Using the Forest Vegetation Simulator to Reconstruct Historical Stand Conditions in the Colorado Front Range

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Abstract—Presettlement ponderosa pine/Douglas-fir forests of the Colorado Front Range were open and heterogeneous. Logging, grazing, and fire suppression over past 100 to150 years have altered stand structure by changing diameter distributions and increasing overstory density. In an effort to guide forest restoration toward presettlement conditions, we are currently using the Forest Vegetation Simulator (FVS) to validate estimates of 1900 forest structure, and calibrate the model for future use, for an unmanaged landscape (unlogged, ungrazed, but fires suppressed since 1900). In 1997, tree data were collected in 15 0.1-ha plots at Cheesman Lake. For trees larger than 1.4 m tall, diameter at breast height, height, species, live/dead status, age, and diameter growth increment were recorded; for trees less than 1.4m tall, basal diameter, height, species, live/dead status, age, and height growth increment were measured. FVS was first calibrated with diameter and height growth increments from the plots so that it more adequately depicted our study area. A 1900 tree data file was derived from data collected in 1997 for each plot by including only the tree records that pre-dated 1900, and measuring 1900 d.b.h. on increment cores. The plot was then grown forward to 1997, with natural regeneration added each decade to represent ingrowth in the plot since 1900. The modeling results were compared to the actual data. Growth and mortality multipliers were modified and FVS was rerun until FVS-generated 1997 diameter distributions, stand densities, and canopy covers were similar to those observed in 1997. Results from this intermediate phase of research will help to guide restoration activities in the South Platte Watershed, Colorado, and will also be critical in future stages of our research.

Stand structure in ponderosa pine/Douglas-fir (*Pinus ponderosa*/*Pseudotsuga menziesii*) forests of the Colorado Front Range has changed dramatically in the past 150 years. Prior to Euro-American settlement in the late 19th century, these forests were open and heterogeneous in age and size (GLO Field Notes 1879, 1882; Jack 1900). Logging, grazing, and fire suppression over the past 100 to 150 years have altered stand structure by removing many of the large or old trees and by allowing more regeneration to become established (Marr 1961; Veblen and Lorenz 1986; Kaufmann and others 2000). As a result, the current forest structure is younger, denser, and more homogeneous, and shade-tolerant Douglas-fir has become more prevalent on the landscape.

Restoring ponderosa pine/Douglas-fir ecosystems to historical stand conditions is vital if we wish to maintain ecological sustainability and reduce the risk of catastrophic, stand-replacing forest fires. Treatment projects intended to restore ponderosa pine ecosystems to a historical condition require an understanding of what this historical condition was.

We are fortunate to be able to study at the Cheesman Lake landscape, a relatively undisturbed 35- km^2 ponderosa pine/ Douglas-fir forest in the Upper South Platte Watershed of the Colorado Front Range. Cheesman Lake, a reservoir created on the South Platte River at the beginning of the 20th century, and the surrounding land are owned and managed by Denver [City] Water. Unlike most montane forests in the Colorado Front Range, this landscape has experienced only minimal, localized logging (mostly below the current water line of the reservoir during the time of dam construction). At the time of dam completion in 1905, a six-strand barbed-wire fence was erected around the property, which has excluded domestic grazing. Wildfires, however, have been suppressed since the early 1900s.

We used the Forest Vegetation Simulator (FVS; Spruce-Fir submodel of the Central Rockies variant, version 6.31) to "de-grow" plots on the current Cheesman Lake landscape to 1900, just prior to the effects of fire suppression during the 20th century (fig. 1). FVS was first calibrated with diameter and height growth increments so that it more adequately depicted our study area. A 1900 tree data file was then derived from data collected in 1997 for each plot by removing all trees that germinated after 1900, and estimating the 1900 diameter for all pre-1900 trees. Each 1900 plot was grown forward to 1997, with natural regeneration added each decade to represent ingrowth in the plot since 1900. The modeling results were compared to the current data. Growth and mortality multipliers were modified, and FVS was rerun until FVS-generated 1997 diameter distributions, stand densities, and canopy covers were similar to those observed in 1997. Results from this research will help guide restoration activities in the South Platte Watershed, and will also be critical in future stages of our research.

