HAVE FORESTS REALLY BECOME DENSER?
AN OBJECT-ORIENTED CASE STUDY OF A KEY PREMISE IN WILDFIRE POLICY

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ABSTRACT:

In the wake of numerous catastrophic wildfires, forest management policies have been implemented in recent years in the United States, including the Healthy Forest Restoration Act of 2003. A key premise underlying these policies is that fire suppression has resulted in denser forests than were present historically in some forest types. We evaluate this premise for the montane zone of the northern Front Range, Colorado. Historical photographs from 1938 and 1940 were scanned, orthorectified, and overlaid on DOQQs from 1999. Using an object-oriented image classification technique, the photos were then finely segmented and classified into two classes: tree and non-tree. Trees are heterogeneous in appearance in black and white aerial photography, so we employed separate membership functions to identify four visually distinct types: 'interior forest', 'isolated trees', 'dark forest', and 'edge forest'. A particular challenge was making the classification robust to differences in illumination across topographic features. Based on the classification of fine objects, we then calculated the % tree cover within a larger set of objects for the two time periods. We estimate that average tree density across the study area increased by 4%, with considerable spatial variation within the landscape. The results of the analysis illustrate that, consistent with tree-ring evidence, the highest increase in tree density has taken place in areas characterized by low initial density, south-facing slopes, low elevations, and ponderosa-pine domination. In contrast, the highest elevation areas dominated by mixed-conifer and lodgepole pine forests demonstrated no significant change in tree cover.

1. INTRODUCTION

Wildfires have imposed increasing economic and environmental costs in recent years. Annual appropriations to federal agencies to prepare and respond to wildland fires approached $3 billion during the years 2001-2005 (US GAO 2007). A small but increasing fraction of federal money goes toward forest treatments that aim to reduce the intensity and spread of wildfires. In 2007, the final year of the Healthy Forests Restoration Act, 13 million dollars were spent on such treatments (DOI and USDA 2007)

A key premise of fuel-reduction treatments– such as mechanical thinning and controlled burns – is that fuel loads have become heavier as a result of fire suppression activities as well as drought, insect infestations, and disease. Illustrating this is the rationale for the Healthy Forests Initiative, which aims to reduce wildfire risk: "America's public lands have undergone radical changes during the last century due to the suppression of fires and a lack of active forest and rangeland management. Our forests and rangelands have become unnaturally dense, and these unhealthy forests are vulnerable to unnaturally severe wildfires." (White House 2003).

But have fuel loads – and in particular tree density – increased everywhere since the advent of fire suppression? Numerous studies in the ponderosa pine forests of the southwestern United States indicate that fire suppression has indeed resulted in fuel accumulation and susceptibility to crown fires (Covington and Moore 1994; Fule, Covington and Moore 1997). In contrast, in the Colorado Front Range reconstruction of historic forest structures paired with tree-ring based fire history records indicate that ponderosa pine ecosystems were spatially heterogeneous, containing patches of dense stands even before fire suppression (Kaufmann, Regan, and Brown 2000; Ehle and Baker 2003; Sherriff and Veblen 2008). Generally, the degree to which forests have become denser in since the fire suppression era varies along environmental gradients (Schoennagel et al. 2004).

To complement existing tree-ring data, which is not spatially contiguous, we compared orthorectified historic aerial photography (from 1938 and 1940) to modern digital orthophoto quarter quads (DOQQs) from 1999 in the northern Front Range of Colorado. This area is dominated by ponderosa pine, but also includes mixed-conifer and lodegepole pine forests at higher elevations. Our research questions are: 1) How much has tree cover increased from 1938-1999 and 2) How has tree cover changed with respect to elevation, aspect, slope, dominant vegetation type, and historic tree cover?

To make these comparisons, we applied an object-oriented technique whereby we segmented the images into heterogeneous objects and then analyzed the objects. Object-oriented image analysis holds two primary advantages over traditional pixel-based methods. First, while pixels are classified solely on spectral and textural information, objects can also be classified on size, shape, pattern and spatial relationships. This is especially important in this case, as black and white aerial photographs have limited spectral data on which to base a classification. Secondly, while pixels are arbitrarily sized, objects vary in size to represent ecologically meaningful areas at multiple scales (e.g. groups of trees, or landscape patches) (Laliberte et al. 2004). Objects may also be used to represent areas of stability or change over time, making them well suited to change analysis.

