By W. Wallace Covington, Peter Z. Fule, Margaret M. Moore, Stephen C. Hart, Thomas E. Kolb, Joy N. Mast, Stephen S. Sackett, and Michael R. Wagner

Restoring Ecosystem Health in Ponderosa Pine Forests of the Southwest

A controlled burn was set by researchers in thinned stands of southwestern ponderosa pine to reconstruct the open, parklike landscape that once characterized the ecosystem.

A major stumbling block to ecosystem management is the lack of healthy ecosystems to serve as points of comparison. Aldo Leopold (1934) recognized this problem and suggested using ecological restoration techniques to reconstruct reasonable approximations of naturally functioning ecosystems (Callicott and Flader 1992). We have initiated an integrated set of research projects designed to accomplish this goal and in the process determine ecosystem health attributes for a southwestern ponderosa pine ecosystem.

Previous research has established that forests of ponderosa pine *(Pinusponderosa)* in the Southwest were much more open before Euro-American settlement (Cooper 1960; Covington and Moore 1994b). Until the 1870s, light surface fires every two to five years, along with grass competition and regular drought, maintained an open and parklike landscape dominated by grasses, forbs, and shrubs with scattered groups of ponderosa pine trees. After Euro-American settlement, heavy livestock grazing, fire suppression, logging disturbances, and climatic events favored dense ponderosa pine regeneration, and the open parklands closed.

Various authors (Covington and Moore 1994a, 1994b; Kolb et al. 1994) have described unhealthy characteristics of the postsettlement ponderosa pine ecosystems, including increases in tree density, forest floor depth, and fuel loading, with the following consequences: (1) decreases in soil moisture and nutrient availability, (2) decreases in growth and diversity of both herbaceous and woody plants, (3) increases in mortality in the oldest age class of trees, (4) decreases in stream and spring flows, and (5) increases in fire severity and size.

Our research was guided by the following general hypotheses:

- that both restoration of ecosystem structure and reintroduction of fire are necessary for restoring rates of decomposition, nutrient cycling, and net primary production to natural, presettlement levels; and
- that the rates of these processes will be higher in an ecosystem that approximates the natural structure and disturbance regime.

Specifically, we hypothesized that reestablishing presettlement stand structure alone (thinning a majority of the postsettlement trees) would result in lower rates of decomposition, nutrient cycling, and net primary production compared with thinning, forest floor fuel manipulation, and prescribed burning in combination; but that both treatments would result in higher rates of these processes compared with controls. We further hypothesized that without periodic burning to hold them in check, pine seedling irruptions would recur on the thin-only treatment area. We addressed three specific questions:

1. How have ecosystem structure (by biomass component) and nutrient storage changed over the past century of fire exclusion in a ponderosa pine–bunchgrass ecosystem?

2. What are the implications of these changes for net primary production, decomposition, nutrient cycling, and other important ecosystem characteristics?

3. Does partial restoration (restoring tree structure alone by thinning postsettlement trees) differ from complete restoration (the same thinning, plus forest floor removal, loading with herbaceous fuels, and prescribed burning) in its effects on ecosystem structure and function?

