Peter Z. Fulé

Measuring Forest Restoration Effectiveness in Reducing Hazardous Fuels

Peter Z. Fulé, Amy E.M. Waltz, W. Wallace Covington, and Thomas A. Heinlein

ABSTRACT

Forest restoration treatments of thinning young trees followed by prescribed burning in northwestern Arizona led to significantly lower stand density, lower crown fuel load, and higher crown base height than untreated stands. Simulated fire under extreme weather conditions caused 48 percent more canopy burning and higher flame lengths, heat/area, and rate of spread in untreated stands. Wind speeds required for passive crown fire (torching) were twice as high in treated stands. Treated stands were highly heterogeneous, but restoration treatments clearly enhanced crown-fire resistance.

Keywords: fire management; prescribed burning; thinning

Because of fire exclusion and inappropriate past management actions, approximately two-thirds of the 200 million acres of federally managed wildlands adapted to frequent fire regimes are in moderately to severely degraded condition (Interagency Working Group 2001). The extraordinary severity of the Cerro Grande fire in New Mexico in 2000 underscored both the scale of the problem in ponderosa pine forests and the challenges associated with prescribed burning without benefit of mechanical fuel treatments. Reduction of hazardous fuels can be attempted at levels ranging from prescribed underburning, a minimal-impact approach, to complete stripping of forest cover, the maximum-impact method used in Califor-

Above: **Recent prescribed burning of a forest restoration experimental unit on the Fort Valley Experimental Forest, Coconino National Forest, near Flagstaff. The stand's attributes of relatively high crown base height, low crown fuels, and diverse structure are associated with high resistance to torching and active crown fire.**

nia's Ponderosa Way fuelbreak (Pyne et al. 1996). For resource managers and communities struggling to deal with wildfire hazards, it is increasingly important to test treatment alternatives and compare the relative efficacy of fire hazard reduction techniques.

Modeling potential fire behavior is the most common approach to comparing treatments, because most treated areas cannot be "tested" by deliberately igniting a crown fire (see Agee et al. [2000] for an unplanned test—and failure—of a fuelbreak). Models of crown-fire behavior are complex and poorly understood (Scott 1998), but they are important for assessing the potential behavior of high-intensity crown fires with high resistance to control. For example, Kalabokidis and Omi (1998) thinned lodgepole pine plots in Colorado, applied standard models to predict surface fire behavior, and inferred crown-fire impacts using nomograms (Rothermel 1991). Scott (1998) integrated surface and crown-fire algorithms to develop a stand-scale modeling approach for testing alternative thinning and burning treatments in a Montana ponderosa pine forest. At the landscape scale, Stephens (1998) used the Farsite model as an assessment tool for contrasting treatments.

Restorative management approaches offer the prospect of improvement in ecological parameters such as productivity and diversity, while simultaneously reducing fuel hazards and fire severity (Covington et al. 1997). Many ecosystems adapted to frequent fire, such as ponderosa and related long-needled western pines, exhibit hazardous fuel accumulations and severe wildfires as the symptoms of ecological imbalances (Wagner et al. 2000). Although experiments initiated by Scott (1998), Lynch et al. (2000), Moore et al. (1999), and others are beginning to provide information on ecological responses, these studies are in early post-treatment phases. Many variables are likely to fluctuate widely in the first years after treatment because rapid successional changes are altering plant and animal communities. Potential fire behavior, however, is an environmental factor that can be affected by treatment in a short time and have long-term effects.

One of the first replicated stand-level experiments in forest restoration in the Southwest began in 1995 as a collaboration between the Bureau of Land Management (BLM) Arizona Strip District, the Arizona Game and Fish Department, and the Ecological Restoration Institute of Northern Arizona University.

Methods

The overall project is broad in scope, testing both landscape- and stand-scale treatments, with researchers investigating a broad array of ecosystem responses. Here we report on the effects of forest restoration on fuel reduction, comparing potential behavior of wildfire modeled under extreme weather conditions to assess differences between treatment and control stands.