Object-oriented analysis has been used successfully for similar forest-mapping tasks such as mapping shrub encroachment in the Southwest US (Laliberte et al. 2004), extracting forest inventory parameters (Chubey et al. 2006), and measuring woodland expansion (Pillai et al. 2005). Like these studies, we used Definiens Developer software (formerly eCognition) for our analysis.

2. METHODS

2.1 Study Area and Data

Our study area is the montane zone of the northern Front Range of Colorado, which contains parts of Gilpin, Jefferson, Boulder, and Larimer Counties (Figure 1). The montane zone is located approximately between 1830-2740m. At the lowest elevations, the montane zone is dominated by a mixture of ponderosa pine (*Pinus ponderosa)*, Douglas-fir (*Pseudotsuga menziesii*), and grasses. Prior to fire suppression, these areas were characterized by frequent fires at an interval of 10-40 years (Veblen, Kitzberger, and Donnegan 2000; Sherriff and Veblen 2007). At the higher elevations ponderosa pine and Douglas-fir still dominate on south-facing slopes, but other species such as lodgepole pine (*Pinus contorta)* and aspen (*Populus tremuloides)* can also be important on north-facing slopes. Historic fire intervals at the higher elevations were 30-100 years prior to fire suppression and included high-severity crown fires (Veblen and Lorenz 1986; Sherriff and Veblen 2008). We would expect an increase in tree density at the lowest elevations of the montane zone since these areas were historically kept open by frequent fires, but we would expect little change in tree density at the highest elevations where fires were less frequent and mixed-severity and as a consequence stands were often historically dense.

We used 39 historic aerial photographs (approximate scale 1:20,000, ~1m pixels) covering the full range of the montane zone (1737-3125m), including 26 images taken on October 25-26 1938, and 13 images taken on October 9th, 1940 (Figure 1). We orthorectified each historical image using 7-10 ground control points (GCPs) and a 10m DEM. The average root mean square (RMS) error for the control points was 16 meters. We assessed the average displacement between the orthorectified historical images and modern DOQQs taken October 10, 1999 (1m pixels), by measuring displacement at 10 non-GCP locations within each image pair.

After the orthorectification process, 13 image pairs were rejected due to poor overlay, image quality, or match of sun azimuth/elevation between the historic and modern images. This left 39 image pairs for the analysis. Before analysis, we applied a 3x3 Median filter to the historical images to minimize the effects of image grain on the segmentation procedure.

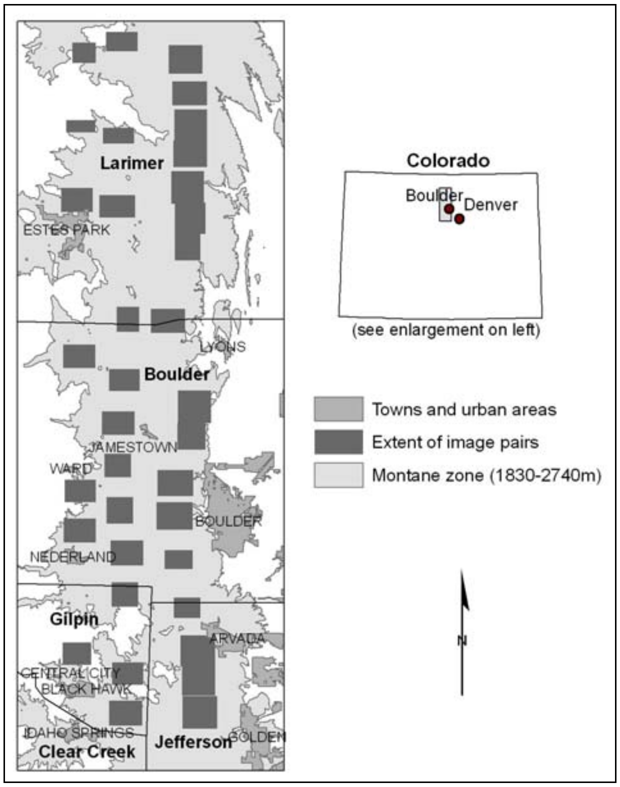

Figure 1: Study Area

2.2 Object-Oriented Image Analysis

2.2.1 Segmentation of Image Objects

The goal of segmentation was to create a single set of coarse objects that roughly approximated the size and boundaries, of the Common Vegetation Units used by the USDA Forest Service (2003). Nested within the coarse objects, we aimed to create fine objects that delineate individual trees and groups of trees in the historical images and in the modern images.

