

# *Biomass Flow* in **Western** **Forests**

## Simulating the Effects of Fuel Reduction and Presettlement Restoration Treatments

**Kurt Hollenstein, Robin L. Graham, and Wayne D. Shepperd**

### ABSTRACT

Fuel treatment silviculture and the resulting long-term flow of biomass were examined using data from selected western stands. An uneven-aged management regime with reserve trees was modeled, using a canopy closure of 40 percent for the dominant trees as a target and a harvest cutting cycle of 20 years. Fuel reduction treatments in currently overstocked stands resulted in an initial peak of removal for the first and second cutting cycles. Yields stabilized in subsequent cutting cycles. Removal of some large reserve trees was crucial for maintaining stand structure and fire resilience.

**Keywords:** fire; modeling; silviculture; thinning

**M**ore than 100 years of fire-free growth in many short-interval fire-adapted forest ecosystems has increased stand density and fuel loads compared to those existing before Euro-American settlement (Dahms and Geils 1997; Moore et al. 1999). Catastrophic stand replacement fires are easily ignited and can propagate over large areas in such forests. Suppression is often difficult, due to the continuity of fuels and resulting high fire intensities. These large ahistoric fires endanger lives, property, and ecosystem integrity.

One approach to lowering the risk of catastrophic fire and improving the ecologic resiliency in short-interval fire-adapted forests is to restore them to pre-

settlement structural conditions (Dahms and Geils 1997; Mast et al. 1999; Moore et al. 1999). Where these forests are accessible to equipment, the recommended treatment is to mechanically remove high accumulations of flammable dead material and most small trees, while retaining the largest trees in the forest (Covington et al. 1997). This treatment mimics the effect of past frequent surface fires. In contrast to prescribed burning, mechanical removal is immediately effective, does not result in air pollution or escaping fires, and may be economically self-sustaining. Reducing fuel loadings by thinning the forest in this manner will slow or prevent the propagation of catastrophic fires, but will also produce large

amounts of wood of various sizes, usually with a high ratio of unmerchantable material (tops, limbs, and small trees). The unmerchantable material, or “biomass,” can serve as feedstock for various energy technologies, including ethanol production from cellulose or electricity generation. However, a long-term supply of woody feedstock is needed for such industries to develop. This study explores a silvicultural option and a modeling approach for evaluating the amount of biomass feedstock that might be sustainably produced by managing forests using uneven-aged silviculture with large reserve trees to mimic presettlement conditions in short-interval fire-adapted ecosystems in the Sierra Nevada and central Rockies.

The study had three objectives:

- Define a silvicultural regime for the creation and long-term maintenance of fire-resilient stands where large trees are reserved for wildlife habitat and aesthetics.
- Provide a modeling framework for simulating the long-term consequences to stand structure and flow of biomass that would result from applying the silviculture regime.

- Demonstrate the approach by applying the modeling framework to selected stands in the Sierra Nevada and central Rockies.

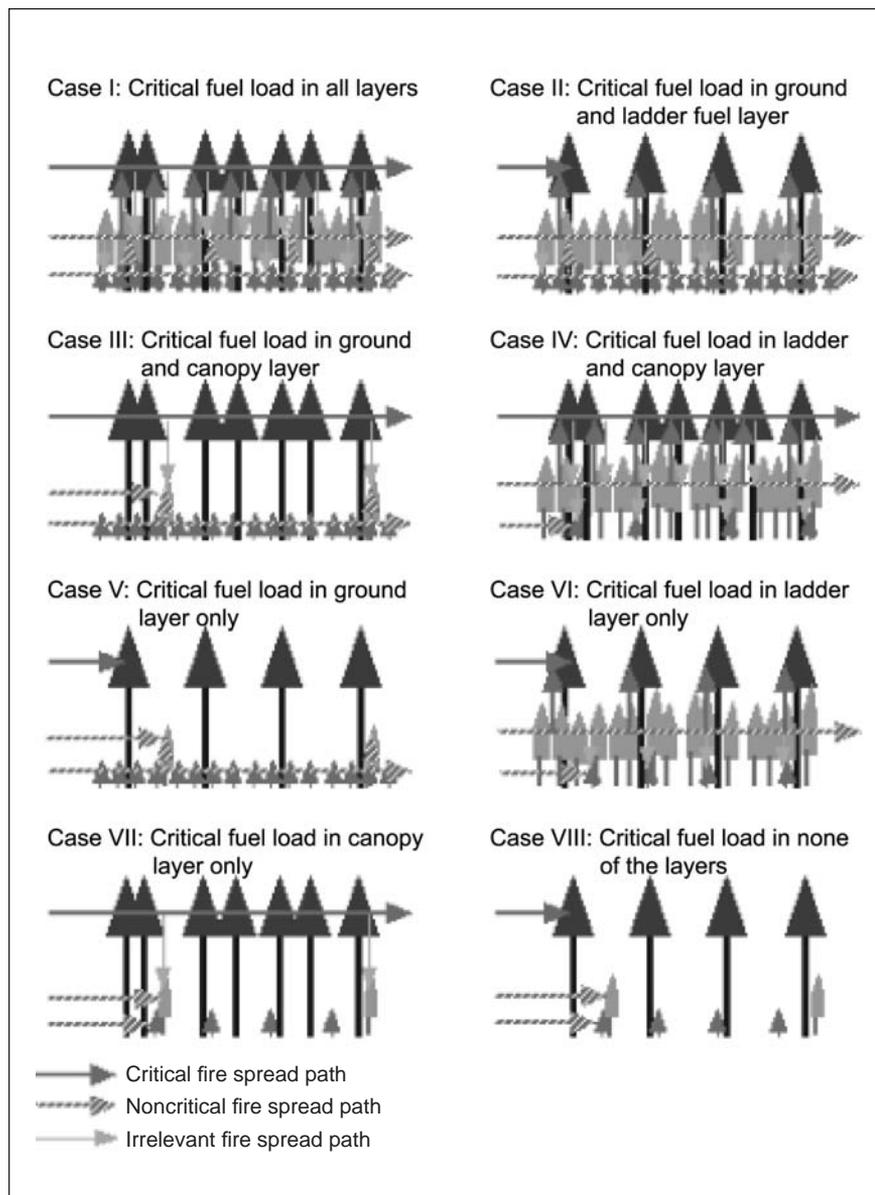
The focus of this article is on results of the simulation with regard to fire resilience, stand structure development, and biomass flow under uneven-aged management regimes that will most likely be used to maintain desired ecosystem attributes in short-interval fire-adapted western forests.