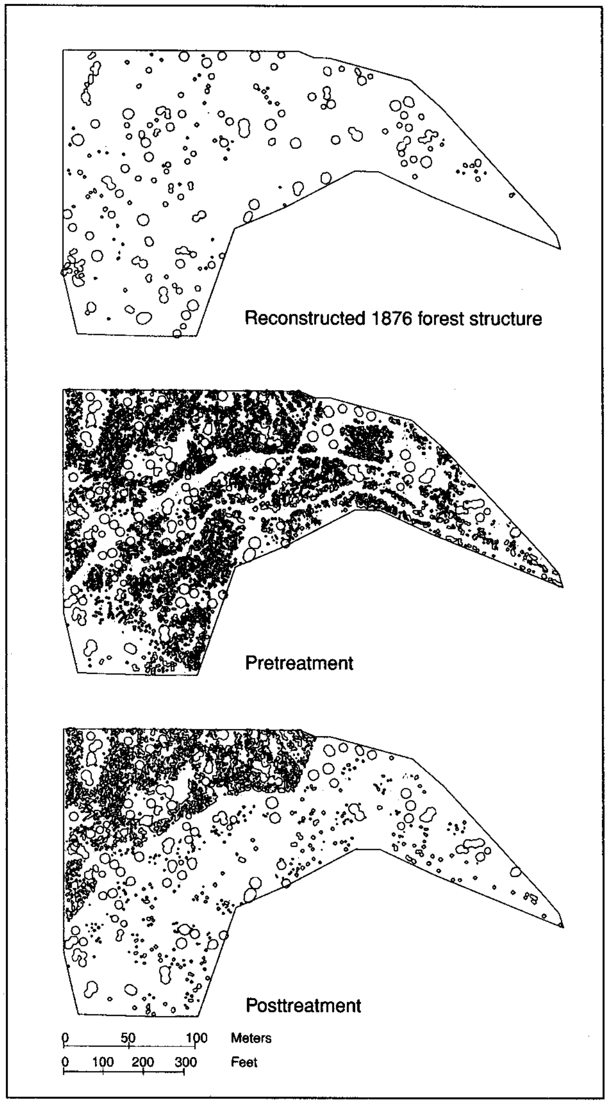

Figure 1. Canopy maps of the study area within the FortValley Experimental Forest, near Flagstaff, Arizona. Scattered groups of southwestern ponderosa pine predominated in the late 19th century *(top),* before settlement suppressed natural wildfires. This suppression caused a far greater profusion of vegetation in dense "doghair" thickets of pine saplings *(middle).* Researchers are now attempting, through prescribed burns and manual thinning, to restore the ecosystem to its original condition *(bottom).*

> The time has come for science to busy itself with the earth itself. The first step is to reconstruct a sample of what we had to begin with.
>
> ***--Aldo Leopold, 1934***

The Study

Our study area is a virgin stand of ponderosa pine within the Fort Valley Experimental Forest approximately seven miles northwest of Flagstaff, Arizona. Stand structure is an uneven-aged forest with trees in small, uneven-aged groups *(fig.1),* typical of ponderosa pine in the Southwest (Cooper 1960; Schubert 1974; White 1985). Pole-sized trees, approximately 4 to 14.5 inches dbh, are the predominant size class, with scattered groups of presettlement trees 14.5 to 41 inches dbh and dense "doghair" thickets of saplings up to 3.9 inches dbh. The treatment plots are in an eight-acre portion of the G.A. Pearson Natural Area, which was decommissioned in 1987. Individual tree growth and mortality records for all trees greater than six inches dbh are available at five-year intervals from 1920 to the present (Avery et al. 1976; and unpublished data).

The area is gentle in topography (slopes less than 5 percent) with a southwest aspect. Elevation is 7,200 to 7,400 feet. The climate is cool and subhumid with early summer drought. Mean annual precipitation is 22.3 inches and mean annual temperature is 45.5°F. Approximately half the precipitation falls as snow. The average frost-free growing season is 94 days. Soils at the study site are derived from basalt and volcanic cinders and are a fine montmorillonitic complex of frigid Typic Argiborolls and Argiboralfs.

The understory consists primarily of Arizona fescue *(Festuca arizonica),* mountain muhly *(Muhlenbergia montana),* mutton bluegrass *(Poa fendleriana),* pine dropseed *(Blepharoneuron tricholepis),* bottlebrush squirreltail *(Sitanion hysterix),* and a variety of forbs. Buckbrush *(Ceanothus fendleri)* is the only common shrub.

The site has never been harvested; the only major disturbances have been livestock grazing between 1876 and 1910 and fire exclusion since 1876. Dieterich (1980) determined that the last natural fire in the vicinity occurred in 1876, before that, fires occurred at an average interval of about two years.

Rationale for Treatments

A fundamental issue is what treatment or combination of treatments will rapidly achieve some facsimile of a healthy ponderosa pine ecosystem. The two leading candidates for ecological restoration of ponderosa pine ecosystems are prescribed burning and thinning from below (Covington and Moore 1994b; Arno et al. 1995).

Previous research near our study area had shown that although prescribed burning alone (without thinning or manual fuel removal) could reduce surface fuel loads, stimulate nitrogen availability, and increase herbaceous productivity, it caused high mortality of the presettlement trees (60 percent mortality over a 20-year period) and lethal soil temperatures under presettlement tree canopies (Covington and Sackett 1984, 1990, 1992; Harrington and Sackett 1990; Sackett et al. 1993). Although some thinning of postsettlement ponderosa pine trees was accomplished by prescribed burning (Harrington and Sackett 1990), results were localized, unpredictable, and difficult to control. Furthermore, even under very conservative prescriptions (low air temperatures and low windspeed), reburning can produce dangerous fires (Covington and Sackett, pers. observ., 1984–95) because the continuing high density of postsettlement trees provides a continuous fuel ladder and thus a high crown-fire potential. Clearly, research shows that prescribed burning in today's unnatural structure will not restore natural conditions in ponderosa pine–bunchgrass ecosystems. Thus, some combination of thinning, manual fuel removal, and prescribed burning will be necessary to quickly restore these systems to natural conditions.