The size and shape of image objects are controlled by a set of parameters: scale, color, shape, smoothness and compactness. The average size of image objects is a function of the scale parameter, a unitless number which sets the maximum allowable heterogeneity within objects. Heterogeneity has a spectral component (the sum of standard deviations of each image band) and a shape component. The contribution of color and shape to heterogeneity is determined by the color and shape parameters, which must add up to 1. In turn, the shape parameter is comprised of compactness (the ratio of the border length and the square root of the number of object pixels) and smoothness (the ratio of the border length and the shortest possible border length). The contribution of smoothness and compactness to shape is determined by the compactness and smoothness parameters, which must add up to 1.

To derive the coarse objects (Figure 2a), we used the following criteria: scale parameter of 1000, a color parameter of 0.8, a shape parameter of 0.2, a smoothness parameter of 0.5, and a compactness parameter of 0.5. We segmented the historic and modern imagery together as if they were two bands of a single image. Thus, individual objects should delineate areas of stability and areas of change, but should not include a mixture of stability and change within a single object. The resulting objects were 24 hectares on average, with a standard deviation of 18 hectares.

To derive the two sets of fine objects (one for the historical imagery, and one for the modern imagery), we used the same parameters as for the coarse segmentation process, but a scale parameter of 5. We then merged adjacent objects with similar brightness values (spectral difference < 16 for objects of brightness >= 75, and spectral difference < 100 for objects of brightness < 75). The resulting objects were an average of 15 m^2 with a standard deviation of 138 m^2.

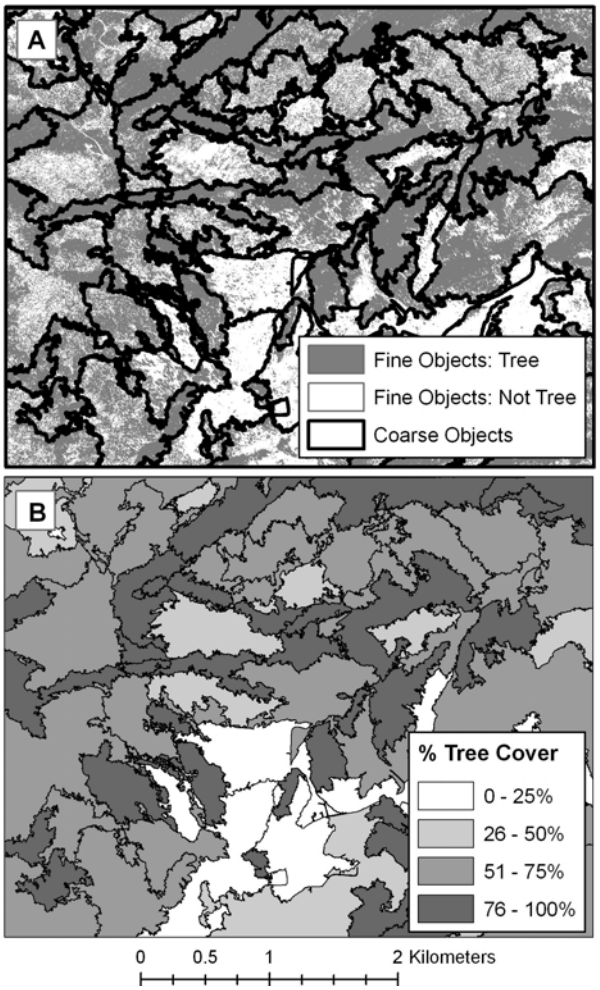

Figure 2a Segmentation and 2b Classification

2.2.2 Object Classification

We then classified the fine objects into two categories: tree and non-tree (Figure 2a). A particular challenge was making the classification robust to variations in illumination across the scene. The brightness level of trees varies depending on the level of illumination, but trees appear dark compared to the surrounding soil, rock, and grass. Thus, in addition to the "mean brightness" of each object, we calculated "mean difference to brighter neighbors" and "relative border to brighter objects" (the percentage of the border of an object that touches a brighter neighbor-object) to identify objects that were dark relative to their surroundings. Water and topographic shadows also appear dark in the image, and were also classified as "tree" in this classification of fine objects. Iteratively, we developed membership functions (both crisp and fuzzy) to identify four visually distinct forest types:

