In: Landscape Ecology Research Trends
Editors: A. Dupont and H. Jacobs, pp.
ISBN 978-1-60456-672-7

Chapter 2

MAPPING THE EXTENT AND DISTRIBUTION OF CONIFER COVER INCREASE IN THE GREATER YELLOWSTONE ECOSYSTEM

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Abstract

The objective of this study was to quantify the extent and distribution of conifer cover increase in the Greater Yellowstone Ecosystem (GYE) between 1985 and 1999. In many locations across the GYE, conifer forests have increased in density and expanded into grasslands and shrublands, but the actual extent of change is unknown. Accurate quantification is critical for assessment of ecological consequences, including biogeochemical cycling. The 67,156 km^2 study area was located in the GYE, encompassing parts of Montana, Wyoming, and Idaho, U.S.A. We used a combination of aerial photos, Landsat satellite imagery, and statistical methods to quantify percent conifer cover and change across the study area between 1985 and 1999. We used aerial photos to characterize the rates of conifer cover increase, and satellite imagery to estimate the spatial extent of conifer cover increase. We analyzed the spatial distribution of conifer cover increase with respect to biophysical gradients. We estimated that the area impacted by conifer cover increase between 1985 and 1999 was 685,075 ha (~10% of the study area). The majority (87%) of that area was existing conifer forest that increased in density, while the remainder was grassland and shrubland that was encroached upon by conifer forest. Conifer cover increase was more common at lower elevations and on northerly aspects. The significance of this study is that it demonstrates an integrated approach to answering critical questions about the extent and rate of conifer cover increase across a large region. This study represents an important step towards improved understanding of the scope of conifer cover increase, potential drivers, and consequences for carbon dynamics.

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Introduction

Increases in the extent and density of woody vegetation are pervasive in many regions worldwide (Arno & Gruell, 1986; Archer et al., 1995; Kullman & Engelmark, 1997; Mast et al., 1997; Knapp & Soulé, 1998; Rupp et al., 2001; Soulé et al., 2003; Turner & Krannitz, 2001). Accurate quantification of the extent and distribution of this phenomenon are critical for assessment of ecological consequences, including biogeochemical cycling (Houghton et al., 2000), susceptibility to insect outbreak (Lynch et al., 2006), and fire behavior and risk to human communities (Arno & Brown, 1989). Carbon sinks attributed to increases in the extent and density of woody vegetation, for example, are hypothesized to account for a significant fraction of the "missing sink" in global carbon budgets (Houghton et al., 1999; Schimel, 2002, King et al., 2007), yet knowledge of the spatial extent and distribution of this phenomenon are lacking.

Repeat historical photography of sample locations throughout the Greater Yellowstone Ecosystem (GYE) documents widespread changes in the structure and composition of conifer forests and adjacent grasslands and shrublands (Gruell, 1983; Meagher & Houston, 1998; Powell & Hansen, 2007). While conspicuous disturbances like fire have been well studied, more subtle dynamics associated with vegetation succession are occurring across large areas, but present a greater challenge for regional quantification (Coops et al., 2007). In many locations across the GYE, conifer forests have invaded nearby shrublands, grasslands, and hardwood forests (Arno & Gruell, 1986; Powell & Hansen, 2007). In existing conifer woodlands and forests, notable increases in density have been documented (Arno et al., 1997; Powell & Hansen, 2007). In this paper we refer to both the changes in the extent and density of conifer forests and woodlands as conifer cover increase. These changes are likely associated with changes in climate (Miller & Halpern, 1998) and atmospheric composition (Soulé & Knapp, 1999), suppression of fires (Arno & Gruell, 1986), and dynamic grazing regimes (Butler, 1986).

Subtle changes associated with conifer cover increase present a challenge for regional quantification. While rates of conifer cover change can be accurately measured by manual aerial photo interpretation (Soulé et al., 2003; Powell & Hansen, 2007), satellite detection of conifer cover increase across large landscapes is more difficult. Harsh climate, poor soils, and a short growing season result in generally slow conifer growth rates in the GYE, rendering change associated with conifer cover increase relatively subtle over the interval of moderate resolution (30 m) Landsat TM/ETM+. As a result, the spatial distribution and extent of these changes remain unquantified.