Key Ecological Attributes and Appropriate Measurement Techniques

Ecosystem structure and production

Tree biomass and above-ground production:
Dimension analysis (Baskerville 1965)

Stand age structure:
Dendrochronology (Fritts and Swetnam 1989)

Herbaceous and shrub biomass and production:
Seasonal clipping and allometric techniques (Cook and Stubbendick 1986)

Below-ground primary production:
Sequential root harvesting (Caldwell and Virginia 1989)

Litter fall:
Litter traps and permanent transects (Covington and Sackett 1984, 1990)

Forest floor biomass:
Planar intercept technique (Brown 1974, Sackett 1980)

Soil bacterial and fungal biomass:
Substrate-induced respiration plus selective metabolic inhibitors (Beare et al. 1991)

Soil processes

Litter decomposition and nitrogen and phosphorus release:
Litterbag method (Hart et al. 1992)

Net nitrogen mineralization:
Resin core technique (Binkley and Hart 1989)

Leaching loss of nutrients:
Tension lysimeters (Parizek and Lane 1970)

Soil respiration:
Soda-lime technique (Edwards 1982)

Tree physiology

Tree growth efficiency:
Growth efficiency index (Waring and Pitman 1985)

Net photosynthetic rate:
Infrared gas analyzer (Leverenz and Hallgren 1991)

Water stress:
Pressure bomb (Ritchie and Hinckley 1975)

Foliar N and P concentrations:
Micro-Kjeldahl (Binkley and Hart 1989)

Tree resistance to insects

Indicator of bark beetle resistance:
Xylem resin flow (Kozlowski et al. 1991)

Indicators of resistance to folivores:
Foliage toughness (Wagner and Zhang 1993)

Insect populations

Turpentine beetle populations:
Pitch tube sampling (Smith 1971)

Microenvironment

Soil moisture:
Time-domain reflectometry (Rundel and Jarrell 1989)

Air and soil temperature:
Thermocouples and data logger

Design and Sampling

The study area was divided into 15 plots, five each in the complete restoration (3.5 acres), partial restoration (3.3 acres), and control (3.8 acres) treatments. Permanently marked photo points were established. All plots were completely stem-mapped in 1992, including all living and dead trees and large downed logs. Species, condition class, and diameter at breast height (4.5 feet) were recorded for all trees, and all retained and control plot trees were permanently tagged. All presettlement and potentially presettlement trees—those with diameter at breast height >14.8 inches or yellowed bark (White 1985)-were cored and crossdated (Stokes and Smiley 1968) to determine age. Cross-sections or increment cores were taken from all ponderosa pine snags, stumps, and downed trees that were potentially of presettlement age. Samples were crossdated and, when possible, death date, pith date, and diameter in 1876 were determined. A random 5 percent subsample of postsettlement trees was also cored and aged.

Herbaceous and fuel variables were measured on 55 replicated circular subplots (16.4 feet in diameter) located within four overstory strata: (1) presettlement patches, (2) postsettlement patches to be thinned with some trees retained, (3) postsettlement patches to be converted to openings, and (4) remnant natural grassy openings. Herbaceous species composition, basal cover, and production were measured on two 10.7 ft^2 quadrats within each subplot. Forest floor fuels were averaged from two 16.4-foot planar transects on each subplot (Sackett 1980).

Both partial and complete restoration areas were thinned in fall 1993 and the stumps cut to ground level. All presettlement trees were retained, as were all trees above 16 inches dbh. In addition, smaller-diameter postsettlement trees were retained near stumps, snags, and down presettlement logs in an attempt to recreate the clumped pattern of the presettlement forest. Realizing that many of the spindly postsettlement trees would not survive, we left approximately three postsettlement trees for every dead presettlement tree.