### Defining Stands in Need of Treatment

Two factors must be considered when determining whether a stand is at risk from an unnatural fire event and therefore suitable for thinning and biomass removal:

- The stand's potential to propagate stand-replacing fires that kill all trees and mineralize most of the organic soil material. This mainly depends on the available fuel load.
- The frequency of successful ignition. This depends on the quality of the fuel load and also on environmental conditions (e.g., precipitation and wind).

Neither the fuel load nor the ignition frequency alone is sufficient to define unnatural fire regimes. For example, boreal forests often have high fuel loads and chaparrals experience frequent ignitions, but these fire regimes are not unnatural (Keeley et al. 1999). However, many forests, including mid-elevation forests of the Rockies and Sierra Nevada, were historically subject to fires with a return interval in the order of decades. These low-intensity fires regularly eliminated ground, surface, and ladder fuels; partially reduced crown fuels; and, by killing seedlings, kept stand densities low. In the Sierra Nevada and Southwest, these return intervals have increased by an order of magnitude (SNEP 1996; Moore et al. 1999). Current fuel loads and tree densities create fire intensities comparable to boreal forests (Alexander 1982), where survival of trees is unlikely. Total mortality over large areas was historically a rare fire pattern in ponderosa pine and mixed conifer forests (Moore et al. 1999).



**Figure 1.** Stand structures and fire spread. Any tree whose crown intersects with a fire-spread path is assumed killed. Solid thick arrows show spread paths affecting upper canopy trees. Only the structures in case V and case VIII reliably prevent continuous loss of upper canopy by keeping the fuel density subcritical in the canopy and the ladder layer.

### Defining Fire Resilience

*Fire resilience* can be defined as a stand's ability to survive fires without permanent loss of functional or structural elements. The upper canopy with the oldest and largest trees represents such a structural element. A stand can be considered fire resilient if the probability of a complete loss of the upper canopy is reasonably low. This is the case if (1) propagation of a fire within the upper canopy and (2) continuous lethal scorching of canopy trees from

crowning surface fires is avoided. Both of these spread paths can be largely eliminated by reducing the fuel density below a critical threshold (for a detailed discussion, see Agee 1996). Experiences from real fires and simulations (e.g., van Wagtenonk 1996) suggest that this threshold can be approximated using a canopy closure value of 40 percent. Therefore, in our modeling we use 40 percent canopy closure as our target for fire resilience (fig. 1).

## Silvicultural Concept

The need to address the vertical dimension of the stand when restoring and maintaining short-interval fire-adapted western forests makes even-aged management approaches inappropriate. The historic stand structure of the forests of interest was not even-aged. Frequent fire-return intervals under historic fire regimes created forests of many age classes with a diverse canopy structure and spatial distribution of trees. We therefore chose an individual tree selection model (Alexander and Edminster 1977) to define desired stand structure because it is easy to simulate and well suited to handle a continuum of tree sizes. The model controls stocking across defined upper- and lower-diameter classes (hereafter called  $dbh_{Q_{min}}$  and  $dbh_{Q_{max}}$ ) using a negative exponential Q ratio defined as the number of trees in one diameter class divided by the number of trees in the next larger class. The Q ratio and desired basal area stocking define the numbers of trees to be left in each diameter class. We discovered that maintaining a 40 percent canopy cover target and a diameter range of  $\geq 40$  inches (realistic in the Sierra Nevada) resulted

in extremely flat diameter class distributions; i.e., the Q ratio was close to 1, or required extremely open (low basal area) stands. To avoid this, we created a hybrid management scheme for Sierra Nevada forests that could accommodate the larger trees needed to meet desired presettlement conditions. In our hybrid scheme, trees with less than a target  $dbh_{Q_{max}}$  (usually 30 inches) are managed under the uneven-aged individual tree selection model. Of the trees that exceed  $dbh_{Q_{max}}$  in the Q stocking curve, a fixed percentage termed "large tree removal intensity" (LTRI) is harvested in every selection cutting cycle such that  $(1 - LTRI)$  percent of the trees with  $dbh > dbh_{Q_{max}}$  remain on site. This hybrid approach facilitates the desired retention of large trees (Covington et al. 1997) in presettlement restoration and allows evaluation of the long-term effects of retaining large trees on stand structure and yield. Recent work by Graham et al. (1999) shows that type of thinning has a crucial influence on fire resilience. The uneven-aged regime modeled here results in the desirable conditions of low crown-fuel bulk densities but high crown bases.