Traditionally, land cover maps derived from satellite remote sensing relied on thematic classifications that depicted fixed edges between classes. Subtle changes associated with conifer cover increase, however, are not easily addressed in a thematic context. GYE vegetation has previously been mapped thematically, with some classes representing mixtures, such as conifer and herbaceous (Parmenter et al., 2003). These mixed classes, however, contained high biophysical variability, and therefore were unable to support estimates of compositional and structural changes that did not involve transitions between discrete classes. Subtle increases in conifer cover were often undetected as a result. In this study, we sought to improve upon the characterization of conifer forests in the GYE by using a continuous modeling approach. We modeled conifer cover along a gradient between pure conifer and pure grassland-shrubland. Continuous estimates of vegetation and biophysical variables tend to more accurately represent natural gradients (White et al., 1997; Atkinson, 1999; Cohen et al., 2003; Hansen et al., 2003) and have become increasingly relied upon as inputs to ecosystem and biogeochemical models (Running et al., 1999).

The intent of this study was to focus solely on conifer cover increase not associated with forest regeneration following fire, logging, or other stand replacing disturbance. Many remote sensing studies have focused on changes associated with forest harvest (Cohen et al., 2002), forest regeneration (Fiorella & Ripple, 1993), wildfire (Hudak & Brockett, 2004), urbanization (Qi et al., 2004), agricultural expansion (Guild et al., 2004), and agricultural abandonment (Brown, 2003), among other trajectories of forest change. For this reason, we have chosen to exclude from the analysis areas that have recently burned, or that have a marked anthropogenic footprint, such as agricultural, urban, and logging areas.

The objective of this study, therefore, was to quantify the extent of conifer cover increase in the GYE between 1985 and 1999, and analyze the distribution of change with respect to biophysical factors. We present methods for estimation of conifer cover and change in conifer cover between 1985 and 1999 across a large portion of the GYE. We quantified the rates of conifer cover increase for a large sample of sites using a time series of aerial photos. We then spatially quantified the extent of conifer cover change using multi-temporal Landsat imagery.

Methods

Study Design

We used a combination of aerial photos, Landsat satellite imagery, and statistical methods to quantify conifer cover across the study area for 1985 and 1999. We developed reference data, including percent conifer cover, from a time series of aerial photos to characterize the rates of conifer cover increase. Based on these reference data, we developed empirical regression models with Landsat data to predict pixel-level percent conifer cover across the study area for 1985. We then performed satellite image change detection to determine where conifer cover increase had occurred between 1985 and 1999. Then, to estimate the percent conifer cover for 1999, we derived the average rates of conifer cover change from aerial photo interpretation, and applied these rates to the 1985 pixels. Finally, we analyzed the spatial distribution of conifer cover increase with respect to biophysical gradients.

Study Area

The GYE encompasses parts of Montana, Wyoming, and Idaho, with Yellowstone and Grand Teton National Parks at its core. The study area was a 67,156 km^2 portion of the GYE (Figure 1). The GYE contains a diversity of biotic and abiotic conditions, with wide ranging elevation (969 m to 4,198 m), climate, and soils.