Slash was removed in spring 1994 and an eight-foot electrified elk fence was constructed around the study area perimeter. On the complete restoration treatment plots, the litter layer (O_i) was raked aside, accumulated duff (O_a and O_e) was removed, and litter was scattered back across the forest floor. Coarse woody fuels of presettlement origin, such as the limbs and boles of fallen presettlement trees, were retained, but postsettlement woody fuels were removed. Average duff depth in the presettlement stratum dropped from 3.3 to 0.4 inches even though litter depth was nearly unchanged (0.5 to 0.6 inches). Because the presettlement fuel structure was composed primarily of grasses, approximately 600 pounds per acre of supplemental native grass fuels (harvested from a nearby natural meadow in September 1994) was scattered across the complete restoration plots. Soil and tree cambial thermocouples were installed in representative locations in each complete treatment plot (Sackett and Haase 1992). The plots slated for complete restoration were then burned on October 12, 1994, when the temperature was 58° to 60°F, winds were five to 10 mph from the east-southeast, and relative humidity was around 30 percent.

In addition to tree density, herbaceous vegetation cover, and fuel loading, we are monitoring a broad range of ecological attributes related to ecosystem health.

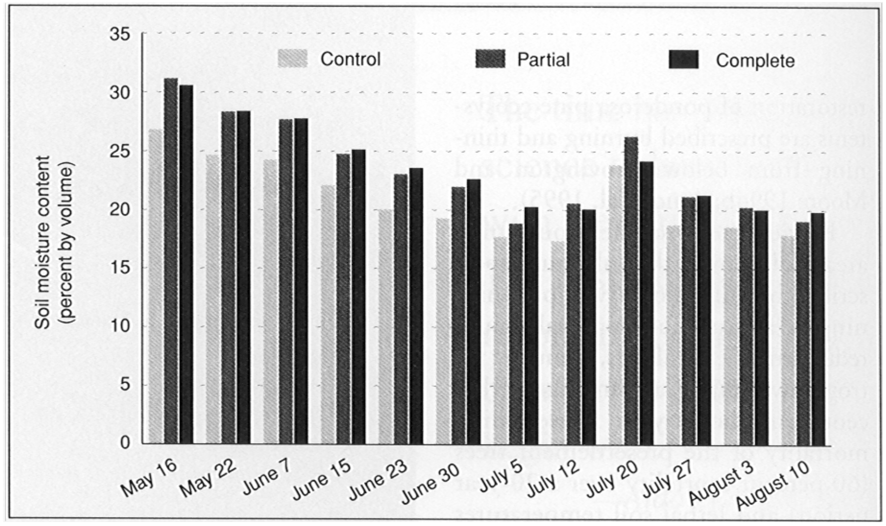

Figure 2. **Mean volumetric soil moisture content of mineral soil (0- to 12-inch depth) for control, partial, and complete restoration treatments during the 1995 growing season. Soil moisture in treated areas is appreciably higher during the normal early summer drought, creating more favorable conditions for the survival of young trees and other vegetation.**

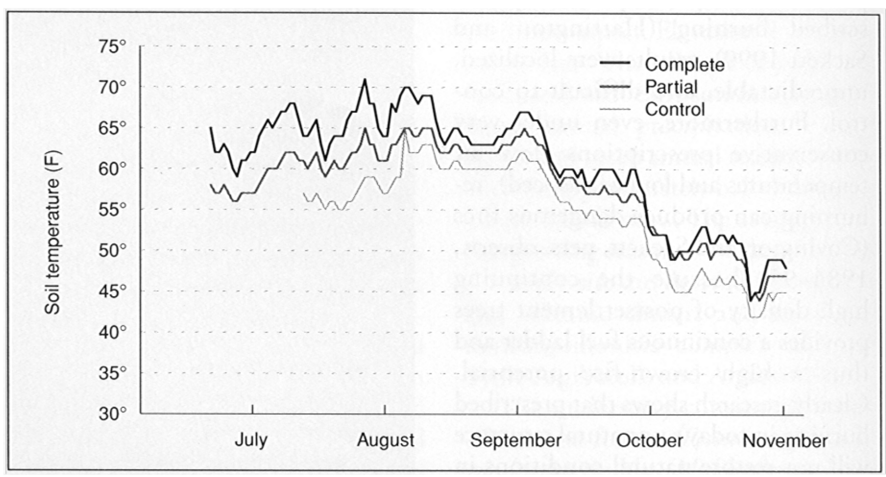

Figure 3. **Mean mineral soil temperature (3-inch depth) in control, partial, and complete restoration treatments during summer and fall 1995. The higher mineral soil temperatures in treated areas are presumed to be the result of increased insolation at the soil surface and decreased insulation at the forest floor.**