## Simulation Tools

We chose the USDA Forest Service Forest Vegetation Simulator (FVS) (Teck et al. 1996, 1997) as the primary tool for simulating the effect of our hybrid management model on typical mid-elevation stands in the Sierra Nevada, the central Rockies, and the Southwest. We used the WS variant of FVS for Sierra Nevada data and the CR variant for central Rockies and Southwest data. Using FVS, however, poses the challenge that the WS and CR variants do not simulate natural regeneration. Because small trees represent a source of surface and ladder fuels, regeneration must be included. Our solution to this was to assume that enough trees regenerated following each cutting cycle to fill the smallest diameter class of the Q distribution. Because the uneven-aged selection automatically eliminated surplus trees in the next cutting cycle, a greater number of trees regenerated at the time of treatment has no effect on long-term stand structure. Regeneration density is irrelevant to fire-resilience considerations provided the small trees have not grown rapidly enough to provide fuel ladders into the canopy (unlikely with

**Table 1. Data set information for Sierra Nevada, Coconino, and Manitou stands at the beginning of the simulation period.**

Data set, stand type	Trees (stems per acre)	Basal area (square feet per acre)	$D_{max}$ (inches)	Volume (cubic feet per acre)	Accretion (cubic feet per acre per year)	Mortality (cubic feet per acre per year)
<b>Sierra Nevada</b>						
plu557, P3G	956	262	62.8	10,101	169	48
plu566, M4G	1,074	296	55.7	11,322	241	88
plu570, P4G	962	253	44.7	8,562	192	56
plu620, P2G	636	101	49.0	3,399	41	8
plu621, P2G	752	167	51.2	3,956	102	25
plu713, M4G	956	143	67.3	4,981	136	20
plu715, P2G	1,103	74	41.3	1,556	68	10
plu716, P2G	247	64	24.6	1,150	52	1
plu718, P3G	844	310	74.0	11,185	250	84
plu721, P2G	1,247	205	53.4	6,272	342	58
plu814, P4G	473	160	45.5	4,152	114	30
plu817, M3G	666	206	60.8	7,659	166	36
<b>Coconino</b>						
6930.003, PP	1,119	81	26.5	1,148	41	1
6990.012, PP	1,436	92	30.1	1,803	57	2
6990.033, PP	482	110	25.9	2,063	107	2
<b>Manitou</b>						
Manitou, PP	404	110	21.0	1,637	79	2

NOTE: P2G, P3G, P4G, and PP = ponderosa pine stands; M3G and M4G = mixed conifer stands.

a 20-year cutting cycle). Problems arise only if there is not enough regeneration, but the small number of trees required to fill the smallest class (< 100 trees per acre every 20 years) makes this approach justifiable.

Rather than using the Suppose user interface, which allows interactive operation of FVS (Crookston 1997), we ran FVS in batch mode, with the management prescription supplied by a keyword file. The mathematically exact uneven-aged stocking model allowed us to automate the keyword development, and a Tcl/Tk script called “keyword file builder” was written for this purpose. The script includes statements for computing several stand structure variables and for generating tree lists for use with the Stand Visualization System (SVS) (McGaughey 1998). Reports from the FVS output files were generated using Suppose. (For a detailed explanation of FVS and Suppose, see Wykoff et al. 1982; Crookston 1990, 1997; Teck et al. 1996; FMSC 2001.)

### Stand Data

Test data sets were chosen from the Sierra Nevada and the Rocky Mountain Front Range and the southwestern United States. The Sierra data were inventory plot data from Plumas National Forest, the Front Range data

were inventory data from Manitou Experimental Forest (Colorado), and the southwestern data were FVS sample files from Coconino National Forest (Arizona). Simulations were run on 12 data sets (nine dense ponderosa pine and three dense mixed conifer) for the Sierra Nevada. The Coconino and Manitou stands were ponderosa pine. *Table 1* shows stand data for the beginning of the simulation period.

### Treatment Prescription

Because of the different growth conditions and tree shapes, different treatment prescriptions were applied to the Sierra Nevada and the Manitou and Coconino data sets to achieve the target of 40 percent canopy closure. For the Sierra Nevada example described below, variations were focused on the policies for large trees (different LTRI values); for the Manitou and Coconino stands, a single prescription was tested. *Table 2* displays the parameters for the respective individual tree selection treatments. No species preference for the removal was defined, i.e., the probability for each individual tree to be harvested did not depend on its species.

### Sierra Nevada

*Figures 2 through 4* show the results when the Sierra Nevada treatment prescription (*table 2*) is applied to the

ponderosa pine data sets plu557 and plu718 (*table 1*). The results are typical of the general patterns observed across all the Sierra Nevada simulation runs.

*Stand development.* The stand structure variables show that over time the proposed thinning regime achieves a stable stand structure. Because of initial deficits and surpluses in tree numbers for certain diameter classes, it takes two cutting cycles to come close to the steady state; a single treatment is not likely to transform an unbalanced stand into a balanced one (Alexander and Edminster 1977). After the steady state is reached, a single thinning with biomass removal each 20-year cutting cycle maintains the equilibrium. Consequently, fuel treatments as outlined here are part of a long-term intensive silviculture, where selective harvesting and biomass removal provides the fuel reductions that previously resulted from frequent fires before Euro-American settlement.

The hybrid management approach clearly illustrates the effect of varying the removal intensity for large trees (> 30 inches dbh). Increased mortality limits the standing live volume if no large trees are removed; i.e., there is a “holding capacity” of the site that cannot be exceeded. However, with a moderate thinning ( $0 < \text{LTRI} \leq 20$  percent), the mortality is almost elimi-

**Table 2. Treatment prescriptions used for the simulations.**

Region	dbh <sub>Qmin</sub> (inches)	dbh <sub>Qmax</sub> (inches)	Q ratio	Number of trees per acre in largest class of the Q range	BA <sub>Q</sub> (square feet per acre)	LTRI values (percent)	Regeneration (species, percent)
Sierra Nevada	2	30	1.25	1	64	0, 10, 20, 40, 60, 80, 100	PP, 50; DF, 50
Coconino and Manitou	2	24	1.43	1.2	55	100	PP, 100

NOTES: BA<sub>Q</sub> = target basal area of trees in Q range; LTRI = large tree removal intensity (percent of trees larger than the upper Q diameter limit [dbh<sub>Qmax</sub>] that were removed every 20 years); PP = ponderosa pine; DF = Douglas-fir.