The Mount Trumbull study site is located in the Uinkaret Mountains on the Arizona Strip, north of the Colorado River (latitude 36° 22' N, longitude 113° 7' W). Soils are derived from volcanic substrates. Annual precipitation at Mount Trumbull averaged 19.9 inches (1977 to 1997), mostly occurring in winter and during the summer monsoon (July–September). Vegetation includes ponderosa pine *(Pinus ponderosa)*–Gambel oak *(Quercus gambelii)* forest. Utah juniper *(Juniperus osteosperma),* pinyon *(Pinus edulis),* New Mexican locust *(Robinia neomexicana),* and shrub species are interspersed in the pine-oak forest. As elsewhere in the Southwest, surface fires were frequent (mean fire intervals of 5–7 years [P.Z. Fulé et al., unpublished data]) prior to European settlement of the region beginning in 1870, when livestock grazing, logging, and fire suppression led to substantial increases in forest density (Moore et al. 1999).

Four experimental blocks were established in 1997, representing the range of elevation and forest structure in the Mount Trumbull forest. Treatments (restoration and control) were randomly assigned to nominally 20-acre units in each block. Twenty permanent monitoring plots were established in each unit during July–August 1997 (block 1) and April–July 1998 (N = 160 plots). Plots were located on a 196.8-foot grid, corresponding to a measured experimental area of 17.8 acres per treatment unit. Overstory trees taller than breast height (4.5 feet) were measured on a 4,306-square-foot circular fixed-area plot. Trees below breast height and shrubs were tallied by condition class and by height classes on a nested 1,076-square-foot subplot. Plant species, substrate, and overstory canopy cover (vertical projection) were recorded every 11.8 inches along a 164-foot line transect–oriented upslope. Dead woody biomass and forest floor depth were measured on a 50-foot planar transect in a random direction from each plot center.

The forest restoration prescription was designed to rapidly emulate historic forest structure, followed by reintroduction of surface fire. All old-growth (predating 1870) trees of all species were retained. Where snags, fallen trees, or stumps evidenced old conifers that had died, three younger trees of the same species within a 30- to 60-foot radius were selected as replacements (Covington et al. 1997). Fire-susceptible deciduous species (oak and locust) were not thinned. Thinning was carried out by commercial contractors and BLM crews in 1999. Slash was lopped and scattered. Deep duff layers were raked 1 to 3 feet away from boles of all old-growth trees and snags. Treatment units were burned in the winter of 1999–2000. Plots were remeasured during May–July 2000.

Weather conditions for fire model-

Table 1. Fuel moisture, wind, and temperature for the Tusayan weather station (Kaibab National Forest, Arizona), entire fire season and month of June, 1966–99.

	Fire season (April 23–October 16)		June	
	90th percentile	97th percentile	90th percentile	97th percentile
1-hour moisture (percent)	3.3	2.6	2.3	1.7
10-hour moisture (percent)	4.4	3.4	3.0	3.0
100-hour moisture (percent)	6.8	6.4	4.5	4.5
Wind speed (mph)	13	16.9	15	19
Temperature (°F)	84.7	84.7	90	90

Table 2. Canopy fuel and stand characteristics of control and treatment stands, Mount Trumbull forest.

	Block 1	Block 2	Block 3	Block 4	Mean
Control					
Crown bulk density (lbs/ft^3)	0.00220	0.00335	0.00321	0.00610	0.00372
Average crown base height (ft)	8.6	9.4	5.1	10.0	8.3*
Low quintile crown base height (ft)	5.2	5.6	2.9	7.2	5.2
Crown fuel load (tons/acre)	3.61	5.41	3.67	6.86	4.89**
Stand height (ft)	84.0	85.3	57.7	61.7	72.2
Basal area (ft^2/acre)	117.7	155.1	117.6	192.3	145.7
Pine density (trees/acre)	245.5	264.2	248.0	658.4	354.0**
Oak–locust density (trees/acre)	30.4	241.4	48.1	154.4	118.6
Pinyon–juniper density (trees/acre)	0	5.6	2.6	149.3	39.4
Treatment					
Crown bulk density (lbs/ft^3)	0.00156	0.00260	0.00217	0.00643	0.00319
Average crown base height (ft)	16.2	14.3	17.5	34.2	20.6*
Low quintile crown base height (ft)	9.9	4.5	10.2	25.2	12.4
Crown fuel load (tons/acre)	2.01	2.65	2.23	3.63	2.63**
Stand height (ft)	75.4	61.0	64.6	60.0	65.3
Basal area (ft^2/acre)	67.8	65.0	74.1	115.0	80.5
Pine density (trees/acre)	36.4	18.7	40.5	186.2	70.5**
Oak–locust density (trees/acre)	14.2	210.0	16.2	11.1	62.9
Pinyon–juniper density (trees/acre)	0	1.5	0	13.7	3.8