Results and Discussion

Dendrochronological analysis revealed that forest structure had changed substantially in our study area since fire regime disruption *(table 1).* Particularly striking is the population growth of ponderosa pine from 22.8 trees per acre in 1876 to 1,253.5 trees per acre in 1992. Although small-diameter trees (<16 inches dbh) increased from 3.4 per acre in 1876 to 1,240.7 in 1992, larger trees decreased from 19.4 per acre in 1876 to 12.8 in 1992, despite protection from logging. The irruption of smaller-diameter pine trees also created a continuous tree canopy cover *(fig. 1)* at the expense of herbaceous vegetation. In 1876 only 19 percent of the surface area was under pine canopy, with the balance (81 percent) representing grassy openings, whereas in 1992 pine canopy covered 93 percent of the area, with only 7 percent left as grassy openings.

The spatial pattern of presettlement trees in the Pearson Natural Area is striking. These trees grew in distinct

0.05- to 0.7-acre groups of two to 40 trees (White 1985; Fule et al. 1993). Although canopy cover within a group can be quite high, when averaged with the interspaces that have no tree canopy cover, the result is a low canopy cover overall.

Thinning resulted in the removal of 901 trees per acre. A total of 5,500 board feet per acre (3,700 board feet per acre of 9- to 16-inch dbh trees plus 1,800) board feet per acre of 5- to 8.9-inch dbh trees) was removed. Most of the smaller-diameter trees (629 trees per acre in the 1- to 4.9-inch dbh class) were used as latillas for adobe home construction, but the 37 tons per acre of thinning slash posed a major problem. Because there was no market for this material, it was hauled to a borrow pit and burned; the removal required about 75 loads in 18-wheel dump trucks.

Before the forest floor was raked, fuel loads averaged 28.3 tons per acre. Approximately 21.3 tons per acre of duff was removed by raking, some of which became garden mulch. Addition of mown grass (0.3 tons per acre) on the complete restoration treatment increased forest floor fuel loading to 7.5 tons per acre; burning consumed 3.2 tons per acre, leaving 4.3 tons.

For the complete restoration treatment, fire intensity was low: flame lengths averaged approximately six inches with occasional flareups of one to two feet. Several large dead and down presettlement logs, however, burned intensely and were completely consumed. Cambial heating was also low or insignificant, showing minor heat pulses (mean increase = 44°F, n = 23) during the burn. Individual thermocouples on two trees registered higher temperatures (maximum increases 82° and 147°F), but only on one of the six probes per tree. Surface soil temperatures peaked in excess of 400°F during burning, but subsurface temperatures (one to four inches) exceeded 150°F on only one of five soil temperature sampling sites. Temperatures under dead presettlement-era logs remained high for the longest period, with surface and soil temperatures exceeding 200° F (peak temperature >400°F) for 24 to 48 hours. Fuels were reduced by the burn to an average 4.3 tons per acre—a total reduction of 85 percent from the pretreatment fuel loading.

During the 1995 growing season, soil moisture and temperature were consistently higher in treated areas than in the control (*figs. 2 and 3).* Soil moisture in treated areas is higher probably because the canopy and forest floor no longer intercept as much precipitation, and there is also less transpiration by postsettlement trees. Higher mineral soil temperatures are presumably the combined result of increased insolation at the soil surface and decreased insulation at the forest floor.

We hypothesize that those microenvironmental differences between treated and control areas will result in higher rates of such soil processes as fine root production, litter decomposition, and nitrogen mineralization in treated stands. Furthermore, we hypothesize that the changes in the soil process rates will in turn increase herbaceous production, tree growth, and resistance to insect attack. In fact, resin flow of presettlement trees was higher on the thinned area (4.4 ml per 24 hours) than on the control area (3 ml per 24 hours), as was foliar toughness (76 g of tension on thinned trees compared with 69.8 g of tension on control trees), suggesting increased resistance to bark beetles and foliage-feeding insects. No changes in populations of turpentine beetles *(Dendroctonus valens)* were observed.

Table 1. Comparison of stand structure in 1876 (reconstructed) and 1992.