**Table 3. Average number of trees per acre with dbh > 30 inches for years 20–140 of the simulation period.**

Data set	Initial value	Large tree removal intensity (LTRI)						
		0%	10%	20%	40%	60%	80%	100%
plu557	13.8	16.5	13.2	10.3	6.2	4.4	2.9	2.0
plu718	13.6	19.1	15.1	11.9	7.8	5.2	3.7	2.7
Average	13.7	17.8	14.1	11.1	7.0	4.8	3.3	2.4

Notes: Years 0–19 and 141–150 were not considered to prevent distortion caused by initial stand condition and calculation effects. Both data sets are from representative stands of ponderosa pine on the Sierra Nevada.

nated and the stand still maintains a significant component of larger live trees, typically 10 to 15 trees > 30 inches dbh (table 3).

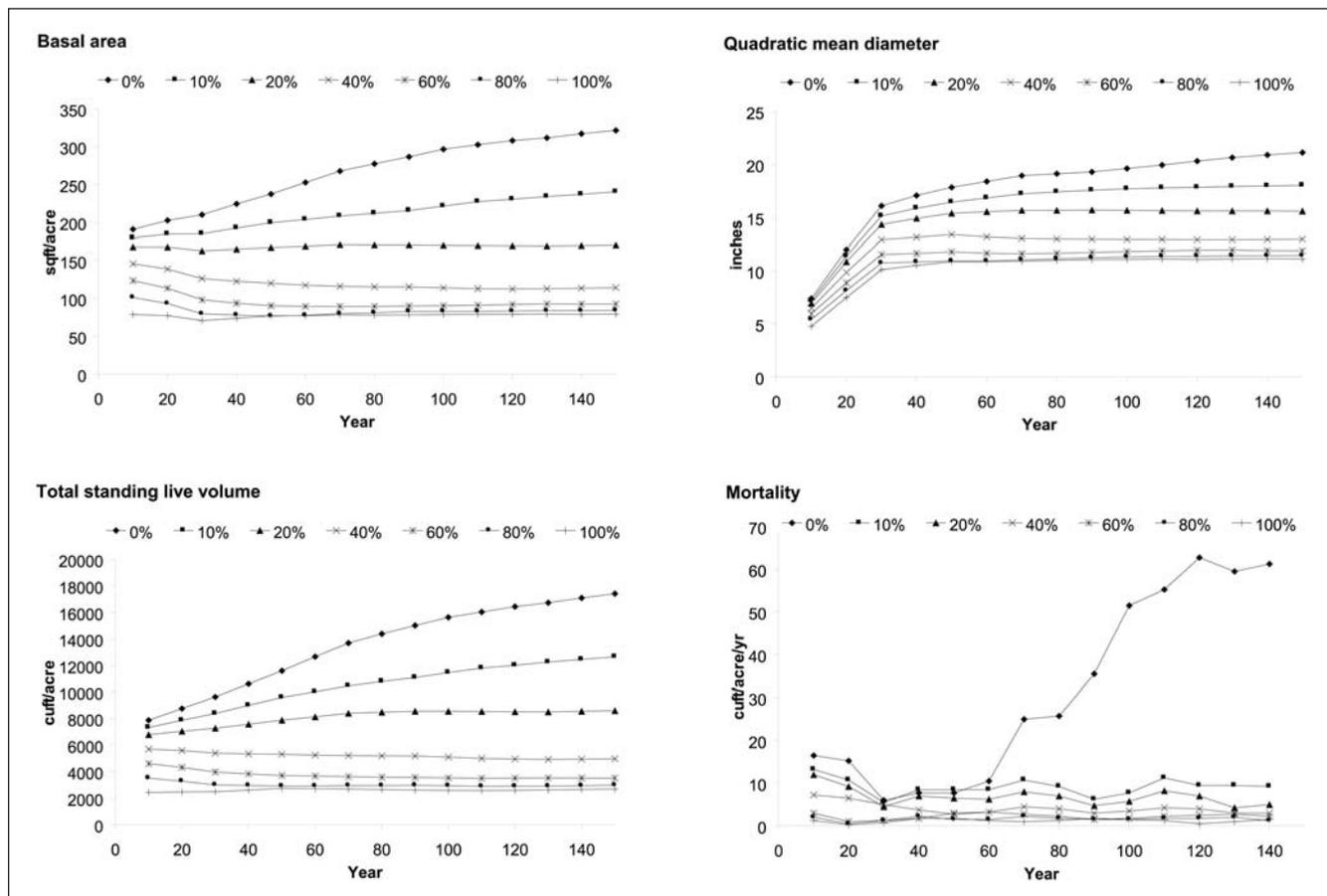
**Fire resilience.** Again, the treatment of large trees is crucial for the fire resilience of the stand. As the left chart of figure 3 shows, if no thinning of large trees occurs (LTRI of 0 percent), these trees will eventually form a dense, continuous upper canopy. Large trees that could survive surface fires may thus be eliminated by a crown fire they propagate themselves. Another important aspect is what appears to be density-dependent mortality (fig. 2). The sharp increase in mortality after year 60 under the 0 percent LTRI thinning regime creates a large pool of dead trees in addition to the increased live fuel density associated with this thinning regime. It would appear that fire resilience and presettlement conditions can be maintained only if the fuel treatments remove at least a portion of the large tree segment of the stand.