1. Dark forest
    - Objects must be dark (mean brightness < 65 for 1999, < 75 for 1938)
2. Edge forest
    - Objects must be dark (mean brightness < 135 for 1999, < 195 for 1938).
    - Objects must contrast brighter neighbors (mean difference to brighter neighbors > 10).
    - Within objects that met these criteria, a probability function was applied. An object had a higher probability of being "tree" if it was characterized by high contrast to brighter neighbors, high relative border to brighter neighbors, and low mean brightness. If the probability was over 50%, the object was classified as "tree".
3. Interior forest
    - Objects must be dark (mean brightness <100 for 1999, <115 for 1938).
    - Objects must be primarily surrounded by darker neighbor objects (relative border to brighter neighbors < 50).
4. Isolated trees:
    - Objects must not be too large (< 300 m^2).
    - Objects must not be too light (brightness threshold <175 for 1999, <205 for 1938).
    - Objects must contrast brighter neighbors (mean difference to brighter neighbors >25 for 1999, >20 for 1938)
    - Objects must be primarily surrounded by brighter neighbor objects (relative border to brighter neighbors >0.5).

Because the average brightness of the images varied, we iteratively adjusted the thresholds slightly upward or downward for many images (17 of 39 historical images, and 7 of 39 modern images), to create a classification that visually corresponded to the distribution of trees.

Within coarse objects, we then calculated the percent area covered by fine objects classified as "tree" in each time period (Figure 2b). We also coded coarse objects in to the following classes: elevation class (quartile), majority aspect (north, east, south, west), slope (above or below 10%), majority vegetation type from Landfire existing vegetation type layer (shrub, ponderosa pine, lodgepole pine, mixed conifer) (The National Map LANDFIRE 2006), and historical % tree cover (quartile).

Before running the analysis, we identified and removed 7 coarse objects that were dominated by water (contained lakes or ponds delineated by the USGS) and 278 objects that were dominated by topographic shadows. Shadow-dominated objects were identified by creating a hillshade model based on the time and date of the photography acquisition. We removed coarse objects that were below a threshold predicted illumination (mean hillshade value < 60) and were dark in the image (mean brightness < 40 for 1999 and < 80 for 1938).

With the remaining 2112 objects, we used an ANOVA to compare the mean change in % tree cover within different classes related to topography and vegetation.

2.3 Verification

To check the quality of our 1999 % tree cover estimates, we directly compared our calculations to % tree cover recorded in Common Vegetation Units of the Forest Service's Integrated Resource Inventory (IRI) database (USDA Forest Service 2003). The IRI dataset covers 367 km^2, or 70% of the area of the image tiles within the study area. The IRI dataset was created through manual photointerpretation of 1994 orthophotos, supplemented with field inventory and interpretation of Landsat Imagery. While our image objects were designed to approximate the size and shape of the manually digitized forest stands in the IRI data, they usually did not directly correspond. Therefore we calculated % tree cover within image objects by finding an area-weighted average of the IRI polygons that intersect the image objects. We then compared the two estimates of % tree cover.

3. RESULTS

3.1 Orthorectification and Verification

The average displacement between the two sets of images was 11 meters, indicating fairly good orthorectification of the historical photos. We found that there is a moderate linear relationship ($R^2 = 0.64$) between % tree cover in our dataset compared to the Forest Service IRI dataset sets. However, the comparison is imperfect because of the date change (1994 for IRI vs 1999 for image objects), the area-weighted re-sampling, and because only 24 out of 2364 vegetation units in the study area were field verified.

3.2 Change in tree cover between time periods

We found that mean change in % tree cover within coarse objects between time periods was highly significantly different ($p<0.0001$) for all classes except for slope, which was significant at the $p<0.05$ level (Table 1).

To evaluate whether the change in % tree cover was significantly different than zero at the $p<0.05$ level, we checked to see if the upper and lower bounds of the mean estimate (95th percentile) straddled zero (Table 2). We found that objects at the upper two elevation quartiles (2432-2778m and 2779-3125m) did not change significantly between the two time periods (Table 2). Objects at the second to lowest quartile (2432-2778 meters) changed by an average of 5% and objects at the lowest quartile (1737-2084 meters) changed by a mean of 13%.

Table 1: ANOVA: change in % tree cover 1938-1999 between classes.