Note: Means indicated with asterisks are significantly different ($p < .10$, **$p < .05$).*

ing were based on the 90th and 97th percentiles of low fuel moisture, high winds, and high temperature from 34 years of data on the Kaibab National Forest (Tusayan weather station) using the FireFamily Plus program (Bradshaw and Brittain 1999). Weather values were calculated for the entire fire season (April 23 to October 16) as well as for June, historically the month with the most severe fire weather *(table 1).*

Fire behavior was modeled with the Nexus Fire Behavior and Hazard Assessment System (Scott and Reinhardt 1999). Crown fuels were estimated with allometric equations for foliage and fine twigs of ponderosa pine (Fulé et al. 2001), Gambel oak (Clary and Tiedemann 1986), and pinyon and juniper (Grier et al. 1992). Crown volume was estimated by the averages of maximum tree height (top of the canopy) and crown base height (bottom of the canopy). Crown bulk density was calculated as crown biomass divided by crown volume. For the purposes of predicting passive crown-fire behavior (torching), we used the lowest quintile (20 percent) of crown base heights in each stand. Stand characteristics and model outputs were compared with multivariate analysis of variance followed by post-hoc univariate comparisons (F test, alpha = 0.05).

Results

There were no significant differences in tree density or basal area between treatment and control pairs prior to thinning and burning. After treatment, restoration stands had significantly lower pine density, lower crown fuel load, and higher crown base height *(table 2).* Although crown fuel load in treated stands averaged only half that of control stands (54 percent), crown bulk density in the treatments averaged 85 percent of control stands. This counterintuitive result is an artifact of raising crown base height when small trees were thinned, reducing crown volume. For instance, in block 4 the treated stand had a slightly higher crown bulk density than the control despite having half the crown biomass.

Fire model results *(table 3)* should be interpreted with caution. The mod-

Table 3. Fire behavior outputs under the June 97th-percentile weather conditions with 30-mph winds and lowest quintile crown base height.

	Block 1	Block 2	Block 3	Block 4	Mean
Control					
Fire type[1]	Passive	Passive	Passive	Active	—
Crown percent burned	38	65	69	100	68*
Rate of spread (ft/min)	81.3	108.9	112.2	143.0	111.5*
Heat/area (Btu/ft^2)	986	1,796	1,396	2,942	1,780*
Flame length (ft)	20.0	37.7	30.1	64.3	38.0*
Crown fire outputs					
Torching index (mph)	12.9	13.9	6.4	17.9	12.8
Crowning index (mph)	48.2	36.4	36.9	22.4	36.0*
Treatment					
Fire type[1]	Passive	Passive	Passive	Surface	—
Crown percent burned	11	49	18	0	20*
Rate of spread (ft/min)	55.1	92.5	61.7	43.6	63.3*
Heat/area (Btu/ft^2)	583	962	644	501	673*
Flame length (ft)	9.5	20.0	11.1	6.9	11.8*
Crown fire outputs					
Torching index (mph)	24.1	11.2	24.6	55.9	29.0
Crowning index (mph)	61.6	43.0	48.8	22.4	44.0*

[1]Fire types are surface, passive crown-fire or "torching," and active crown-fire.
*Notes: Foliar moisture content was held constant at 100 percent, fire behavior fuel model was 9 (hardwood and long-needled conifer litter), and wind reduction factor was 0.3 for all simulations. Means indicated with asterisks are significantly different (*p < .10, **p < .05).*

els are highly sensitive to crown base height, wind speed (or wind reduction factor), fuel moisture, and surface fuel model variables (1H fuel loading, herbaceous fuels, surface-area-to-volume ratio, fuel bed depth). The behavior of real fires in these stands would be affected by variability in fuels and weather, roads, meadows, surrounding forest fuels, landscape topography, and suppression activities. The standard fire behavior fuel model 9 was intended to represent long-term surface fuels, not the activity fuels that were actually present immediately after thinning. However, when used to compare the treatment alternatives under a common weather scenario, the analysis provided an excellent basis for assessing relative differences in potential fire behavior.