**Biomass removal.** Two stages are distinguishable with regard to biomass removal. For the first two cutting cycles (years 0–39), the production of unmerchantable stemwood calculated by the model is in the range of 4.5 to 9 bone dry tons (bdt) per acre (0.22–0.45 bdt/acre/year). However, FVS considers unmerchantable material to be only stemwood whose diameter is below some threshold merchantability diameter. The additional extraction of branches (usually as chips) is necessary to prevent an increase in fuel loads right after thinning. The removal of branch material dramatically increases the biomass yield. The allometric equations of Gholz et al. (1979) suggest that the branch biomass for ponderosa pine and Douglas-fir is  $\geq 20$  percent of the stem biomass. As  $\geq 80$  percent of the harvested stemwood is merchantable, inclusion of branch wood triples the flow of biomass to 13 to 26 bdt per acre (0.65–1.3 bdt/acre/year) during the first two cutting cycles. These predicted val-

ues correspond with experience from real fuel treatments performed in the Sierra Nevada, where 60 green tons of biomass per acre (approximately 24 bdt/acre) have been reported (Sheehan 1999, pers. commun.). This high initial flow reflects the need to reduce current fuel loading, and is not sustainable in the long run.

After 40 years there is a decrease in the yield of both merchantable and unmerchantable volume. The more or less constant flow for the remainder of the simulation (usually about one-third of the initial flow, i.e., 4.5 to 9 bdt per acre including branches, 0.22–0.45 bdt/acre/year) represents the amount of biomass that can be sustainably produced by these forests.

The large tree treatment also affected the biomass yield. The increase in mortality for 0 percent LTRI significantly reduced the volume (both merchantable and total) removed. This is critical for any industry that requires a large supply of wood (e.g., bioenergy plants typically use more than 100,000



**Figure 2.** Average stand development for two ponderosa pine data sets from the Sierra Nevada (plu557 and plu718). The data series represent the different levels of removal of trees > 30 inches dbh (0 to 100 percent). The data points represent moving averages over two 10-year periods.

tons per year). Lower yields per unit treated result in longer and more expensive transportation, ultimately making the use of harvests for either biomass-based or conventional wood products industries economically unviable. Thus, completely excluding large trees from the harvest negatively affects both the fire resilience of the stand and the economic performance of the treatment. However, these negative effects disappear if only 10 to 20 percent of the large trees are harvested. Mechanical treatment for fire resilience and maintenance of large trees for ecosystem integrity are therefore not incompatible. The harvest of a few large trees most likely mimics natural mortality that probably occurred in the past when surface fires determined stand structure.

### Rocky Mountains and the Southwest

Figures 5 through 7 show the results when the fuels reduction prescription (table 2) was applied to the three Coconino stands and the Manitou stand (table 1). The results for the Coconino stands are averaged.

*Stand development.* As in the Sierra Nevada stands, a steady yield state is achieved after the initial fuels reduction. The fact that the basal area remains almost unchanged from the very beginning is the result of the combined effect of the number of trees (not displayed) and the quadratic mean diameter (QMD). For the Coconino data, the number of trees decreases while their average diameter increases. For the Manitou stand, the opposite effect occurs (most likely a result of differ-

ences in initial stocking among the modeled stands). A stable equilibrium is achieved only after the second cutting cycle and only if the trees whose dbh exceeds  $dbh_{Qmax}$  are not excluded from treatment. As before, provisions for the treatment of large trees must be made to maintain the desired uneven-aged structure of the stand (see dashed line in figure 5).

*Fire resilience.* Figure 6 suggests that fuel treatments are effective in keeping the canopy closure down. However, this is true only if trees in the diameter range greater than 24 inches are thinned (see dashed line in figure 6). If they are left untouched, the total canopy closure will finally exceed the threshold considered critical with regard to fuel density.

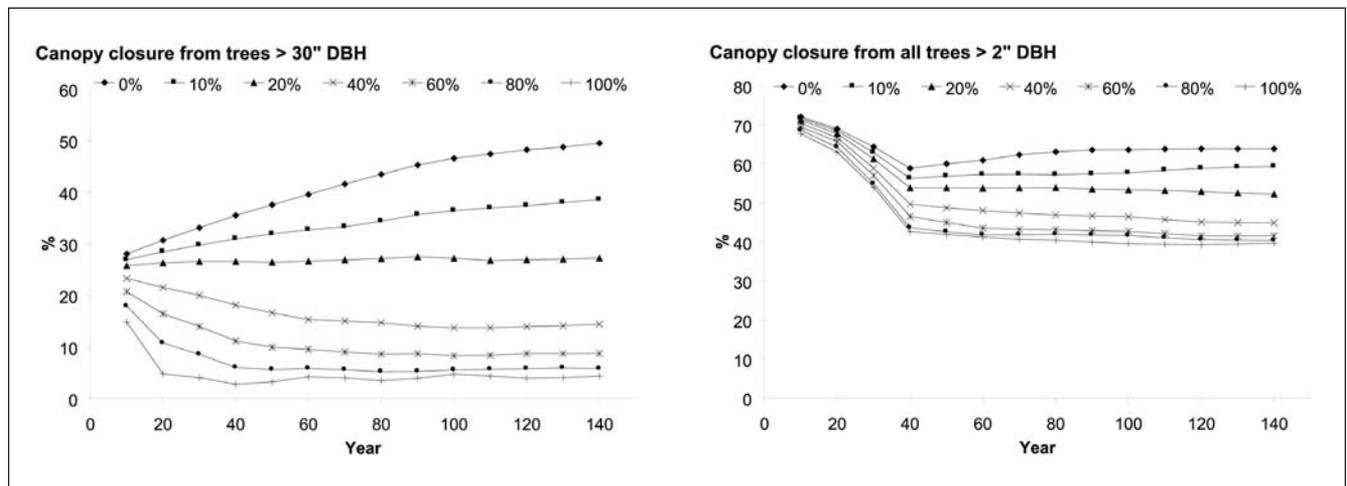


Figure 3. Average canopy closure development for two ponderosa pine data sets from the Sierra Nevada (plu557 and plu718). The data series represent the different LTRI values (0 to 100 percent removal of trees > 30 inches dbh). The data points represent moving averages over two 10-year periods.