Class	Sum of Squares	df	MSE	F	Sig.
Elevation	3.1586	3	1.05	29.17	< 0.0001
Aspect	0.6630	3	0.22	5.93	0.0005
Slope	0.1720	1	0.17	4.59	0.0323
Dominant Veg	3.3202	3	1.11	30.80	<0.0001
Historical % Cover	28.4250	3	9.48	393.08	<0.0001

Table 2: Change in % tree cover within classes.

Elevation	Mean	95th Lower	95th Upper	Std. Dev	N
1737-2084m	13%	10%	15%	20%	259
2085-2431m	5%	4%	6%	19%	1011
2432-2778m	0%	-1%	1%	18%	763
2779-3125m	2%	-2%	6%	18%	79
Aspect					
North	1%	-1%	3%	18%	414
East	4%	2%	5%	20%	751
South	6%	5%	8%	19%	677
West	4%	1%	6%	22%	270
Slope					
<= 10 deg.	2%	0%	4%	17%	333
> 10 deg.	4%	3%	5%	20%	1779
Dominant Veg					
Lodgepole Pine	-1%	-3%	1%	17%	283
Mixed Conifer	0%	-1%	2%	20%	598
Ponderosa Pine	8%	7%	9%	19%	967
Shrub	5%	2%	8%	13%	111
Historical % Cover					
0% -25%	17%	15%	18%	15%	534
25%-50%	15%	13%	16%	16%	440
50%-75%	0%	-2%	1%	18%	464
75%-100%	-10%	-11%	-9%	14%	674
Global Mean	4.0%	3.6%	4.4%	19%	2112

In terms of aspect, we found that in objects dominated by south-facing slopes % tree cover increased by an average of 6%, while north-facing slopes did not change significantly between the two time periods. Objects dominated by east and west aspects increased % tree cover by a mean of 4%. These results are consistent with tree ring evidence (Sherriff and Veblen 2008) and photographic evidence (Veblen and Lorenz 1986) suggesting that tree cover has increased the most at the lowest elevations and on south-facing slopes.

In terms of slope, we found that areas of steep slope (> 10 degrees) has a slightly higher change in % tree density than relatively flat areas (<= 10 degrees) which did not change significantly. This result was marginally significant and low in magnitude.

We found that objects that are currently dominated by ponderosa pine or shrub have increased the most in tree cover (8% and 5% respectively), whereas objects that are currently dominated by lodgepole pine and mixed conifer did not change significantly between the two time periods.

We also found that objects characterized by low historical cover (0-25%) increased in tree cover by 17%, while objects characterized by high historical cover (75-100%) actually decreased by 10% between the two time periods. The decrease in cover over time in the densest historical cover class may be an artifact of the historical imagery where, due to the lower quality imagery, resolving gaps between trees was more difficult in some cases. Therefore, the proportion of the landscape in the historical 75-100% tree cover class may be overestimated. Also, closed-canopy forests may experience self-thinning, insect outbreaks or stand-replacing fires that would decrease tree cover.

Overall, we estimate that tree cover increased by an average of 4% across the entire study area (Table 2). However, the average change in % tree cover is likely to be closer to 7% if the observed decrease in tree cover in objects of high historical cover is primarily caused by the poorer quality of the historical imagery. Very little change in % tree cover across the study area is consistent with tree-ring reconstructions of fire regimes in Boulder County where less than 20% of the ponderosa pine zone were predicted to have frequent fire regimes where fire suppression would have promoted increased tree cover (Sherriff and Veblen 2007).

4. CONCLUSIONS

In this analysis we used a novel approach to evaluate to what degree % tree cover has changed between historical (1938-1940) and modern (1999) imagery taken along the Northern Front Range of Colorado. Object-oriented image classification allowed us to analyze objects representing forest stands, instead of individual pixels of arbitrary size, which allows meaningful characterization of changes in % tree cover within stands over time. It also enabled us to develop a classification strategy that employs spatial relationships between objects in addition to spectral information, so that our classification is fairly robust to variations in illumination.

Overall increase in tree cover was minimal across the study area. Tree cover did not increase between 1938/40 and 1999 in many places: objects > 2432m in elevation, and dominated by mixed conifer and lodgepole pine. This finding contradicts the assumption that “mixed conifer” with its substantial proportion of ponderosa pine, has become denser. We found % tree cover increased only at the lowest elevations, on south-facing aspects, in areas currently dominated by ponderosa pine and shrubs, and where historical cover was < 50%. Our results are consistent with tree-ring and photographic evidence that suggest that the major increase in tree density has taken place only at the lowest elevations and south facing slopes, which also tend to be dominated by the ponderosa pine vegetation type.