Dbh class	Trees per acre 1876	Trees per acre 1992
0 – 3.9 inches	0.3	945
4 – 7.9	0.7	243
8 – 11.9	1.0	46
12 – 15.9	1.4	6.7
16 – 19.9	1.7	1.6
20 – 23.9	2.1	2.5
24 – 27.9	2.4	2.4
28 – 31.9	2.8	4.1
32 – 35.9	3.1	1.7
36 – 39.9	3.5	0.3
40 – 43.9	3.8	0.2
Total	22.8	1,253.5

Furthermore, herbaceous production has responded markedly to the treatments *(fig. 4)* with the greatest response to date in the grassy substratum. By 1995 the treated areas were producing almost twice as much herbaceous vegetation as the control.

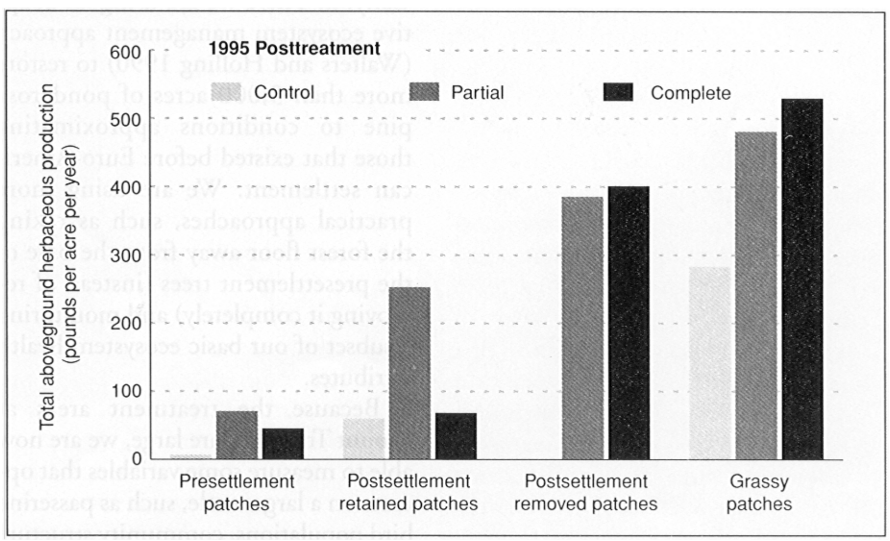

Figure 4. **Total aboveground herbaceous production (pounds per acre per year) by treatment and patches. In postsettlement retained patches, postsettlement trees were retained to replace presettlement trees that had died since 1876. Control treatment has no patches where postsettlement trees were removed. Grassy patches are natural openings in the overstory.**

Conclusions and Outlook

Preliminary results from our ecosystem restoration work are encouraging. The combination of thinning and burning — the complete restoration treatment — has changed forest structure from fire behavior fuel model 9 (Anderson 1982), in which crown fires are common, to fuel model 2, in which surface fires occur but crown fires are highly improbable.

The reduction in tree competition has improved moisture availability and has likely increased insect resistance of presetdement trees. Grasses, forbs, and shrubs are responding favorably as well, indicating a shift away from a net primary productivity dominated by pine trees toward a more diverse balance across a broader variety of plants.

Ecosystem restoration research requires a long-term, interdisciplinary commitment. We expect the ecosystem attributes we are measuring to be in transition for the next 10 to 20 years before they stabilize around some long-term mean. We plan to continue this project for the next 24 years with eight burnings at three-year intervals, rimed to coincide with the natural spring and summer burning season. Data on other attributes will be used to increase understanding of the restoration treatments on a range of ecosystem characteristics. For example, we hypothesize that the complete restoration treatment will increase soil moisture and mineralization and uptake of nitrogen, leading to increased photosynthesis, growth efficiency, and resin production by presettlement trees, and increased cover and production by shrubs and herbaceous vegetation. With favorable climatic events, we expect pine seedlings to become established on the partial restoration rreatment, repeating the pine irruptions that occurred after fire regime disruption in the 1870s.

Realizing that the intensive research-oriented treatments we have used in this research project are impractical on an operational scale, we have joined with the Arizona Strip District of the Bureau of Land Management to test practical ecosystem restoration treatments on a larger scale in the Mount Trumbull Resource Conservation Area, north of the Grand Canyon. There we are using an adaptive ecosystem management approach (Walters and Holling 1990) to restore more than 3,000 acres of ponderosa pine to conditions approximating those that existed before Euro-American settlement. We are using more practical approaches, such as raking the forest floor away from the base of the presettlement trees (instead of removing it completely) and monitoring a subset of our basic ecosystem health attributes.