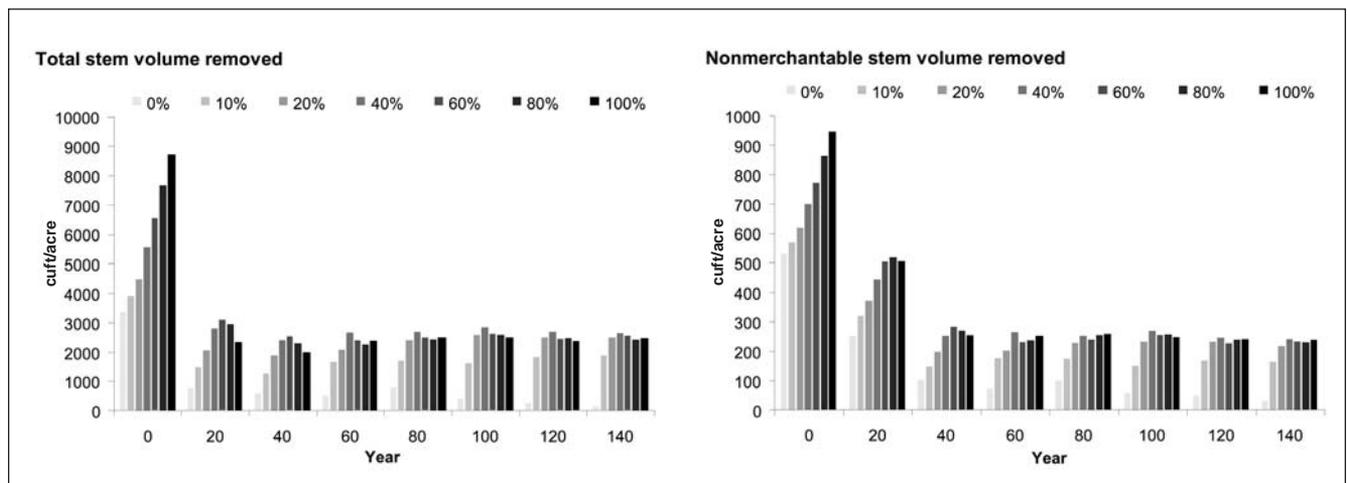
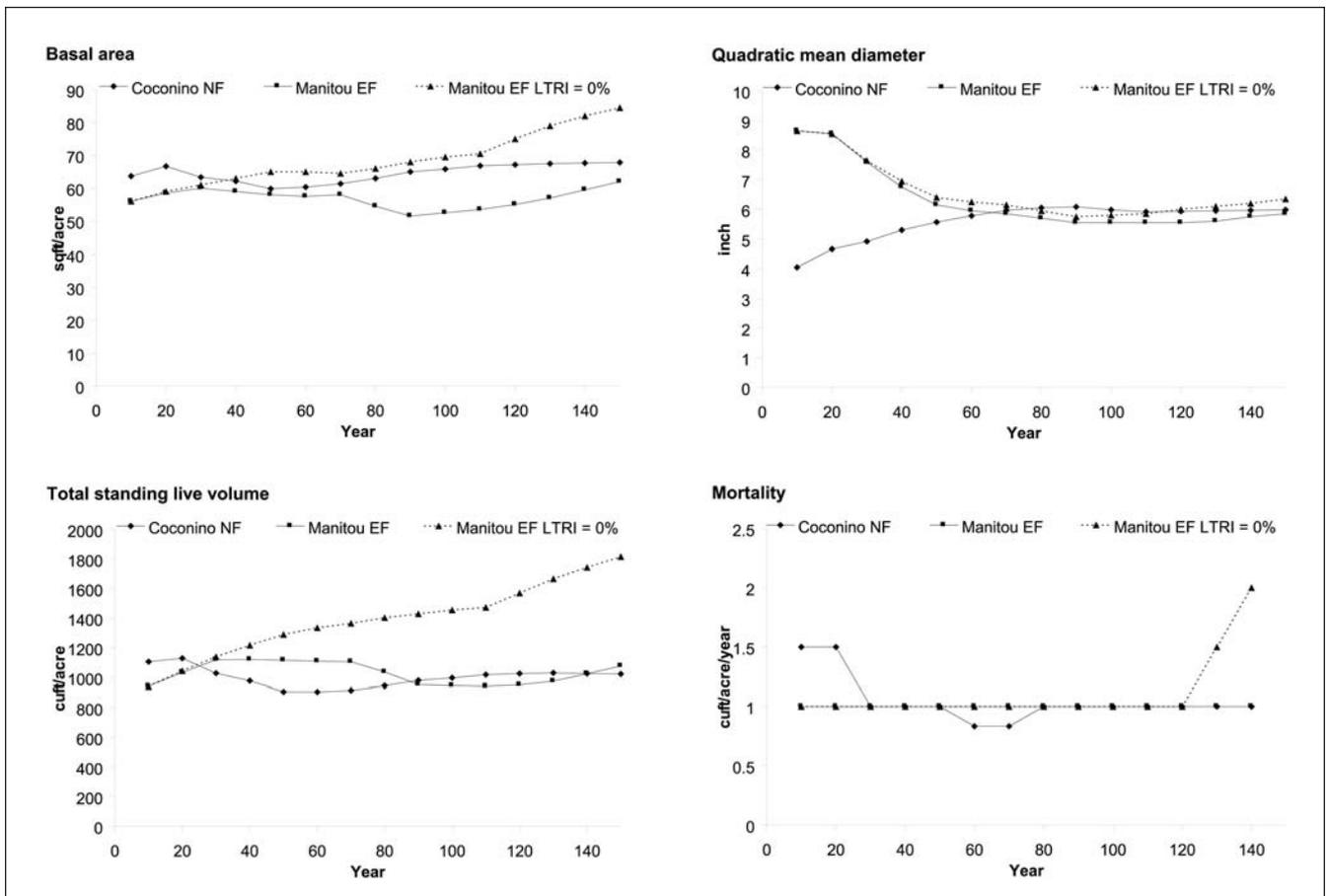


Figure 4. Average flow of stemwood for two ponderosa pine data sets from the Sierra Nevada (plu557 and plu718). The data series represent the different LTRI values (0 to 100 percent removal of trees > 30 inches dbh).