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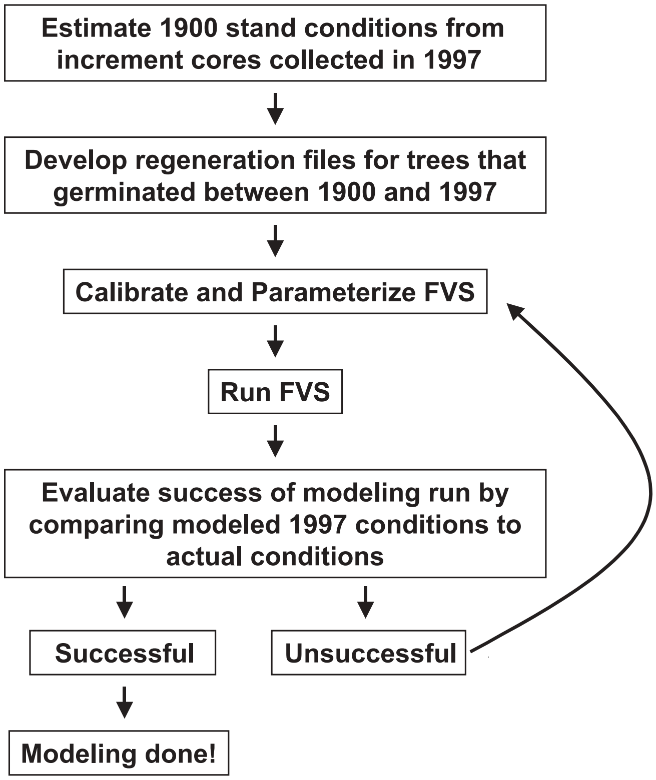

Figure 1—Flow chart depicting the methods used to "degrow" the plots at Cheesman Lake.

Estimating Plot Condition in 1900

In 1997, we established 15 0.1-ha (0.25 acre) plots within a 4-km^2 portion of the Cheesman Lake landscape (Kaufmann and others 2000). Five plots were randomly located in the 4 km^2 area on each of three topographic categories: north-facing slopes, south-facing slopes, and east- or west-facing slopes. In each plot, for all trees taller than breast height (1.4 m), tree diameter at breast height (d.b.h.), species, and live or dead status were recorded. Basal diameter, species, height, and 5-year height growth increment were measured for trees less than breast height tall. Also in each plot, 20 randomly selected live trees were cored for age at 30 cm above the ground; every tree in the plot that appeared to be over 200 years old was also cored (Kaufmann and others 2000). Tree germination dates were then determined by crossdating with a local chronology (Stokes and Smiley 1968; Kaufmann and others 2000). If a tree's germination date was not measured, it was predicted using a kernel density function (Venables and Ripley 1999). We also measured 10-year diameter growth increments on the cores.

We relied on our increment cores to reconstruct the 1900 stand condition. For all increment cores taken from trees that germinated prior to 1900, we measured the distance from the pith to the ring that was laid down in 1900. This 1900 radius was doubled to get the 1900 diameter (inside the bark and at a coring height of 30 cm). We then estimated the tree's 1900 diameter at breast height (outside the bark) from allometries developed by VanDeusen (1975).

For trees that were not cored but whose estimated germination date was prior to 1900, we ran backward stepwise regressions to predict 1900 d.b.h. from age, 1997 d.b.h., and 1997 height for the rest of the pre-1900 trees. Only variables that were significant at the alpha = 0.15 level were retained in the backward stepwise model.

We also relied on our increment core data to estimate tree recruitment that occurred in the plots since 1900. For trees that germinated after 1900, we determined the number of trees, by species, that germinated in each decade between 1900 and 1997.

The pre-1900 stand conditions were entered into FVS as tree data files ('.fvs'). The tree data files contained the species, live or dead status, and 1900 d.b.h. for all trees that germinated prior to 1900. We used the 'NATURAL' keyword to enter the number of trees (by species) that germinated in each decade between 1900 and 1997. To compensate for trees that were alive at some time between 1900 and 1997 but have since died, we assumed a mortality rate of 2 percent per decade.

Calibrating, Parameterizing and Running FVS

Several keywords were used to calibrate and parameterize FVS. These keywords can be divided into two groups: those whose values were fixed for all FVS runs for an individual plot, and those whose values were adjusted for each FVS run so that the FVS simulation results more closely matched what was observed in the plot.

The keywords that were fixed for all simulation runs of a plot were 'READCORD,' 'READCORR,' and 'SDIMAX'. 'READCORD' is a multiplier for the large tree diameter growth model. The values for this keyword were determined by FVS, based on diameter increment measurements. 'READCORD' was 0.651 for Douglas-fir and was 0.749 for ponderosa pine. 'READCORR' is a multiplier for the small tree height growth model. FVS determined the values for this keyword from height growth measurements on small trees. 'READCORR' was 0.708 for Douglas-fir and 0.928 for ponderosa pine. The 'SDIMAX' keyword changes the maximum stand density index (SDI) for a stand, and how maximum SDI affects a stand's density dependent growth and mortality rates. While we did not alter maximum SDI, we did decrease the percent of maximum SDI where density dependent mortality begins (field 5) from 55 to 40 percent. We also decreased the percent of maximum SDI where the stand reaches maximum density (field 6) from 85 to 70 percent. A stagnation effect, where tree growth stagnates when plot density exceeds 70 percent of the maximum SDI, was also invoked (field 7). These alterations to 'SDIMAX' were based on our plot data.