Because the treatment areas at Mount Trumbull are large, we are now able to measure some variables that operate on a larger scale, such as passerine bird populations, community structure of selected insect guilds (butterflies), and other indicators of landscape-scale ecosystem health. Our hope is that through such a set of integrated, adaptive ecosystem restoration projects, we can alleviate many of the symptoms of ecosystem pathology while simultaneously increasing our understanding of ecosystem structure and function.

We argue that healthy conditions should be based on an understanding of the environmental conditions that shaped the evolution of native forest ecosystems, and we urge the use of multidisciplinary measures of ecosystem condition for understanding ecosystem health.

Literature Cited

ANDERSON, H.E. 1982. ***Aids to determining fuel models for estimating fire behavior.*** General Technical Report INT-122. Ogden, UT: USDA Forest Service.

ARNO, S.F., M.G. HARRINGTON, C.E. FIEDLER, and C.E. CARLSON. 1995. Restoring fire-dependent ponderosa pine forests in western Montana. ***Restoration and Management Notes*** 13(1):32–36.

AVERY, C.C., F.R. LARSON, and G.H. SCHUBERT. 1976. ***Fifty-year records of virgin stand development in southwestern ponderosa pine.*** General Technical Report RM-22. Fort Collins, CO: USDA Forest Service.

BASKETVILLE, G.L. 1965. Estimation of dry weight of tree components and total standing crop in conifer stands. ***Ecology*** 46:867-69.

BEARE, M.H., C.L. NEELY, D.C. COLEMAN, and W.L. HARGROVE. 1991. Characterization of a substrate-induced respiration method for measuring fungal, bacterial and total microbial mass on plant residues. ***Agriculture, Ecosystems and Environment*** 34:65-73.

BINKLEY, D., and S.C. HART. 1989. The components of nitrogen availability assessments in forest soils. ***Advances in Soil Science*** 10:57-112.

BROWN, J.K. 1974. ***Handbook for inventorying downed woody material.*** General Technical Report INT-16. Ogden, UT: USDA Forest Service.

CALDWELL, M.M., and R.A. VIRGINIA. 1989. Root systems. In ***Pland physiological ecology: Field methods and instrumcntation,*** 367-98. New York Chapman and Hall.

CALLICOTT, J.B., and S.L. FLADER, eds. 1992. ***The River of the Mother of God and other essays by Aldo Leopold.*** Madison: University of Wisconsin. Press.

COOK, C.W., and J. STUBBENDICK, eds. 1986. ***Range research: Basic problems and techniques.*** Denver: Society for Range Management.

COOPER, C.F. 1960. Changes in vegetation, structure, and growth of southwestern pine forest since white settlement. ***Ecological Monographs*** 30(2):129–64.

COVINGTON, W.W., and M.M. MOORE. 1994a. Changes in multiresource conditions in ponderosa pine forests since Euro-American settlement. ***Journal of Forestry*** 92(1):39-47.

--------, 1994b. Post-settlement changes in natural fire regimes and forest structure: ecological restoration of old-growth ponderosa pine forests. ***Journal of Sustainable Forestry*** 2(2):153-81.

COVINGTON, W.W., and S.S. SACKETT. 1984. The effect of a prescribed burn in southwestern ponderosa pine on organic matter and nutrients in woody debris and forest floor. ***Forest Science*** 30(3): 183-92.

-------, 1990. Fire effects on ponderosa pine soils and their management implications. In ***Effects of fire management of southwestern natural resources,*** 105-11. General Technical Report RM-191. Fort Collins, CO: USDA Forest Service.

------, 1992. Spatial variation in soil mineral nitrogen following prescribed burning in ponderosa pine. ***Forest Ecology and Management*** 54(2):175-91.

EDWARDS, N.T. 1982. The use of soda-lime for measuring respiration rates in terrestrial ecosystems. Pedobiologia 28:321-30.

FRITTS, H.C., and T.W. SWETNAM. 1989. Dendroecology: A tool for evaluating variations in past and present forest environments ***Advances in Ecological Research*** 19:111-88.

FULE, P.Z., W.W. COVINGTON, and M.M. MOORE. 1993. Scaling sample plots to estimate patch characteristics in southwestern ponderosa pine. Paper presented at the Eighth Annual US Landscape Ecology Symposium, March 24-27, 1993, Oak Ridge, TN.

HARRINGTON, M.G., and S.S. SACKETT. 1990. Using fire as a management tool in southwestern ponderosa pine. In Effects of fire management ***of southwestern natural resources.*** General Technical Report RM-191. Fort Collins, CO: USDA Forest Service.