Fires simulated under the severe weather conditions were fast and hot in all stands, but fire behavior was significantly less intense in the treated stands *(table 3).* Crown-fire behavior includes both passive (torching) and active canopy burning. Crown burning was predicted in all of the control stands, three with passive crown fire consuming 38 to 68 percent of the canopy and the fourth with active crown fire and complete canopy consumption. Treated stands were not immune from passive crown fire because small oak and locust trees were not thinned, so the lowest quintile crown base heights remained below 10 feet in three of the four treated stands. The treatment unit in block 2, with the most oak, had the lowest crown base and lowest torching index (minimum wind speed that would support passive crown fire). However, treated stands averaged only 20 percent canopy burned, while controls averaged 68 percent. High flame lengths (average 11.8 feet) and heat/area values (average 673 Btu per square foot) were predicted in the treated stands, consistent with torching expected to occur in portions of the units, but flame length and heat/area were significantly higher in controls (average 38.0 feet and 1,780 Btu per square foot).

In contrast to the torching index, crowning index was most closely related to crown bulk density. The two indices were poorly correlated. For example, the treated stand in block 2 had a low crown base height (4.5 feet), so the torching index was correspondingly low (11.2 miles per hour), but block 2 had an intermediate crown bulk density value (0.00260 pounds per cubic foot), so the crowning index was also intermediate (43.0 miles per hour). The opposite occurred in the treated stand in block 4: The high crown bulk density led to a low crowning index of 22.4 miles per hour, less than the 30-mile-per-hour modeled winds, but no canopy burning was predicted because the high crown base height (25.2 feet) prevented fire from entering the crowns.

Treatment and control stand characteristics from Mount Trumbull are compared graphically with other southwestern sites in *figure 1,* p. 28. Other experiments included a restoration treatment at Grand Canyon (Kaibab National Forest: Fulé et al., in review); at the Flagstaff wildland-urban interface (Coconino National Forest: Fulé et al. 2001); and the Forests Forever! treatment designed by the Southwest Forest Alliance (1996), a consortium of environmental activist groups. Stand characteristics were broadly variable, but restoration sites at Mount Trumbull and on the national forests clearly grouped toward high crown-fire resistance (high crowning index), associated with low crown biomass and basal area. Only the most dense of the treated stands—Mount Trumbull