The keywords whose values were changed for any individual simulation run were 'REGHMULT,' 'FIXDG,' and 'MORTMULT'. 'REGHMULT' is a multiplier for the height growth of small trees. 'FIXDG' is a multiplier for diameter growth of large trees. We entered this keyword into our simulation file five times, so that growth rates of trees 0 to 10 cm d.b.h., 10 to 20 cm d.b.h., 20 to 30 cm d.b.h., 30 to 40 cm d.b.h., and greater than 40 cm d.b.h. could be adjusted independently of each other. 'REGHMULT' and 'FIXDG' varied from 0.1 to 1.9 (plus or minus 90 percent of the default value); 'MORTMULT' varied from 1.0 to 2.0. Note that these values were not changed during a simulation (that is, from decade to decade), but were changed for any individual simulation. During a simulation, the values for these parameters remained constant.

During each simulation, we computed the number of trees per hectare in 10 cm d.b.h. classes (0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm, 40 to 50 cm, and greater than 50 cm d.b.h.). We also computed total canopy cover. The 'Compute 2' postprocessor was invoked so that the output file ('.cp2') could be read into SAS for evaluation with the observed plot data (SAS release 8.1, SAS Institute Inc.).

Evaluating the Success of the FVS Run

To determine whether an FVS run was successful at producing the observed 1997 plot conditions from a given set of inputs, we evaluated our FVS run in four ways. The first way was qualitative; histograms of the d.b.h. distributions for the plot and the FVS output were visually compared. If the histograms appeared similar, the modeling run was deemed successful by this method. Second, we calculated a 10 percent "confidence interval" for each d.b.h. class; if the FVS-generated output was within these confidence intervals for at least four of the six d.b.h. classes, the modeling run successfully passed this test. The third way we compared the FVS output to the plot data was with a chi-square goodness-of-fit test. An FVS modeling run successfully mimicked the plot data if the p-value was greater than or equal to 0.80. Fourth, percent canopy cover for the plot and the FVS output were also compared, and if the FVS-generated canopy cover differed from the plot canopy cover by 10 percent or less, then the modeling run was successful by this method.

When an FVS run successfully passed all four "tests," it was considered acceptable. If all of the above conditions were not met, then the keyword parameters were altered and FVS was rerun until the conditions were met. We will use one plot, 'CL0111,' as an example, and describe each of these evaluations for both an unparameterized (default) FVS run, and a parameterized (modified) run.

We generated histograms for a graphic comparison of the plot and the FVS-generated data, shown in figures 2a, b, and c. Figure 2a shows the number of trees per hectare by d.b.h. class observed in plot CL0111 in 1997. Plot CL0111 has the classic inverse-j shaped curve characteristic of uneven-aged stands. While the diameter distribution of our unparameterized stand (where the keywords 'REGHMULT,' 'MORTMULT,' and 'FIXDG' are all equal to the default values) does not really mimic what is on the ground, our parameterized run looks similar to real life (fig. 2b, c).

We calculated a 10 percent "confidence interval" for the number of trees per hectare in the plot in each diameter class. It is important to note that what we calculated was not a true confidence interval; rather, it was the number of trees per hectare by d.b.h. class observed in the plot, plus or minus 10 percent. Results from an unparameterized FVS run and a parameterized run are shown in tables 1a and 1b. While the number of trees predicted by FVS for each d.b.h. class is never within 10 percent of those observed in the plot (never 'OK') in the unparameterized run, the parameterized run is 'OK' in five of the six d.b.h. classes.

The third way that we evaluated the success of our modeling run is with a chi-square goodness-of-fit test. Again, our FVS run with the default parameters does not match observed conditions as well as the parameterized FVS run (unparameterized run: p=0.0005; parameterized run: p=0.9882).

Evaluating canopy cover is important for us because canopy cover serves as a link to apply the results from our plots to the rest of the Cheesman Lake landscape in the next phase of our research. Canopy cover (calculated by FVS) for CL0111 in 1997 was 38.6 percent; the unparamaterized model estimated canopy cover to be 45.8 percent, while the parameterized model estimated it to be 40.6 percent. Again, the FVS run with the modified parameters more closely mimicked what is actually on the ground.

Preliminary Results and Their Application To Date

Table 2 shows modeled 1900, observed 1997, and modeled 1997 canopy covers for all plots, averaged by aspect. Values for our example plot, which is east-facing, are also included. Average historical forest density for our plots was estimated to range from 13 to 22 percent canopy cover, while average current forest density (actual data) ranged from 39 to 65 percent. For plots that were successfully modeled, FVS canopy cover was within 10 percent of the actual data for all aspects.