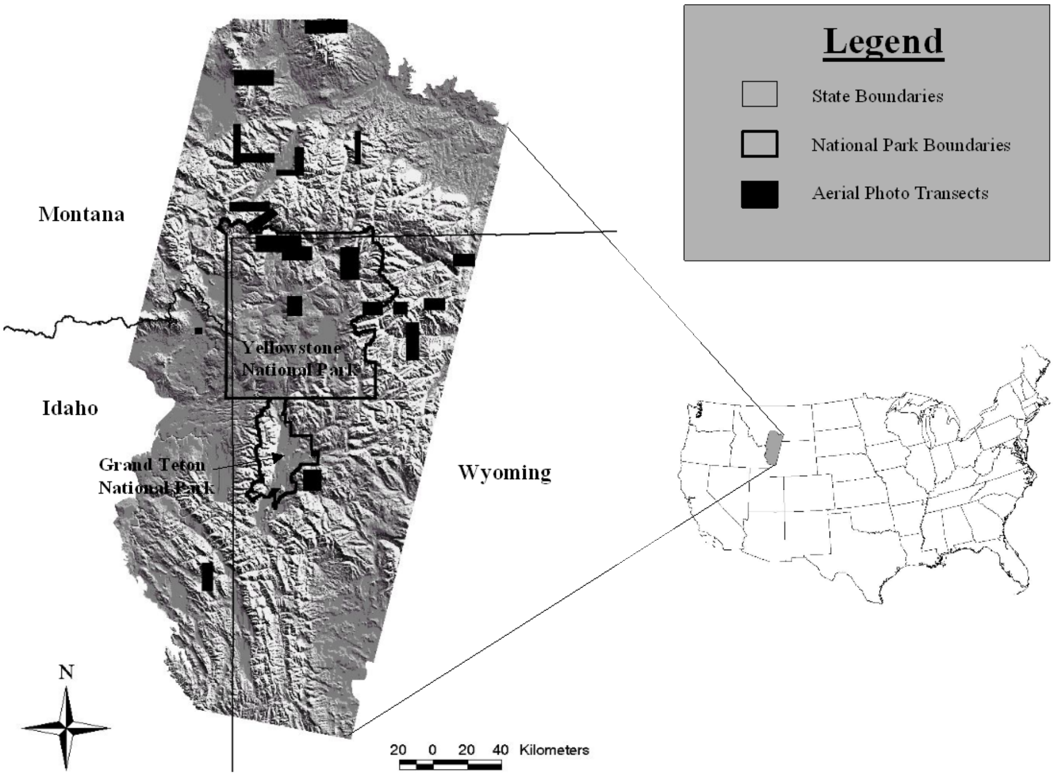

Figure 1. Study area within the GYE, with aerial photo transects shown as black strips.

The distribution of vegetation types in the GYE (Despain, 1990) is governed by steep abiotic gradients (Hansen et al., 2002), disturbance regimes (Arno & Gruell, 1986; Littell, 2002), and land use (Hansen et al., 2000; Parmenter et al., 2003). Lower elevation forests and woodlands are dominated by Douglas-fir (*Pseudotsuga menziesii*), Rocky Mountain juniper (*Juniperus scopulorum*), lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), and limber pine (*Pinus flexilis*). The fire regime in these lower elevation forests and woodlands has been historically characterized as frequent with low severity (Arno & Gruell, 1986), or in some areas as mixed frequency and severity (Littell, 2002). These forests and woodlands have generally been heavily impacted by fire suppression, grazing, and logging. Subalpine and higher elevation forests of the GYE are dominated by Douglas-fir, lodgepole pine, engelmann spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and whitebark pine (*Pinus albicaulis*). The fire regime in these higher elevation forests has been historically characterized as infrequent with high severity (Romme, 1982; Romme & Despain, 1989), and there has been notably less impact from fire suppression (Turner et al., 2003), grazing, and logging.

Table 1. Landsat satellite imagery used in this study

Sensor	Path/Row	Date
Landsat TM	38/28	14 June 1985
Landsat TM	38/29	14 June 1985
Landsat TM	38/30	14 June 1985
Landsat TM	38/28	16 September 1985
Landsat TM	38/29	16 September 1985
Landsat TM	38/30	16 September 1985
Landsat ETM+	38/28	13 July 1999
Landsat ETM+	38/29	13 July 1999
Landsat ETM+	38/30	29 June 2000
Landsat ETM+	38/28	15 September 1999
Landsat ETM+	38/29	15 September 1999
Landsat ETM+	38/30	15 September 1999

Aerial Photo Interpretation

We collected reference data from 2,144 aerial photo plots distributed along 20 transects (Powell & Hansen, 2007) (Figure 1). The transects were designed to represent the range of elevation, aspect, and vegetation types in the GYE. Within each transect, we used stratified random sampling (by elevation, aspect, and vegetation type) to generate 0.81 ha plots (equivalent to 3x3 Landsat pixels). A plot was sampled if it was not immediately adjacent to another plot, it was not located in a distorted region of the photo, and it did not contain discernable rock, water, ice, snow, agricultural or urban areas, roads, or other anthropogenic features. We used color or color infrared photos at 1:15,840, 1:24,000, or 1:30,000 scales, acquired as closely as possible to the years 1985 and 1999 for each transect.

For each time period, we used the point intercept method (Parmenter et al. 2003; Powell & Hansen, 2007) to interpret the fractional composition of coniferous forest, deciduous forest, and grassland-shrubland. We placed a 10-dot matrix over each plot and counted the intersections with vegetation components in 10% increments (e.g., 5 dots on conifer and 5 dots on grassland-shrubland = 50% conifer/50% grassland-shrubland). The response variable of interest for this study was the percent composition of conifer relative to grassland-shrubland. The rate of conifer cover increase between 1985 and 1999 was calculated as the total change per plot (e.g., 30% to 50% = 20% change) divided by the number of years between measurements. We calculated the rates of increase stratified by cover type: grassland-shrubland (0% conifer cover), conifer woodland (1-69% conifer cover), and conifer forest (70-100% conifer cover). We excluded samples containing evidence of previous disturbance from fire or logging, or samples that were not “eligible” for increase; that is, in 1985 they already had a 100% closed conifer canopy. For the purposes of this study, rates of conifer cover increase were calculated only from samples that exhibited conifer cover increase.