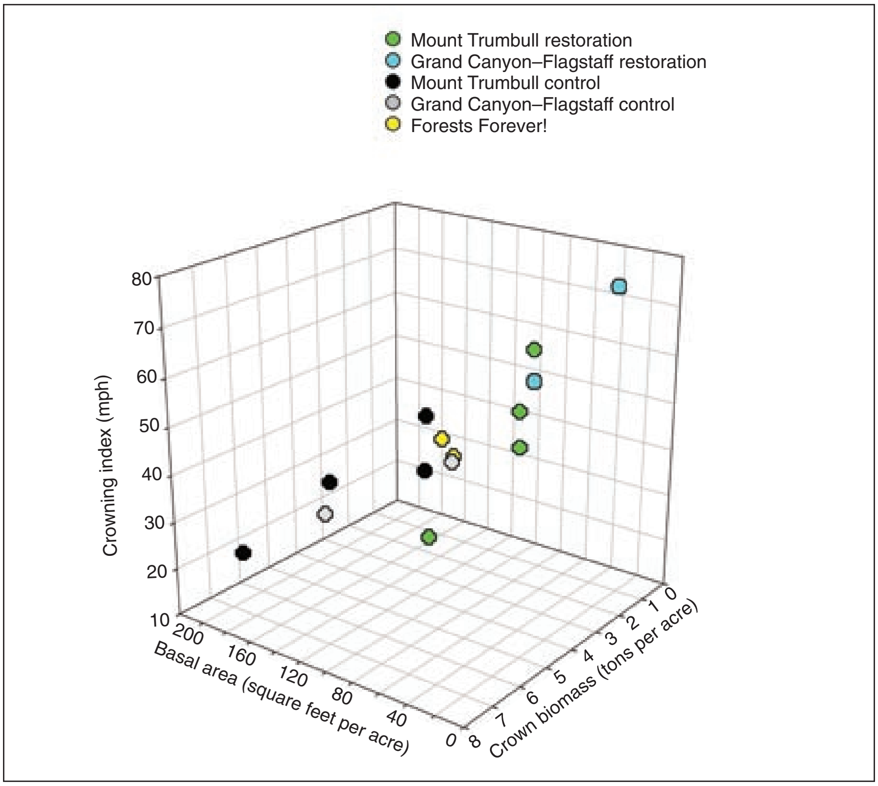

Figure 1. **Comparison of forest basal and crown biomass with crown-fire index (minimal wind speed required to sustain active crown fire) shows that high variability exists in both treated and untreated forests, but restoration treatments lead to higher crown-fire resistance. Study sites include the four Mount Trumbull units described in the text as well as analogous sites on the Kaibab (Grand Canyon) and Coconino (Flagstaff) National Forests. The Forests Forever! treatment was developed by the Southwest Forest Alliance and implemented on the Kaibab and Gila National Forests. It was intermediate in stand and fire characteristics.**

block 4—remained grouped with the controls. Control stands were clustered toward low crown-fire resistance and high crown biomass and basal area. The Forests Forever! treatments, intentionally designed as a lower-impact forest restoration approach (SWFA 1996), fell in the middle between control and restoration stands. This outcome implies that the lighter thinning of Forests Forever! provided measurable but minimal improvement in crown-fire resistance.

Discussion

Nexus and similar fire behavior models offer a valuable approach for making quantitative comparisons across study sites. These comparisons provide a fair, quantitative basis for managers to evaluate the fire behavior implications of alternative treatments. And they make important contributions to public discussions over treatments to reduce hazardous fuels.

Forest stands were highly variable in stand characteristics following the site-specific restoration treatments, as shown in *table 2* and *figure 1,* reflecting the heterogeneity of natural forest conditions. While conserving the range of structural variability, however, restoration treatments shifted the entire distribution toward significantly more crown-fire resistance. Application of restoration treatments across the larger landscape of the Mount Trumbull highlands would be expected to result in a complex, fine-grained mosaic of forest structural conditions, relatively immune from severe wildfire and relatively safe for prescribed burning or wildland fire use for resource benefits.

Forest restoration is a viable approach for shaded fuelbreaks, area treatments (Agee et al. 2000), and urban interface fuel hazard reduction. The primary advantage of restoration is the ability to simultaneously address fire issues and other broad objectives consistent with the evolutionary environment of the ecosystem. Clewell (2000, p. 217) described the process of ecological restoration as "secur[ing] our future by restocking a dangerously depleted global inventory of natural areas." Such comprehensive goals extend well beyond ameliorating wildfire concerns. If restorative management proves even partially successful in recapturing the native productivity and diversity of degraded ecosystems, fuel hazard reduction may eventually be seen as a useful but incidental benefit.

The particular restoration design used at Mount Trumbull may not be suitable in all critical fire areas. We retained moderately dense stands still subject to some degree of passive crown fire. Maintenance burning is required to check new reproduction from reoccupying the lower stratum of the stand. Because conifers were retained well in excess of the historic (pre-1870) forest density, due to the 3:1 replacement ratio, future thinning entries or snag creation treatments might be necessary to maintain open forest conditions.

Fire hazard is only one of many variables that enter into ecosystem management decisions. The fuel hazard reduction benefits of forest restoration are apparent as soon as thinning and burning have been completed, but long-term monitoring is necessary to measure responses of plant and animal communities, tree mortality and regeneration, and biogeochemical and disturbance processes (e.g., Oliver and Powers 1998). Continued experimentation and adaptive application of monitoring results are also necessary. Arguably the most beneficial outcome of the Forests Forever! treatment has been the stimulation of inquiry on the part of environmental activists to formulate *and implement* an alternative restoration approach. Engagement and testing of ideas by groups across the spectrum of public land stakeholders may be one of the most effective ways to advance thoughtful management of ecosystems.

Literature Cited

AGEE, J.K., B. BAHRO, M.A. FINNEY, P.N. OMI, D.B. SAPSIS, C.N. SKINNER, J.W. VAN WAGTENDONK, and C.P. WEATHERSPOON. 2000. The use of shaded fuelbreaks in landscape fire management. *Forest Ecology and Management* 127:55–66.