Table 3 lists the parameter values for all the keywords that were used in each FVS simulation. Five plots could not be successfully degrown, given the bounds we put on our parameters. Of these five plots, two were very sparse (14 or fewer trees per plot, or 140 trees per hectare), and one was very dense (canopy cover was greater than 70 percent). While we are generally satisfied with the results of our modeling runs, we realize that several of our assumptions may be affecting their success. Our assumption that parameters are constant for all decades in a simulation may not be valid. These parameters may change over time as stand density and tree size increases through the decades. Also, these parameters may change over time because of changes in climate.

We mapped 2,500 polygons from 1:6000 color infrared aerial photographs for the entire Cheesman Lake landscape, based on canopy closure and diameter class distribution (Huckaby and others 2001). Of these polygons, 580 were within the 4-km^2 study area.

Based on the preliminary results from this modeling work and the polygon coverage for the 4-km^2 study area, we developed relationships between 1997 canopy cover and 1900 canopy cover for each of the 585 polygons. Aspect and an aspect-by-1997 percent canopy cover interaction variable were initially considered in the regression but were removed because they were not significant predictors. While the correlation between 1900 and 1997 canopy covers is not strong (Adj. R^2 = 0.19, s.e. = 8.83), an initial version of estimated 1900 canopy cover for the 4-km^2 study area (top),