Satellite Image Processing

We used 2 dates of 1985 Landsat TM and 2 dates of 1999 Landsat ETM+ imagery for each of 3 scenes (Table 1). The 1999 Landsat ETM+ images were acquired with Level-1G radiometric and geometric correction. We selected the summer dates as reference images to which all other images were geometrically corrected. Image to image geometric correction using ground control points resulted in root mean square errors less than 0.5 pixels. We radiometrically and atmospherically corrected all images to surface reflectance values using the COST radiometric normalization routine (Chavez, 1996), including haze correction. We then computed the Tasseled Cap transformation for each image (Kauth & Thomas, 1976), using coefficients from Crist (1985) applied to reflectance values. We mosaiced each of the three scene assemblages to create single season images. After mosaicing, we masked out unwanted pixels, such as clouds, cloud shadows, water, rock, ice, snow, urban areas, agricultural areas, and bad scan lines (totaling nearly 20,000 km^2).

Percent Conifer Cover 1985

We developed a 1985 thematic vegetation classification using classification tree analysis in S-Plus (Venables and Ripley, 1997; MathSoft, 1998). To build the classification tree model, we used the vegetation type determined by aerial photo interpretation (conifer forest, grassland-shrubland, and deciduous forest) as the response variable. For predictor variables, we used 1985 summer and fall Landsat TM bands 1-5 and 7, Tasseled Cap brightness, greenness, and wetness, Tasseled Cap difference images between summer and fall, and elevation, slope, and aspect derived from a 30 m digital elevation model. We randomly selected two-thirds of the aerial photo reference data to build the classification tree model and the remaining one-third to independently validate the classification accuracy. The final classification tree rules were applied across the study area, and the conifer forest and grassland-shrubland pixels were isolated for further analyses.

We then modeled 1985 percent conifer cover along a continuous gradient between conifer forest and grassland-shrubland. First, we integrated the spectral reflectance data (1985 TM summer and fall bands 1-5 and 7, and brightness, greenness, and wetness) into a single index using canonical correlation analysis. We then used reduced major axis (RMA) regression to develop a linear relationship ($y = a + \beta x + \varepsilon$) between the canonical correlation index (x) and percent conifer cover (y) by calculating the slope (β (sign (+/-) determined by sign of correlation between x and y) and intercept (a) as follows (after Curran & Hay, 1986):

slope:

$$\beta = \sigma y / \sigma x \tag{1}$$

intercept:

$$a = \overline{y} - \overline{\beta}x \tag{2}$$

Where: σ = sample standard deviation; $\overline{y}$ and $\overline{x}$ = sample means

We then applied the regression model to all conifer forest and grassland-shrubland pixels to predict the 1985 percent conifer cover across the study area.

To evaluate the RMA regression model, we calculated the coefficient of determination (R^2). To independently validate the model, we used the remaining one-third of the reference data to compare observed values to model predictions. We regressed observed versus predicted percent conifer cover values and analyzed the coefficient of determination (R^2), the root mean square error (RMSE), and the model variance ratio (standard deviation of predicted values divided by the standard deviation of observed values).

Conifer Cover Change 1985-1999

We used multi-temporal image analysis to quantify the spatial extent of conifer cover increase between 1985 and 1999. First, for the fall images from both years, we transformed the Landsat spectral data using the Disturbance Index (Healey et al., 2005), which was developed to take advantage of the strong correlation between Tasseled Cap brightness and wetness in change-space:

Disturbance Index = (Tasseled Cap brightness – (Tasseled Cap greenness + Tasseled Cap wetness))

We then differenced the two Disturbance Index images by subtracting the 1985 image from the 1999 one. The differenced image clearly depicted trajectories of forest change between 1985 and 1999, with negative values corresponding to conifer cover increase pixels. To determine the appropriate spectral threshold for change classification, we analyzed a boxplot of spectral value distributions from the difference image for locations of conifer cover increase, conifer cover decrease (e.g., logging), and no-change. From these distributions, we classified all pixels as either conifer cover increase or other (which included both no-change as well as conifer cover decrease).

To minimize errors of commission, we masked out locations where we knew conifer cover increase was unlikely to occur. From analysis of the aerial photo reference data for the 14 year time period between 1985 and 1999, we determined that over 90% of conifer cover increase occurred within 30 m of the nearest conifer stand. Therefore, we restricted the extent of potential conifer cover increase to within this distance. Additionally, to focus the analysis solely on conifer cover increase not associated with forest regeneration following logging or recent fire, we masked out the locations of logging and fire prior to 1985 by compiling publicly available stand and fire GIS data layers for each of the national forests (Beaverhead-Deerlodge National Forest, Bridger-Teton National Forest, Caribou-Targhee National Forest, Custer National Forest, Gallatin National Forest, and Shoshone National Forest) and national parks (Grand Teton National Park and Yellowstone National Park) within the study area. We validated the accuracy of the conifer cover increase map with independent data derived from the aerial photo interpretation.

