and shorter-term aspen change detection in this study indicated three different patterns in aspen cover. First, the results indicated drastically declining aspen cover in the Targhee National Forest. Similar to local-scale studies [13,15,45,46], the results indicated that 94.5% of the aspen mapped in 1920 had declined by 2005. The shorter-term change detection indicated a lesser, but still a substantial decline of 89.5%. These estimates are also similar to the Brown *et al*. [9] regional-scale estimate of up to 80% decline in the GYE between 1956 and 2001, and Gallant *et al*.'s [47] estimate of 75% decline in a smaller area of the Targhee National Forest since the middle 1800s. Furthermore, the estimates are within the overall range of 49-96% aspen decline observed throughout the western United States since Euro-American settlement [2]. The shorter-term aspen decline estimate, however, seemed larger than expected. Possible factors that might have contributed to this potential over-estimate include over- or under-classification of aspen in one or both of the images, errors in image co-registration, and sensitivity to aspen detection threshold. Subtle changes in aspen canopy percent cover over time could have adjusted the target canopy percent cover above or below the aspen detection threshold in MTMF analysis, which could result in aspen presence/absence changes between the two dates.

Secondly, the results indicate that much of the Targhee National Forest experienced no change. Although a majority of the no-change areas have had no aspen at any time, approximately 5%–10% of the historically aspen-covered areas were classified as no-change areas. Such aspen stands have been previously documented as stable or persistent aspen and have comprised 8%–63% of the documented aspen distribution in other studies [5,43,44]. Persistent aspen stands can regenerate continuously through time without disturbance [48].

Third, the change detection found new aspen stands in areas of the Targhee National Forest where aspen were previously not mapped. This change even resulted in a net increase of 0.8% and 0.3% in aspen cover across the study area over the longer and shorter time periods, respectively. The observed trend of increasing aspen cover is similar to the Brown *et al*. [9] estimate of approximately 70% increase in the GYE over 45 years and Kulakowski *et al*.'s [44] estimate of a 14% net increase in northwestern Colorado over a century. However, the longer-term aspen increase estimate might be partially impacted by differences in minimum mapping unit sizes in the 1920 and 2005 aspen maps. The 1920 aspen map included full-canopy aspen stands >1 ha, while the 2005 aspen map detected aspen presence at lesser abundance in individual 28.5 m × 28.5 m pixels. The 2005 aspen map, therefore, potentially detected individual trees or small patches that might not have been mapped in 1920, even though they were present. In addition, the aspen increase estimate from both time periods might be partially impacted by over-classification of aspen in the Landsat image. Some conifers, grasses, and forbs were incorrectly classified as aspen in both image dates. The shorter-term aspen change detection, however, included maps from the same source with the same minimum mapping unit. Yet, this comparison still detected large increase in aspen indicating that the pattern of increased aspen cover is a widely occurring phenomenon.

Taken together, the results of this study demonstrate all possible patterns of aspen change at the regional scale. While aspen cover is declining in some parts of the Targhee National Forest, aspen is stable and even increasing in other parts. This supports the conclusions from previous regional-scale studies that documented greater spatial variability in aspen change patterns than local-scale studies [8,9,49]. Furthermore, the results of this study indicate declining, persistent, and increasing aspen over both time periods. This might indicate that spatial variability is an inherent characteristic in regional aspen dynamics that predominates over varying temporal scales. Further evidence for this inherent characteristic is also provided by the analysis of aspen change patterns with biophysical variables in this study. Grazing, resident vegetation cover type, forest harvest, and stand age all appear significantly correlated with aspen changes, but do not consistently lead to the same pattern of either aspen decline or aspen increase. This might suggest that these variables merely interact with the inherent spatial variability in aspen dynamics at a regional scale, although they appear to be causal factors of aspen change at local scales. The only variable examined in this study that showed a consistent relationship with aspen change was forest stand age. The results indicated that aspen decrease was significantly greater in younger forests compared to the oldest stands. This might indicate that aspen changes are more rapid in newly-established younger forests than in older forests. Aspen suckers establish in high density following disturbance such as fire or clearcutting [1,23]. However, the initial high density of suckers has been previously documented to rapidly decline [1]. In addition, aspen can establish as an early successional species, but later seral species of Douglas-fir can replace aspen over time [25]. These previously-documented processes support the patterns observed at a regional scale in the Targhee National Forest.

The large increases and decreases in aspen cover documented over both time periods do not appear to lead to a substantial net loss or gain at the regional scale. Pixel-by-pixel comparison for each time period indicated local aspen decline and local aspen increase, but the regional-scale change is a net aspen increase of less than one percent over both time periods. This overall pattern might suggest that aspen has had a spatially dynamic presence on this landscape over time, with a relatively consistent total cover at a regional scale, though appearing to have drastically declined or increased at local scales. Future research is needed to explicitly examine this dynamic pattern. Such research might require mapping aspen at a similar spatial extent, but with more frequent temporal sampling than presented here.

5. Conclusions

A subpixel aspen classification approach using Landsat images provides an efficient tool to detect changes in aspen cover at decadal time scales. Shorter-term aspen changes of approximately two decades can be estimated using this approach with recent and older Landsat images, while longer-term aspen changes, of approximately 85 years in this case, can be assessed by combining this method with a historical vegetation cover type map. At both time scales, this study found greater spatial variability in patterns of aspen changes than might be indicated by local-scale studies. These varying patterns appear to result in no substantial net aspen loss or gain. The varying patterns of aspen changes in the Targhee National Forest were significantly correlated with most of the biophysical variables examined, but the variables appear to interact with the inherent spatial variability in aspen dynamics resulting in diverse changes rather than consistently leading to aspen decline or aspen increase only. The observed spatial variability should be taken into consideration when developing and implementing regional aspen management and policies. Management goals might need to be diversified to address all possible trends in aspen dynamics rather than focusing on the widely documented pattern of aspen decline only.

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