Southwestern ponderosa pine forest structure: Changes since Euro-American settlement

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2 authors:

William Wallace Covington
Northern Arizona University

Margaret M Moore
Northern Arizona University

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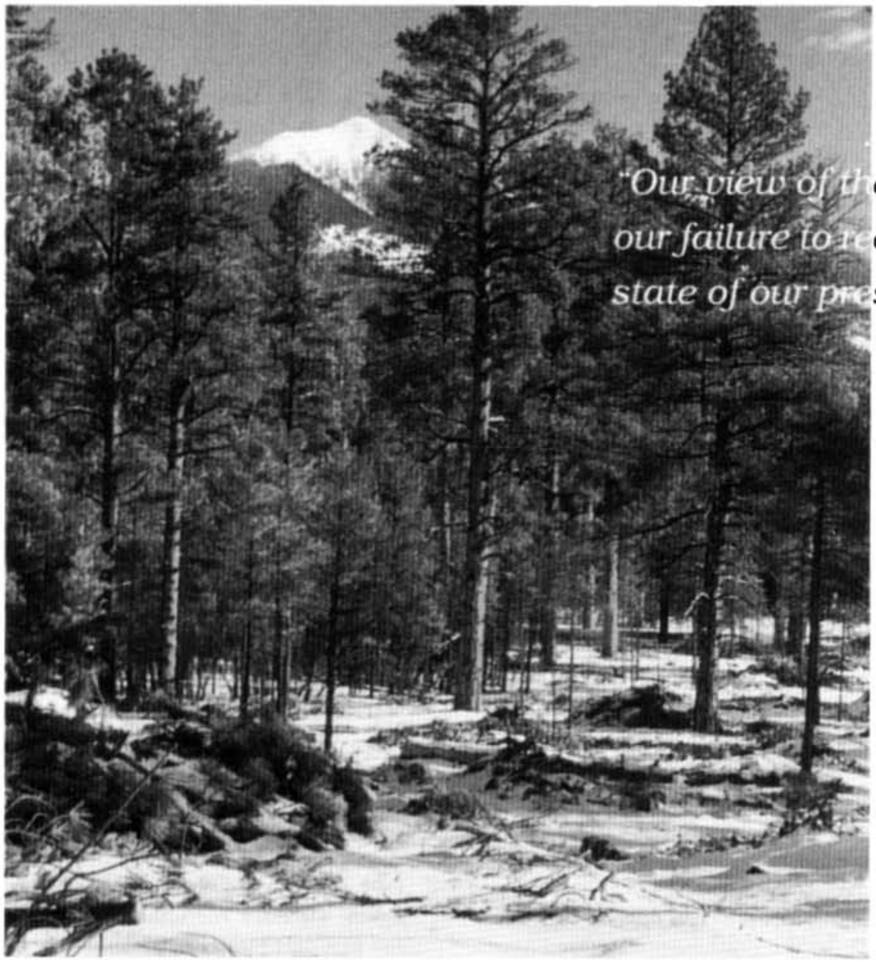

"Our view of the past is compromised by our failure to recognize the uncharacteristic state of our present." (Gould 1991)

SOUTHWESTERN PONDEROSA FOREST STRUCTURE

Changes since Euro-American settlement

By W. Wallace Covington and Margaret M. Moore

BOTH NATURAL RESOURCE professionals and the general public often suffer from the mistaken notion that forests have always looked pretty much like they do today. Nothing could be further from the truth for many forest types, especially the ponderosa pine *(Pinus ponderosa)* forests of the American Southwest. Heavy grazing, logging, and fire exclusion, in conjunction with climatic oscillations and elevated atmospheric CO_2, have led to many more younger and smaller trees; fewer older and larger trees; accumulation of heavy forest floor fuel loads; reduced herbaceous production; and associated shifts in ecosystem structure, fire hazard, and wildlife habitat (Wright 1978, Covington et al., in press). Thus the current forest structure is quite different from conditions that were prevalent throughout the evolutionary history of the native microbes, plants, and animals living in western ponderosa forests.

A central tenet of ecology is that irruptions (outbursts) of ecologically dominant species reduce diversity and lead to declines in ecosystem health and integrity as defined by Leopold (1949). He described health as the ability of the system to recover following disturbance, and ecological integrity as maintaining the coevolved diversity of life. Although most of the public is familiar with the consequences of deer population explosions resulting, in part, from overly zealous predator control, many fail to see the analogy to pine tree population explosions as a result of Euro-American settlement.