We analyzed the spatial distribution of conifer cover increase with respect to biophysical gradients, specifically elevation and aspect. We used an elevation threshold of 2,316 m to distinguish between high and low elevations. This threshold roughly corresponds to the elevation of the Yellowstone plateau, as well as the upper limit of Douglas-fir and the lower limit of whitebark pine. To distinguish between conifer expansion and conifer densification, we analyzed the changes with respect to 1985 starting conditions. Changes that occurred in locations with no conifer cover were classified as conifer expansion, while changes that occurred in locations with existing conifer cover were classified as conifer densification. We characterized the spatial distribution of change by calculating the proportions of conifer cover increase within elevation and aspect classes.

Percent Conifer Cover 1999

Change detection enabled quantification of the spatial extent of conifer cover change. To estimate the rate of conifer cover increase, we used aerial photo interpretation. For pixels classified as conifer cover increase between 1985 and 1999, we estimated the 1999 percent conifer cover by applying the mean 14 year change by cover type to the 1985 percent conifer cover pixel value. For pixels not classified as conifer cover increase, the 1999 conifer cover value remained the same as 1985.

Results

Percent Conifer Cover 1985

The overall accuracy of the 1985 thematic vegetation classification was 84% (Table 2).

Since the purpose of creating this map was to isolate the conifer forest and grassland-shrubland pixels, we were not concerned about misclassification error between these two classes. Deciduous forest comprised a mere 5% of the natural vegetation of the GYE in 1985. The remaining 95% of the pixels were subset to develop a map of percent conifer cover. The RMA regression equation between the spectral index and percent conifer cover was:

$$\text{1985 percent conifer cover} = 130.53 + (1112.38 * \text{spectral index}) \tag{3}$$

Table 2. Error matrix for 1985 thematic vegetation classification

Classified Data	**Reference Data**			**Row total**	**Omission Error (%)**	**Commission Error (%)**
	Conifer	**Deciduous**	**Grass-Shrub**			
Conifer	**320**	11	21	352	11	9
Deciduous	3	**36**	1	40	25	10
Grass-Shrub	36	1	**39**	76	36	49
Column total	359	48	61	**468**		

Overall accuracy = 395/468 = 84%.

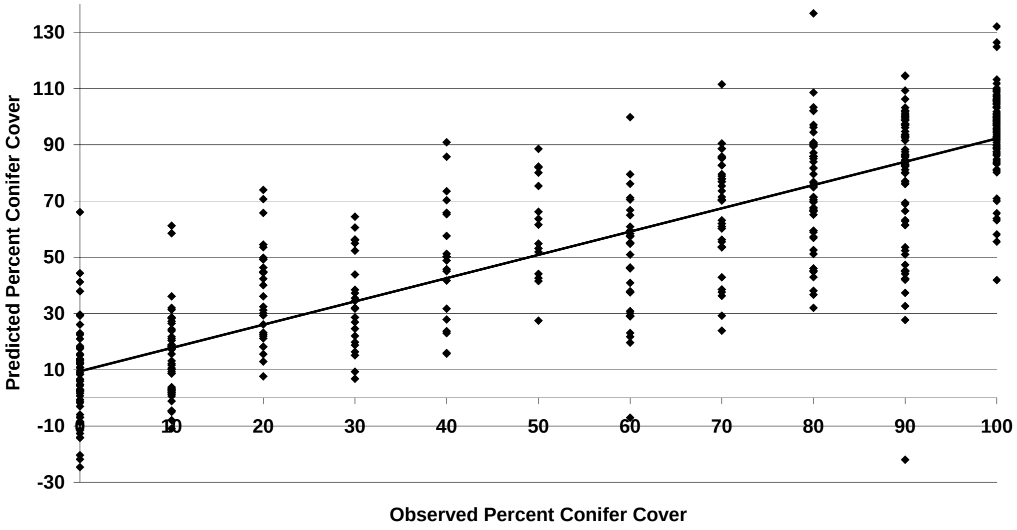

Figure 2. Validation of 1985 percent conifer cover by regression between observed and predicted values.