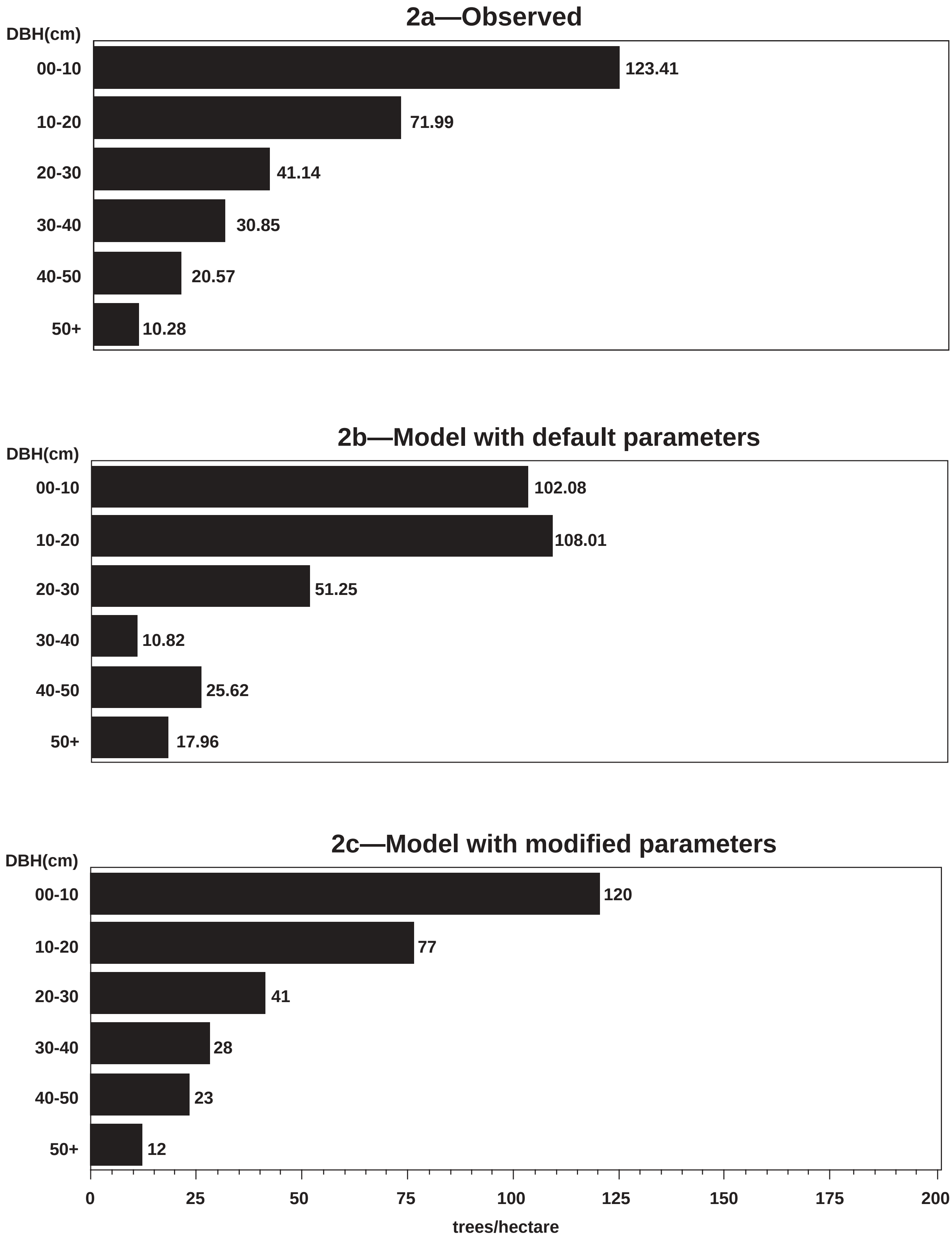

Figure 2—Example output for plot Cl0111. The histograms of diameter class distribution were used to evaluate the success of an FVS run. Figure 2a is the histogram for the actual plot data in 1997. Figure 2b is the histogram for the unparameterized FVS run, and figure 2c is the histogram for the parameterized FVS run. The diameter distribution produced by the parameterized FVS run better reproduces the actual data.

Tables 1a and b—"Confidence interval" evaluation for plot CL0111. Table 1a (top) is the output for the unparameterized FVS run, and table 1b (bottom) is the output for the parameterized FVS run. We calculated a 10 percent "confidence interval" for each d.b.h. class; if the FVS-generated output was within these confidence intervals for at least four of the six d.b.h. classes, the modeling run was successful. While the number of trees predicted by FVS for each d.b.h. class is never plus or minus 10 percent of those observed in the plot (never 'OK') in the unparameterized run, the parameterized run is 'OK' in five of the six d.b.h. classes.

D.B.H. class	Trees per ha for actual plot	Trees per ha estimated by FVS	Low 'confidence interval' (–10%)	High 'confidence interval' (+10%)	High, low, or OK?
a. Unparameterized Run					
0 to 10 cm	123	102	111	136	Low
10 to 20 cm	72	108	65	79	High
20 to 30 cm	41	51	37	45	High
30 to 40 cm	31	11	28	34	Low
40 to 50 cm	21	26	19	23	High
50 cm plus	10	18	9	11	High
b. Parameterized Run					
0 to 10 cm	123	120	111	136	OK
10 to 20 cm	72	77	65	79	OK
20 to 30 cm	41	41	37	45	OK
30 to 40 cm	31	28	28	34	OK
40 to 50 cm	21	23	19	23	OK
50 cm plus	10	12	9	11	High

Table 2—Canopy cover, averaged by aspect class, for 1900, 1997_{Plot}, and 1997_{FVS}. Percent canopy covers for our example plot, CL0111, are also listed. 1900 and 1997_{Plot} percent canopy cover averages are for all plots, not just plots that were successfully degrown; 1997_{FVS} percent canopy covers are only for the plots that were successfully degrown (this number of plots is reported in parentheses next to the canopy cover value).

	Average percent canopy cover		
Aspect[a]	1900	1997_{Plot}	1997_{FVS}
N	21.5	65.4	66.7 (n = 4)
E/W	15.7	45.3	43.0 (n = 2)
CL0111	18.0	38.6	40.6
S	12.9	40.1	40.8 (n = 4)

[a]E/W= East/West, N=North, and S=South.

along with the 1997 estimates from air photos (bottom) is shown in figure 3. Changes in canopy cover from 1900 to 1997 are dramatic. These preliminary results indicate that, in 1900, approximately half of the 4-km^2 study area had a canopy cover of 10 percent or less, and none of the polygons had a canopy cover exceeding 40 percent. Conversely, less than one quarter of the 4-km^2 study area had a canopy cover less than 10 percent in 1997, while more than one quarter of it had a canopy cover exceeding 40 percent. Although this research work is in an intermediate stage of development, these results are supported by historical photographs taken at Cheesman Lake (fig. 4; Denver Water Archives, Denver, CO), by written records from the turn of the century (GLO Field Note 1879, 1882; Jack 1900), and by what we know about the fire history for the 4-km^2 area (Brown and others

Table 3—Parameter values, by plot. Multiplier values of '—' indicate that the plot was not successfully degrown.