**Figure 5.** Average stand development for three Coconino National Forest stands and the Manitou Experimental Forest stand. The dashed line represents the development of the Manitou stand if the same Q model was applied without removing any trees whose dbh exceeds the upper diameter distribution limit of 24 inches. The data points represent moving averages over two 10-year periods.

*Biomass removal.* Both the total and the unmerchantable volumes removed from the Front Range and southwestern stands are significantly smaller than from the Sierra stands. The initial peak biomass of unmerchantable stemwood flow does not exceed 2.4 bdt per acre (0.12 bdt/acre/year), and sustainable levels are about 0.8 bdt per acre (0.04 bdt/acre/year). Inclusion of branches at least doubles these values, but they remain low compared to the requirement of energy production plants. However, the absence of competing industries (sawmills) in these regions may allow the use of some of the merchantable material for energy purposes, increasing the realized biomass yields.

**Limitations and Issues for Further Work**

The interpretation of the simulation results requires that limitations of the input data (plot or stand level rather than landscape level), the simulation layout (absence of disturbances other

than thinnings), and the simulation tools be considered. As presented, the results are valid only for the simulated conditions, and any extrapolation requires not simply an aggregation, but also that a scaling effect is taken into account. This is particularly important for other ecosystem concerns such as water yield or wildlife habitat quality, where the landscape resolution is more important. On this level, FVS, in the format we used, may not be the tool of choice.

Before implementing a fuel treatment concept based on the methodology we present here, it should be critically reviewed in actual ecosystem settings. This includes integration with other forest management goals, more detailed modeling of natural regeneration (especially the lack thereof), and the evaluation of the suggested fuel treatments in an operational context (technical, legal, economic, and political feasibility of treatments and utilization of material).

**Literature Cited**

AGEE, J.K. 1996. The influence of forest structure on fire behavior. In *Proceedings of the 17th Annual Forest Vegetation Management Conference*, 52–68. Redding, CA: USDA Forest Service.

ALEXANDER, M.E. 1982. Calculating and interpreting forest fire intensities. *Canadian Journal of Botany* 60:349–57.

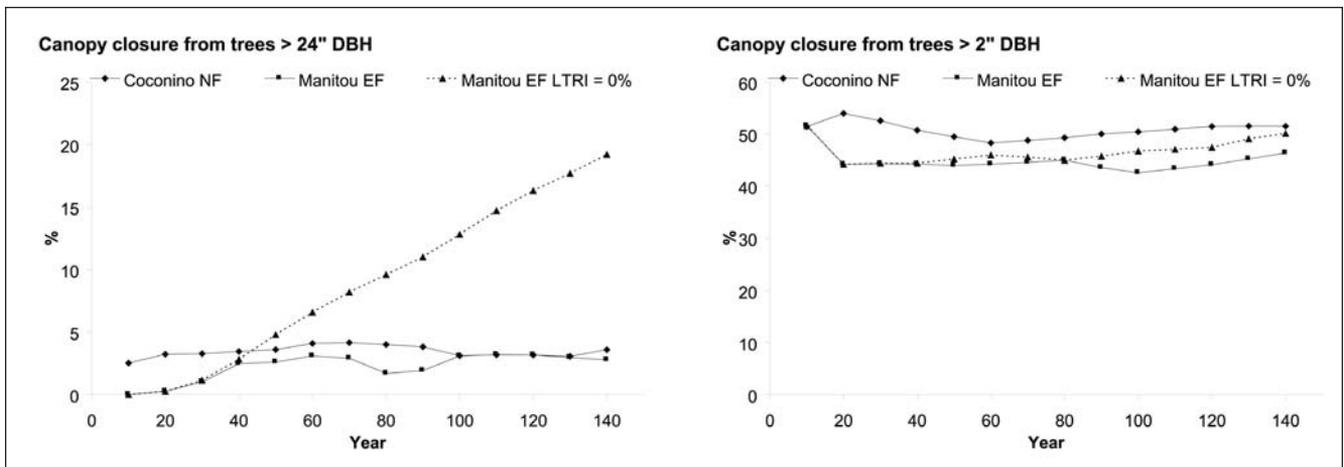
ALEXANDER, R.R., and C.B. EDMISTER. 1977. *Regulation and control of cut under uneven-aged management*. Research Paper RM-182. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station.

COVINGTON, W.W., P.Z. FULÉ, M.M. MOORE, S.C. HART, T.E. KOLB, J.N. MAST, S.S. SACKETT, and M.R. WAGNER. 1997. Restoring ecosystem health in ponderosa pine forests of the Southwest. *Journal of Forestry* 95(4):23–29.