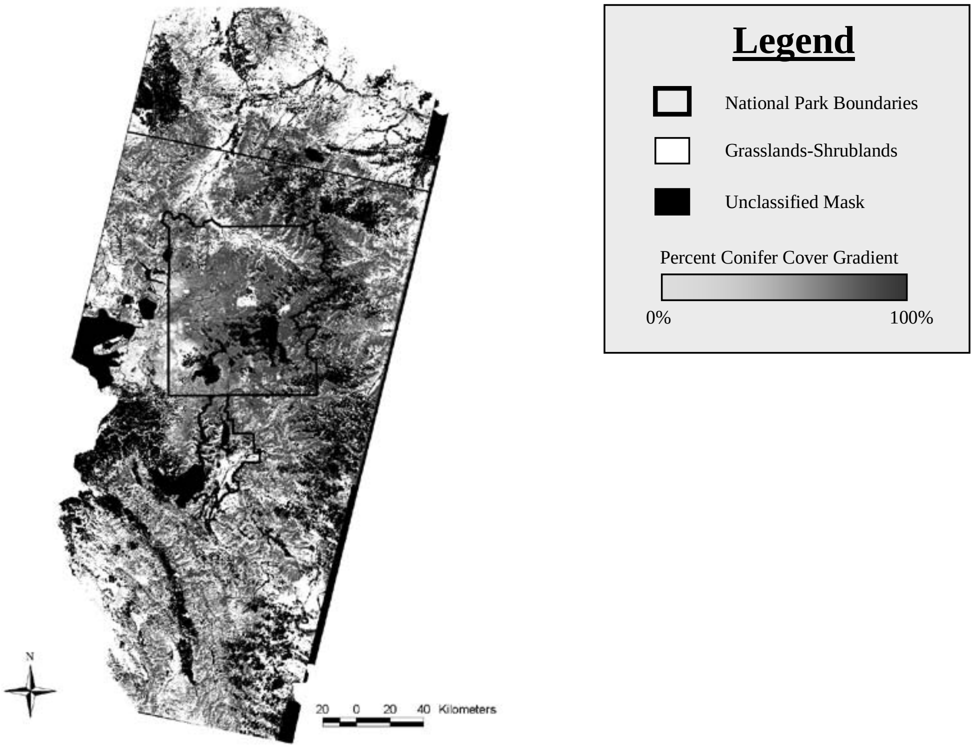

Figure 3. Map of predicted 1985 percent conifer cover.

The RMA regression model explained a large amount of the variation in percent conifer cover, with an R^2 of 0.73. The validation of the regression model against withheld data, by regressing observed versus predicted values, yielded an R^2 of 0.72 (Figure 2). The RMSE between observed and predicted values was 13.5 percent and the model variance ratio was 0.98.

The map of 1985 percent conifer cover (Figure 3) showed that grassland-shrubland dominated the lower elevation valleys to the north and south of Yellowstone National Park. High conifer cover forest predominated within Yellowstone National Park and the surrounding higher elevation mountain ranges, while low conifer cover forest predominated in the lower elevation forests outside Yellowstone National Park and adjacent to the grassland-shrubland valleys.

Conifer Cover Change 1985-1999

Overall classification accuracy for conifer cover increase versus “other” was 76% (Table 3). Omission error for conifer cover increase was 33% but was partially balanced by a commission error of 18%.

The area of conifer cover increase in the GYE between 1985 and 1999 was 685,075 ha (Figure 4), or approximately 10% of the study area, and was especially evident in the lower elevation conifer forests outside of Yellowstone National Park. Conifer expansion resulted in the conversion of 90,323 ha of grassland-shrubland to conifer woodland. The majority of this conifer expansion (63%) occurred at lower elevations (< 2,316 m), where it was slightly more common on northerly aspects (51%). Conversely, at higher elevations, conifer expansion was more common on southerly aspects (57%). Conifer densification resulted in the cover increase of existing conifer forest on 594,752 ha. The spatial distribution of conifer densification was skewed towards lower elevations (54%) and northerly aspects (54%). At lower elevations, densification was more common on northerly aspects (58%), while at higher elevations, it was slightly more common on southerly aspects (51%).

Table 3. Error matrix for 1985 – 1999 conifer cover increase map

Classified Data	Reference Data		Row total	Omission Error (%)	Commission Error (%)
	Increase	Other			
Increase	**58**	13	71	33	18
Other	29	**74**	103	15	28
Column total	87	87	**174**		

Overall accuracy = 132/174 = 76%.