Plot	Aspect[a]	READCORD DF[b]	READCORD PP[c]	READCORR DF	READCORR PP	REGH MULT	FIXDG 0-10	FIXDG 10-20	FIXDG 20-30	FIXDG 30-40	FIXDG 40+	MORT MULT	P-value
							- - - - cm	- - - -	- - - -	- - - -	- - - -		
CL0111	E/W	0.65	0.75	0.71	0.93	0.70	1.00	1.10	1.50	0.60	0.20	1.50	0.9882
CL0113	N	0.65	0.75	0.71	0.93	0.60	1.30	1.30	0.80	0.80	0.80	1.00	0.9194
CL0420	E/W	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL0701	N	0.65	0.75	0.71	0.93	0.40	0.80	1.70	0.70	0.90	0.60	2.00	0.9946
CL0904	N	0.65	0.75	0.71	0.93	0.70	1.10	1.20	0.95	0.50	0.50	2.00	0.9503
CL1208	E/W	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL1312	S	0.65	0.75	0.71	0.93	1.00	1.00	1.00	1.00	0.70	1.10	2.00	0.9505
CL1632	N	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL1711	S	0.65	0.75	0.71	0.93	0.80	0.80	1.00	1.00	0.40	0.10	1.00	0.9653
CL1916	E/W	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL2202	S	0.65	0.75	0.71	0.93	1.20	1.20	1.20	1.00	0.65	0.60	1.50	0.9671
CL2316	S	0.65	0.75	0.71	0.93	—	—	—	—	—	—	—	—
CL2408	S	0.65	0.75	0.71	0.93	0.50	0.83	1.90	0.70	1.00	0.90	1.20	0.9221
CL2503	E/W	0.65	0.75	0.71	0.93	1.00	1.00	1.00	1.00	1.00	1.00	1.70	0.9745
CL2613	N	0.65	0.75	0.71	0.93	1.00	1.00	1.70	0.80	0.30	0.30	1.00	0.9562

[a]E/W= East/West, N=North, and S=South.
[b]DF= Douglas-fir.
[c]PP= ponderosa pine.

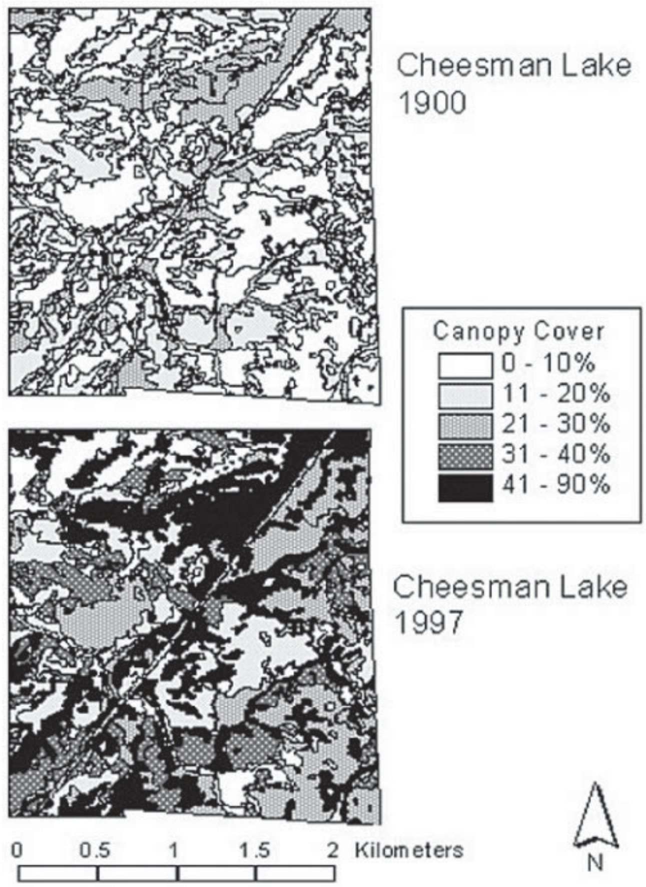

Figure 3—Map of percent canopy cover at Cheesman Lake. The 1900 map (top) was developed from a correlation between 1900 and 1997 percent canopy cover for our 15 plots. Using this correlation, we were able to calculate 1900 canopy cover from the 1997 canopy covers assigned to each polygon. The 1997 map (bottom) was developed from aerial photograph interpretation of 1:6000 color infrared photographs, based on canopy cover and d.b.h. distributions.

1999). The fire history indicates that most or all of this area burned in 1851 as a mixed-severity or stand-replacing fire, where many trees were killed. Consequently, canopy covers in 1900 would be likely to be low, and our results reflect this.

Future Research

The research effort outlined here is an intermediate stage in our overall goal of estimating historical stand conditions, and also in determining what current forest conditions would be at Cheesman Lake if 20th century fires had not been suppressed. Future research will involve incorporating data for 51 additional 0.1 ha plots that are distributed across the entire 35-km^2 Cheesman Lake landscape, and degrowing all of our plots using methods similar to those outlined above, while incorporating the two following changes.