Overall, results from this comparison of changes in tree cover since 1938/40 suggest that fuel-reduction treatments would only restore pre-fire suppression tree cover or densities in very limited areas in the study area.

In the next phase of this study, we will evaluate the possible effects of human activities (housing, roads, mining) as well as ecological disturbance (fires, insect outbreaks) on the change in tree cover.

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REFERENCES

Chobey, M.S., S.E. Franklin, and M.A. Wulder, 2006. Object-based analysis of Ikonos-2 imagery for extraction of forest inventory parameters. *Photogrammetric Engineering & Remote Sensing*, 72(4): 383-394.

Covington, W. W. and Moore, M.,1994. Southwestern ponderosa forest structure. *J. Forest*, 92: 39-47.

Ehle, D. S., and W. L. Baker, 2003. Disturbance and stand dynamics in ponderosa pine forests in Rocky Mountain National Park, USA. *Ecological Monographs*, 73 (4): 543-566.

Fule, P. Z., W. W. Covington and Moore, M. M., 1997. Determining reference conditions for ecosystem management of southwestern ponderosa pine forests. *Ecological Applications*, 7(3), 895-908.

Kaufmann, M. R., C. M. Regan and P. M. Brown, 2000. Heterogeneity in ponderosa pine/Douglas-fir forests: age and size structure in unlogged and logged landscapes of central Colorado. *Canadian Journal of Forest Research*, 30: 698-711.

Laliberte, A. S., A. Rango, K. M. Havstad, J. F. Paris, R. F. Beck, R. McNeedly, and A. L. Gonzalez, 2004. Object-oriented image analysis for mapping shrub encroachment from 1937 to 2003 in southern New Mexico. *Remote Sensing of Environment*, 93:198–210.

The National Map LANDFIRE: LANDFIRE National Existing Vegetation Type layer, 2006. U.S. Department of Interior, Geological Survey. http://gisdata.usgs.net/website/landfire (accessed 15 May 2008).

Pillai, R.B., P.J. Weisberg, and E. Lingua, 2005. Object-oriented classification of repeat aerial photography for quantifying woodland expansion in central Nevada. In: *20th Biennial Workshop on Aerial Photography, Videography, and High Resolution Digital Imagery for Resource Assessment*. October 2-6, 2005. Waslaco, TX.

Sherriff, R.L. and T.T. Veblen, 2007. A spatially-explicit reconstruction of fire regime types in ponderosa pine forests of the Colorado Front Range. *Ecosystems*, 10:311-323.

Sherriff, R.L. and T.T. Veblen, 2008. Variability in fire-climate relationships in ponderosa pine forests of the Colorado Front Range. *International Journal of Wildland Fire*.

Schoennagel, T, T.T. Veblen, and W.H. Romme, 2004. The Interaction of fire, fuels, and climate across Rocky Mountain Forests. *BioScience*, 54(7): 661-676.

Veblen, T. T., T. Kitzberger, and J. Donnegan, 2000. Climatic and human influences on fire regimes in ponderosa pine forests in the Colorado Front Range. *Ecological Applications*, 10(4): 1178-1195.

Veblen, T. T. and D. C. Lorenz, 1986. Anthropogenic Disturbance and Recovery Patterns in Montane Forests, Colorado Front Range. *Physical Geography*, (7)1:1-24.

White House, 2003. Reducing the threat of catastrophic wildfires and improving forest health. http://www.whitehouse.gov/ceq/hfi_12-02_wh_fact_sheet.pdf (accessed May 15, 2008)

US Government Accountability Office, 2007. Wildland fire management: a cohesive strategy and clear cost-containment goals are needed for federal agencies to manage wildland fire activities effectively. GAO-07-1017T. http://www.gao.gov/new.items/d071017t.pdf (accessed May 15, 2008)

US Department of the Interior (DOI) and Department of Agriculture (USDA), 2007. Healthy Forests Report: FY 2007 Accomplishments. http://www.forestsandrangelands.gov/reports/documents/healthyforests/2007/fy2007_final_healthy_forests_report_12112007.pdf (accessed May 15, 2008)

USDA Forest Service, 2003. Arapaho Roosevelt National Forest, Common Vegetation Unit: USDA Forest Service, Fort Collins, Colorado.