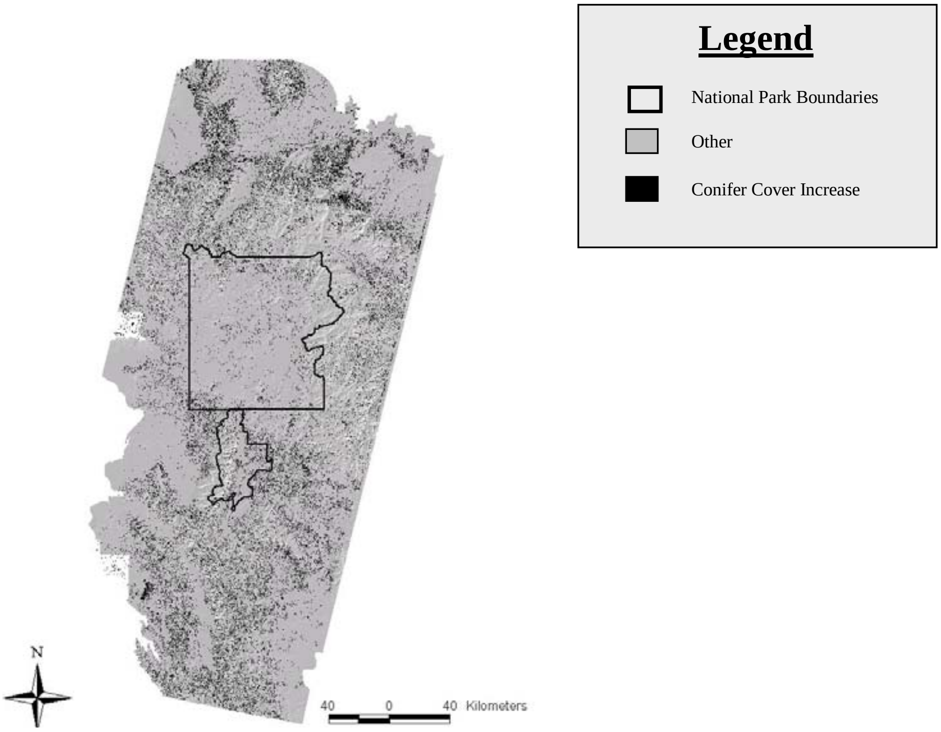

Figure 4. Distribution of conifer cover increase between 1985 and 1999.

Percent Conifer Cover 1999

Mean annual rates of conifer cover increase varied between 0.55% and 0.72% per year depending on vegetation type (Table 4). These rates equated to average 14 year increases in conifer cover between 7.71% for conifer forest to 10.14% for grassland-shrubland. Application of these average increases to 1985 percent conifer cover pixel values yielded 1999 percent conifer cover estimates. Validation of the 1999 percent conifer cover map against independent withheld data, by regressing observed versus predicted values, yielded an R^2 of 0.72.

Table 4. Average annual rate of conifer cover increase (+/-standard error) and 14 year change by vegetation type

Vegetation Type (percent conifer cover)	**Average annual rate (%) of conifer cover increase (+/- SE)**	**Average 14 year increase (%)**
grassland-shrubland (0% conifer)	0.72 (+/-0.08)	10.14
conifer woodland (1-69% conifer)	0.68 (+/-0.02)	9.51
conifer forest (70-100% conifer)	0.55 (+/-0.03)	7.71

Discussion

By determining the spatial extent of conifer cover increase from satellite image change detection, and the rate of conifer cover increase from aerial photo interpretation, we were able to quantify subtle vegetation dynamics across a large portion of the GYE. The results of this study provide a complete picture of the extent and distribution of conifer cover increase in the GYE. To our knowledge, this is the first study to quantify in a spatially explicit manner the extent of conifer cover increase across a region as large and complex as the GYE.

The use of a continuous regression modeling approach for mapping conifer forests across the GYE is a substantial improvement over the use of a thematic classification approach. Previously, Parmenter et al. (2003) thematically classified conifer woodlands in the GYE with low accuracy due to the high biophysical variability represented by this class. In contrast, by modeling the 95% of the study area that fell along the gradient between pure conifer forest and pure grassland-shrubland, we were able to depict more accurately the inherent variability of this mixed class.

RMA regression was an effective technique for continuous modeling of percent conifer cover. We opted to use RMA regression because it generally does a better job than ordinary least squares (OLS) regression of maintaining the variance structure of a data set (Curran & Hay, 1986). In doing so, RMA regression tends to reduce the attenuation of predictions above the mean and the amplification of predictions below the mean (Cohen et al., 2003). The high variance ratio that we attained (0.98) was notable because of the importance of accurately mapping percent conifer cover at the lower end of the gradient, where we tended to observe significant conifer cover changes.