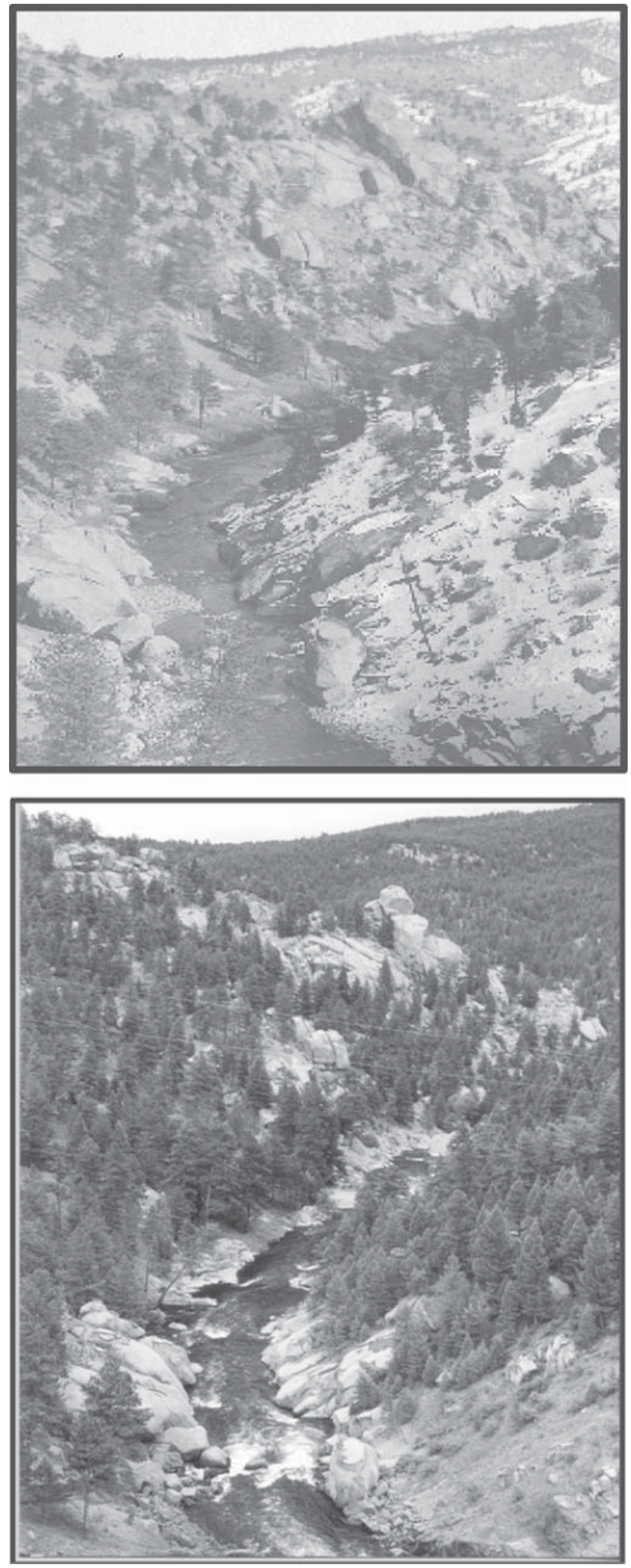

Figure 4—Paired photographs showing forest condition along the South Platte River, just below the Cheesman Lake Dam. The photo on the top was taken in 1903 (courtesy Denver Water Archives), and the photo on the bottom was taken in 1999 (courtesy Laurie Huckaby).

First, we will begin working with a test version of FVS that allows tree age measurements to be incorporated into an FVS tree data file ('.fvs'). Incorporating a tree's actual age into an FVS run will allow us to modify growth rates based on age, rather than d.b.h., and will likely increase our modeling success. While it is generally true that age and d.b.h. are related, they are often not well correlated, especially when growing conditions are extreme and highly variable. Our increment core data indicate that patterns of tree growth rates are more closely related to tree age than to tree size. In the Colorado Front Range, it is not uncommon for two ponderosa pine trees of the same d.b.h. to differ in age by 100 years or more. For example, the two ponderosa pine trees in figure 5 have similar diameters, but differ in age by nearly 130 years.

We will also use a program written by Don Vandendriesche at the Forest Management Service Center in Fort Collins, CO, to perform sensitivity analyses for the keywords that we modify (Hamilton 1997a). This program, named the 'Keyword Iteration Navigator' ('KIN'), allows a user to specify minimum, maximum, and step increments for various keyword parameters that are being used in a simulation (Vandendriesche 2001). In our work for this paper, we varied parameters for seven keywords ('REGHMULT,' five 'FIXDG' keywords, and 'MORTMULT'). To vary these keywords in the ranges used for this paper by increments of 0.1 would require hundreds of thousands FVS runs per plot. Using KIN, we will generate all possible parameter combinations and run them through FVS in much less time and with much less effort than if we did it manually. We will import the KIN output into SAS to determine which of the simulation(s) successfully mimic what we know to exist in the plot. Keyword combinations that are illogical, but are successful by our criteria, will need to be eliminated manually (Hamilton 1997b). Doing this may give us multiple "pathways" with which to grow our forest.