Bradshaw, L., and S. Brittain. 1999. *FireFamily Plus.* Software available from USDA Forest Service, Rocky Mountain Research Station, Missoula Montana.

Clary, W.P., and A.R. Tiedemann. 1986. Distribution of biomass within small tree and shrub form *Quercus gambelii* stands. *Forest Science* 32(1):234–42.

Clewell, A.F. 2000. Restoring for natural authenticity. *Ecological Restoration* 18(4):216–17.

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. Restoration of ecosystem health in southwestern ponderosa pine forests. *Journal of Forestry* 95(4):23–29.

Fulé, P.Z., C. McHugh, T.A. Heinlein, and W.W. Covington. 2001. Potential fire behavior is reduced following forest restoration treatments. In *Ponderosa pine ecosystems restoration and conservation: Steps toward stewardship,* comps. R.K. Vance, W.W. Covington, and C.B. Edminster, 28–35. Proceedings RMRS-P-22. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station.

Fulé, P.Z., W.W. Covington, H.B. Smith, J.D. Springer, T.A. Heinlein, K.D. Huisinga, and M.M. Moore. In review. Testing ecological restoration alternatives: Grand Canyon, Arizona. *Forest Ecology and Management.*

Grier, C.C., K.J. Elliott, and D.G. McCullough. 1992. Biomass distribution and productivity of *Pinus edulis-Juniperus monosperma* woodlands of north-central Arizona. *Forest Ecology and Management* 50: 331–50.

Interagency Working Group. 2001. *Review and update of the 1995 federal wildland fire management policy.* Boise, ID: National Interagency Fire Center.

Kalabokidis, K.D., and P.N. Omi. 1998. Reduction of fire hazard through thinning/residue disposal in the urban interface. *International Journal of Wildland Fire* 8(1):29–35.

Lynch, D.L., W.H. Romme, and M.L. Floyd. 2000. Forest restoration in southwestern ponderosa pine. *Journal of Forestry* 98(8):17–24.

Moore, M.M., W.W. Covington, and P.Z. Fulé. 1999. Evolutionary environment, reference conditions, and ecological restoration: A southwestern ponderosa pine perspective. *Ecological Applications* 9(4): 1266–77.

Oliver, W.W., and R.F. Powers. 1998. Blacks Mountain, California: Interdisciplinary field research in ponderosa pine. *Journal of Forestry* 96(8):4–9.

Pyne, S.J., P.L. Andrews, and R.D. Laven. 1996. *Introduction to wildland fire.* 2nd ed. New York: John Wiley & Sons.

Rothermel, R.C. 1991. *Predicting behavior and size of crown fires in the northern Rocky Mountains.* Research Paper INT-438. Ogden, UT: USDA Forest Service, Intermountain Research Station.

Scott, J.H. 1998. *Fuel reduction in residential and scenic forests: A comparison of three treatments in a western Montana ponderosa pine stand.* Research Paper RMRS-RP-5. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station.

Scott, J.H., and E. Reinhardt. 1999. *Nexus fire behavior and hazard assessment system.* Software program available from Systems for Environmental Management, Missoula, Montana.

Southwest Forest Alliance (SWFA). 1996. *Forests Forever! A plan to restore ecological and economic integrity to the Southwest's national forests and forest-dependent communities.* Flagstaff, AZ.

Stephens, S.L. 1998. Evaluation of the effects of silvicultural and fuels treatments on potential fire behavior in Sierra Nevada mixed-conifer forests. *Forest Ecology and Management* 105:21–35.

Wagner, M.R., W.M. Block, B.W. Geils, and K.F. Wenger. 2000. Restoration ecology: A new forest management paradigm, or another merit badge for foresters? *Journal of Forestry* 98(10):22–27.

Peter Z. Fulé (pete.fule@nau.edu) is assistant professor, Amy E.M. Waltz is research specialist, and W. Wallace Covington is Regents' Professor, Ecological Restoration Institute and School of Forestry, Northern Arizona University, PO Box 15018, Flagstaff AZ 86011; Thomas A. Heinlein is ecologist, USDI National Park Service, Anchorage, Alaska. *This research was supported by the USDI Bureau of Land Management (Arizona Strip District), USDI National Park Service (Grand Canyon National Park), and USDA Forest Service (Coconino, Kaibab, and Gila National Forests, Rocky Mountain Research Station).*