Conifer expansion into adjacent grasslands and shrublands between 1985 and 1999 occurred on approximately 1% of the study area, primarily at lower elevation forest-grassland ecotones (63%). The spatial pattern with respect to elevation is likely explained by the fact that there are longer growing seasons and more favorable conditions at lower elevations, as well as a greater impact from fire suppression and grazing. Conifer expansion has been previously documented at many lower elevation sites in the GYE and elsewhere (Arno & Gruell, 1986 in southwestern Montana; Mast et al., 1997 on the Colorado Front Range; Meagher & Houston, 1998 in Yellowstone National Park; Bachelet et al., 2000 in the Black Hills of South Dakota).

The remaining conifer expansion (37%) between 1985 and 1999 occurred at higher elevation forest-grassland ecotones. While conifer expansion was not as widespread in higher elevation forests, our results are nonetheless corroborated by other research documenting conifer expansion into sub-alpine meadows and grasslands of the GYE and elsewhere (Dunwiddie, 1977 in the Wind River Range in Wyoming; Butler, 1986 in the Lemhi Mountains of Idaho; Jakubos & Romme 1993, in Yellowstone National Park; Miller & Halpern, 1998 in the Oregon Cascade Range).

Conifer densification accounted for the vast majority (87%) of the total area of conifer cover increase. Conifer density increased between 1985 and 1999 on approximately 9% of the study area. Unlike conifer expansion, there was not a strong elevation trend in the distribution of conifer densification, with only a slight majority (54%) of the change occurring in lower elevation forests. Our finding of extensive conifer densification is consistent with other studies that have documented conifer densification across western conifer forests (Covington

& Moore, 1994 in northern Arizona; Arno et al., 1997 in western Montana; Soulé & Knapp, 1999 in central Oregon).

The spatial patterns of conifer cover increase with respect to elevation and aspect draw attention to the importance of soil moisture and temperature conditions for conifer seedling reproduction, establishment, growth, and survival. At lower elevations, where soil moisture is more likely a limiting factor (Daubenmire, 1968), conifer cover increase was more common on moister northerly aspects. Conversely, at higher elevations, where temperature is more likely a limiting factor (Richardson & Bond, 1991) and soil moisture is often adequate or even excessive (in the case of persistent snow pack), conifer cover increase was more common on warmer southerly aspects.

Limitations and Scope

Overall, the area that increased in conifer cover was only a small fraction of the total area that was eligible for conifer cover increase. This was likely a function of several factors. First, conifer growth rates in the GYE are relatively slow given severe climatic and abiotic conditions. Therefore, change over a 14 year time period can be rather subtle. Second, given this subtlety, spectrally discriminating change at a spatial resolution of 30 m is challenging. It is likely that for some samples, conifer cover measurably increased according to aerial photo interpretation, but was not sufficient to register a measurable spectral change.

The method presented here for continuous modeling of conifer cover and quantification of change in conifer cover offers excellent potential for use at broader spatial extents and in other regions experiencing similar forest dynamics. Conifer cover increase is a widespread phenomenon, yet we lack basic information on its rates, extent, and distribution. There is a pressing need for consistent and transparent approaches like this for implementation over large areas. We have demonstrated the utility of this approach for the GYE, despite slow conifer growth rates. With a longer and denser time series of satellite imagery, and in regions with faster rates of change, this method could be expected to yield even more accurate results.

Research and Management Implications

The results of this study lay the groundwork for further analysis of the contribution that conifer cover increase makes towards carbon sequestration in the GYE. Between 1985 and 1999, conifer cover increase across 10% of the study area likely increased the stock of aboveground carbon. However, the Yellowstone fires of 1988 were prominent during this time period as well, and therefore, the loss of aboveground carbon was likely extensive. In fire prone systems like the GYE, the accumulation of carbon, and hence fuels, associated with conifer cover increase has the potential to increase insect susceptibility (Lynch et al., 2006) and fire risk (Allen et al., 2002). As a result, sequestered carbon is of uncertain temporal duration (Sampson & Clark, 1996). Further quantification of these and other land cover dynamics, and how they relate to carbon flux is essential for understanding regional carbon dynamics.

Acknowledgements

Funding for this study was provided by the NASA Land Cover Land Use Change Program. Thank you to Jeremy Lougee, Nick Lyman, Lew Stringer, and Jason Bruggeman for aerial photo interpretation, and special thanks to Monica Turner and her support from NSF for use of aerial photos for Yellowstone National Park. Thanks also to Rick Lawrence, Lisa Graumlich, and Sean Healey for their thoughtful comments on earlier drafts.

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