Once we have reparameterized the current 15 plots and the 51 additional plots using the age-enhanced FVS variant and KIN, we will attempt to determine the 2000 forest condition at Cheesman Lake, under a plausible natural fire regime. Based on the Cheesman Lake fire history and knowledge of fires that were suppressed, we suspect that there were 4 years that had potential to be big fire years at Cheesman Lake during the 20th century (Brown and others 1999). These fire years are 1912, 1954, 1963, and 2000. Trees in Cheesman Lake were scarred by fire in all of these years, but the fires were probably suppressed. The 1912 fire scarred trees in the southeastern portion of Cheesman Lake, and the 1954 fire scarred trees in the northeastern portion of Cheesman Lake; the extent of these fires is unknown. Fire scars and written records indicate that the 1963 fire burned in the southeastern corner of the Cheesman Lake property and burned 50 to 100 ha before it was suppressed. The 2000 fire burned in the northwestern portion of Cheesman but was suppressed before it exceeded 10 ha. We speculate that if these four fires had not been suppressed, based on their ignition locations and what we know about historical fire size, they would each have burned approximately half of the Cheesman Lake property, so that the entire property would have burned twice (with variable intensity) in the past 100 years. This is consistent with the fire history for the area (Brown and others 1999). We hope to use the results of this study, along with our plot data, the 1997 polygon coverage, FVS, and the Fire and Fuels Extension of FVS to help depict the landscape just before and after each of these fires, with forest structure reflecting the effects of these four fires had they been allowed to burn as natural fires.

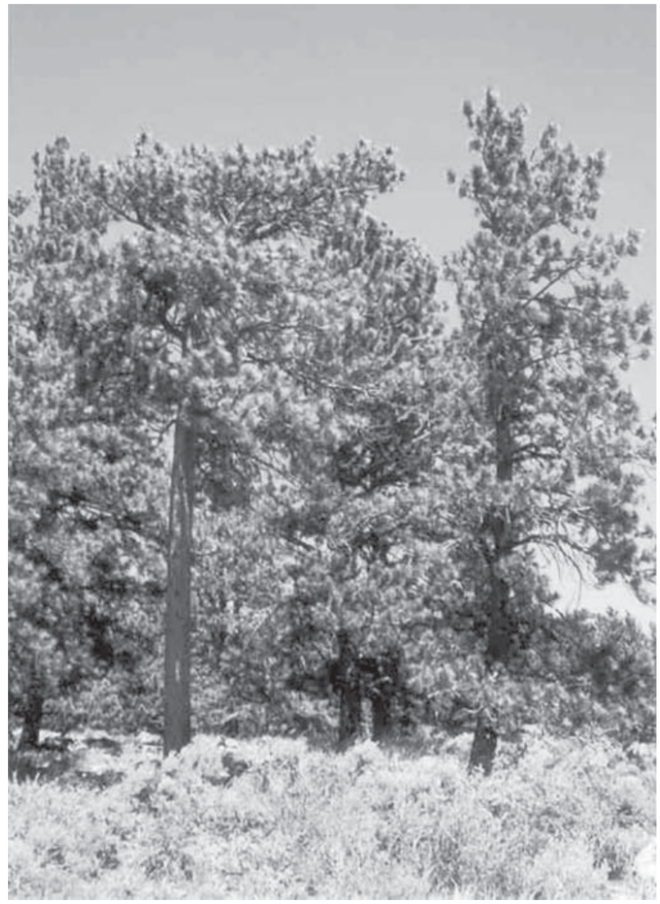

Figure 5—Photograph of an older tree (left) and a younger tree (right) growing side by side. While both of these trees are of similar d.b.h. and height, the older tree has a pith date of 1761 (d.b.h. is 33.6 cm or 13.2 inches), and the younger tree has a pith date of 1889 (d.b.h. is 31.7 cm, or 12.4 inches). The photograph is courtesy of Laurie Huckaby.

Results from this research and previous research using FVS are currently being used to guide restoration efforts on the South Platte Restoration Project (Kaufmann and others 2001). The Upper South Platte Watershed is important in the Colorado Front Range because it provides 70 percent of Denver's water supply and provides the people of the greater Denver area with access to fishing, hiking, and other recreational activities (Foster Wheeler 1999). Because of the watershed's proximity to Denver, it also contains a large area of urban-wildland interface. Two stand-replacing fires well outside the range of historical variability have occurred in the Upper South Platte Watershed since the mid-1990s. The 1996 Buffalo Creek fire, which burned 4,820 hectares (11,900 acres), and the 2000 Hi Meadows fire (4,250 hectares, or 10,500 acres) illustrate the huge risk of wildfire and postfire erosion in these dense forests. Future research results will better guide restoration activities and reduce the risk of catastrophic wildfires such as Buffalo Creek and Hi Meadows, and the research will promote ecological sustainability in these ponderosa pine/Douglas-fir ecosystems.

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