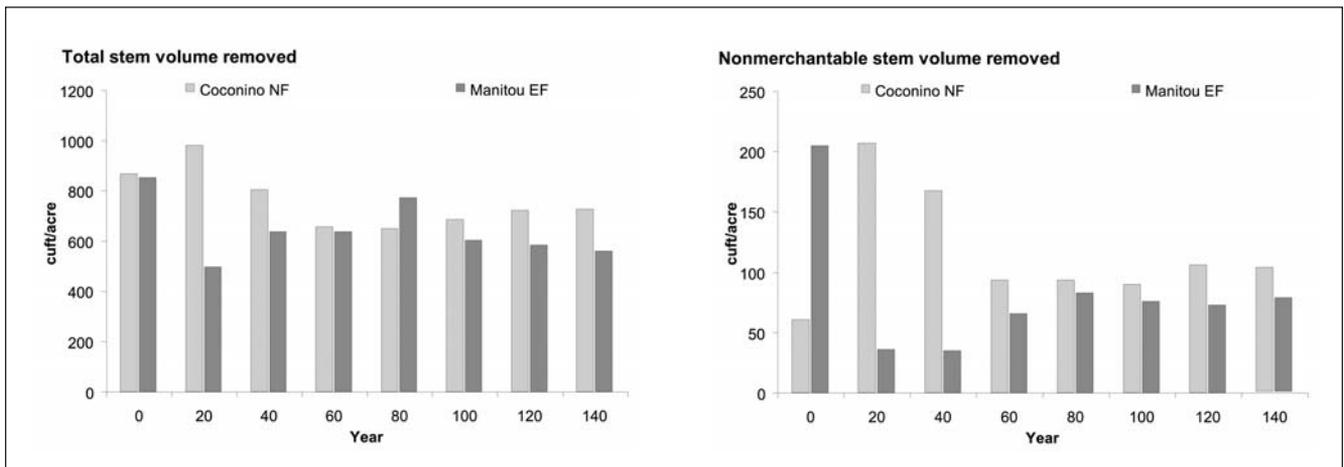
CROOKSTON, N.L. 1990. *User's guide to the Event Monitor: Part of Prognosis Model version 6*. General Technical Report INT-GTR-275. Ogden, UT: USDA Forest Service, Intermountain Research Station.

———. 1997. Suppose: An interface to the Forest Vegetation Simulator. In *Proceedings: Forest Vegetation Simulator Conference*, eds. R. Teck, M. Moeur, and J. Adams. General Technical Report INT-GTR-373. Ogden, UT: USDA Forest Service, Intermountain Research Station.

DAHMS, C.W., and B.W. GEILS, tech. eds. 1997. *An assessment of forest ecosystem health in the Southwest*. General Technical Report RM-GTR-295. Fort Collins, CO: USDA Forest Service, Rocky Mountain



**Figure 6.** Average canopy closure development for three Coconino National Forest stands and the Manitou stand. The dashed line represents the development of the Manitou stand if the same Q model was applied without removing any trees whose dbh exceeds the upper diameter distribution limit of 24 inches. The data points represent moving averages over two 10-year periods.



**Figure 7.** Average flow of stemwood for three Coconino National Forest stands and the Manitou Experimental Forest stand.

Research Station.  
 FOREST MANAGEMENT SERVICE CENTER (FMSC). 2001. *Forest Vegetation Simulator (FVS)*. USDA Forest Service, FMSC. Available online at [www.fs.fed.us/fmcs/fvs/](http://www.fs.fed.us/fmcs/fvs/). Last accessed by authors August 2001.  
 GHOLZ, H.A., C.C. GRIER, A.G. CAMPBELL, and A.T. BROWN. 1979. *Equations for estimating biomass and leaf area of plants in the Pacific Northwest*. Forest Research Lab Research Paper 41. Corvallis: Oregon State University.  
 GRAHAM, R.T., A.E. HARVEY, T.B. JAIN, and J.R. TONN. 1999. *The effects of thinning and similar stand treatments on fire behavior in western forests*. General Technical Report PNW-GTR-463. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.  
 KEELEY, J.E., C.J. FOTHERINGHAM, and M. MORAL. 1999. Reexamining fire suppression impacts on brushland fire regimes. *Science* 284:1829–32.  
 MAST, J.N., P.Z. FULÉ, M.M. MOORE, W.W. COVINGTON, and A.E.M. WALTZ. 1999. Restoration of pre-settlement age structure of an Arizona ponderosa pine forest. *Ecological Applications* 9(1):228–39.  
 MCGAUGHEY, R.J. 1998. *Stand visualization system*. Electronic version distributed February 17. Portland, OR: USDA Forest Service, Pacific Northwest Research Station.

MOORE, M.M., W.W. COVINGTON, and P.Z. FULÉ. 1999. Reference conditions and ecological restoration: A southwestern ponderosa pine perspective. *Ecological Applications* 9(4):1266–77.  
 SIERRA NEVADA ECOSYSTEM PROJECT (SNEP). 1996. *Fire and fuels*. In *Sierra Nevada Ecosystem Project final report to Congress. Vol I: Assessment summaries and management strategies*, 61–71. Davis: University of California, Centers for Water and Wildlife Resources.  
 TECK, R., M. MOEUR, and B. EAV. 1996. Forecasting ecosystems with the Forest Vegetation Simulator. *Journal of Forestry* 94(12):7–10.  
 TECK, R., M. MOEUR, and J. ADAMS. 1997. *Proceedings: Forest Vegetation Simulator Conference*. General Technical Report INT-GTR-373. Ogden, UT: USDA Forest Service, Intermountain Research Station.  
 VAN WAGTENDONK, J.W. 1996. Use of a deterministic fire growth model to test fuel treatments. In *Sierra Nevada Ecosystem Project final report to Congress. Vol. II: Assessments and scientific basis for management options*, 1155–66. Davis: University of California, Centers for Water and Wildlife Resources.  
 WYKOFF, W.R., N.L. CROOKSTON, and A.R. STAGE. 1982. *User's guide to the Stand Prognosis Model*. General Technical Report INT-GTR-133. Ogden, UT: USDA Forest Service, Intermountain Research Station.

*Kurt Hollenstein is forest engineer, Forest Engineering Department, Swiss Federal Institute of Technology, Zurich; Robin L. Graham (grahamrl@ornl.gov) is forest ecologist and head, Ecosystem and Plant Sciences Section, Environmental Sciences Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, TN 37831-6036; Wayne D. Shepperd is research silviculturist, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado. Funding for this study was provided by the Office of Fuels Development, US Department of Energy, Office of Energy Efficiency and Renewable Energy.*