HART, S.C., E.A. PAUL, and M.K. FIRESTONE. 1992. Decomposition and nutrient dynamics in ponderosa pine needles in a Mediterranean-type climate. ***Canadian Journal of Forest Research*** 22:306-14.

KOLB, T.E., M.R. WAGNET, and W.W. COVINGTON. 1994. Concepts of forest health. ***Journal of Forestry*** 92(7):10-15.

KOZLOWSKI, T.T., P.J. KRAMER, and S.G. PALLARDY. 1991. ***The physiological ecology of woody plants.*** New York: Academic Press.

LEOPOLD, A. 1934. The arboretum and the university. ***Parks and Recreation*** 18(2):59-60.

LEVERENZ, J.W., and HALLGREN. 1991. Measuring photosynthesis and respiration of foliage. In ***Techniques and approaches in forest tree ecophysiology,*** eds. J.P Lassoie and T.M. Hinckley, 303-28. Boston: CRC Press.

PARIZEK, R.R., and B.E. LANE. 1970, Soil-water sampling using a pan and deep pressure-vacuum lysimeters. ***Journal of Hydrology*** 11:l-21.

RITCHIE, G.A., and T.M. HINCKLEY. 1975. The pmsure chamber as an instrument for ecological research. ***Advances in Ecological Research*** 9: 165-254.

RUNDEL, P.W., and W.M. JARRELL. 1989. Water in the environment. In ***Plant physiological ecology today—field methods and instrumentation,*** eds. R.W. Pearcy, J. Ehletinger, H.A. Mooney, and R.W. Rundel, 29-56. New York: Chapman and Hall.

SACKETT, S.S. 1980. ***Reducing natural ponderosa pine fuels using prescribed fire: Two case studies.*** Research Note RM-392. Fort Collins, CO: USDA Forest Service.

SACKETT, S.S., and S. HAASE. 1992. ***Measuring soil and tree temperatures during prescrbied fires with thermocouple probes.*** General Technical Report PSW-GTR-131. Albany, CA: USDA Forest Service.

SACKETT, S.S., S. HAASE, and M.G. HARRINGTON. 1993. Restoration of southwestern ponderosa pine ecosystems with fire. In ***Sustainable ecological systems: Zmplementhg an ecological approach to land management,*** eds. W.W. Covington and L.F. DeBano. General Technical Report RM-247. Fort Collins, CO: USDA Forest Service.

SCHUBERT, G.H. 1974. ***Silviculture of southwestern pondnosa pine: The status-of-our-knowledge.*** Research Paper RM-123. Fort Collins, CO: USDA Forest Service.

SMITH, R.H. 1971. ***Red turpentine beetle.*** Forest Pest Leaflet 55. Washington, DC: USDA Forest Service.

STOKES, M.A., and T.L. SMILEY. 1968. ***An introduction to tree-ring dating.*** Chicago: University of Chicago Press.

WAGNER, M.R., and Z.Y. ZHANG. 1993. Host plant traits associated with resistance of ponderosa pine to the pine sawfly ***Neodiprion fulvireps. Canadian Journal of Forest Research*** 23(5): 839-45.

WALTERS, C.J., and C.S. HOLLING. 1990. Large-scale management experiments and learning by doing. ***Ecology*** 71(6):2,060-68.

WARING, RH., and G.B. PITMAN. 1985. Modifying lodgepole pine stands to change susceptibility to mountain pine beetle attack. ***Ecology*** 66(2):889-97.

WHITE, A.S. 1985. Presettlement regeneration patterns in a southwestern ponderosa pine stand. ***Ecology*** 66(2):589-94.

ABOUT THE AUTHORS

W. Wallace Covington is regends' professor, College of Ecoosystem Sciences and Management, Northern Arizona University, Flagstaff 86011; Peter Z. Fulp is research specialist, Northern Arizona University; Margaret M. Moore is associate professor, Northern Arizona University; Stephen C. Hart is assistant professor, Northern Arizona University; Thomas E. Kolb is assistant professor, Northern Arizona University; Joy N. Mast is assistant professor, Northern Arizona University; Stephen S. Sackett is research forester Forest Fire Laboratory, Pacific Southwest Research Station, USDA Forest Service, Riverside, California; Michael R Wagner is professor, Northern Arizona University. *Funding for this research was provided by the National Science Foundation (Grant DEB-9322706).*