Southwestern ponderosa pine forests are a classic example of how Euro-American populations changed forest conditions (Rasmussen 1941, Weaver 1951, Cooper 1960, Cooper 1961). Before settlement, these forests were much more open and parklike. Postsettlement increases in tree density have contributed to changes not only in ecological patterns and processes but also in timber, forage, water, wildlife, and esthetic conditions.

This study quantifies some of the as-

Above: At an ecological restoration study site at the Gus Pearson Natural Area (Arizona), a restoration prescription applied in November 1993 reduced tree density to about 70 trees per hectare, comparable to presettlement site density. All presettlement trees were conserved. Younger trees were selected to reproduce the spatial patchiness of the mature overstory. Dense trees from the companion control area are visible behind the treated area.

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sociated shifts in ecosystem structure and resource conditions and predicts changes 40 years into the future. The results from this and subsequent studies on other sites should serve as a reference point or baseline for eventual restoration of more nearly natural patterns and processes.

If we are serious about restoring ecosystem health and ecological integrity, then we must know what the land was like to begin with.

Postsettlement Changes

Fire exclusion and other factors associated with Euro-American settlement have greatly altered forest conditions in southwestern ponderosa pine forests (Weaver 1951, Cooper 1960, Cooper 1961, Covington and Sackett 1984, White 1985, Covington and Sackett 1986). One line of qualitative evidence comes from various early accounts that described the large size of pine trees, the forest's open structure, the low abundance of underbrush or small trees, and the excellent grass cover; all indicated the rarity of tree establishment. Cooper (1960, p. 130) quoted E.F. Beale's 1858 report:

> We came to a glorious forest of lofty pines, through which we have travelled ten miles. The country was beautifully undulating, and although we usually associate the idea of barrenness with the pine regions, it was not so in this instance; every foot being covered with the finest grass, and beautiful broad grassy vales extending in every direction. The forest was perfectly open and unencumbered with brush wood, so that the travelling was excellent.

Cooper continued, "The overwhelming impression one gets from the older Indians and white pioneers of the Arizona pine region is that the entire forest was once much more open and parklike than it is today."

Further evidence for postsettlement changes comes from examination of photographic time series *(fig. 1)*. Similar comparisons have been published for South Dakota by Progulske (1974); for Wyoming by Gruell (1980); for Montana by Gruell et al. (1982); and for Colorado by Veblen and Lorenz (1991).

Before European settlement of northern Arizona in the 1860s and 1870s, surface fires occurred in ponderosa pine forests at frequent intervals, perhaps every 2–12 years (Weaver 1951, Cooper 1960, Dieterich 1980). Studies of fire scars suggest the average burn covered approximately 3,000 acres (Swetnam and Dieterich 1985, Swetnam 1990). Cooper's (1960) extensive review concluded that, prior to the 1950s, crown fires were extremely rare or nonexistent. Woolsey (1911, p. 11) stated that "a crown fire in mature timber [ponderosa pine] is almost unheard of."

Several factors associated with European settlement caused a reduction in fire frequency and size. Roads and trails broke up fuel continuity. Domestic livestock grazing, reportedly in the hundreds of thousands of animal units in the 1880s and 1890s, greatly reduced herbaceous fuels. Active fire suppression, which commenced as early as 1908 in the Flagstaff area, was a principal duty of early foresters in the southwestern United States. Overstocked forests were a direct result of interrupting and suppressing these periodic fires.

Postsettlement changes in forest structure (tree density, cover, age distribution) in southwestern ponderosa pine forests have been blamed for many forest management problems. The concerns, primarily attributed to fire exclusion and the resulting increased tree density (Cooper 1960, Biswell 1972, Weaver 1974, Covington and Sackett 1990, Covington and Moore 1992, Covington and Sackett 1992), include

- overstocked patches of saplings and pole-sized trees;
- reduced tree growth and increased mortality, especially of the oldest trees;
- decreased decomposition rates;
- stagnated nutrient cycles;
- irruption of insects and diseases;
- decreased herbaceous and shrub forage quality and quantity;
- ecosystem simplification (increasing dominance of ecosystem productivity by ponderosa pine and its dependent food webs);
- higher fuel loads;
- increased vertical fuel continuity due to dense sapling and pole patches;
- greater canopy closure and landscape homogeneity;
- higher severity and destructive potential of wildfires;
- decreased streamflow and onsite water balance;
- less wildlife habitat for species dependent on herbaceous vegetation; and
- lower esthetic values.

Studies in the Southwest

Although qualitative descriptions are relatively abundant in the literature, few quantitative studies exist of presettlement ponderosa pine forest structural characteristics and patterns in the Southwest. Whipple (1856) and Beale (1858) reported that the forest "was open and parklike with a dense grass cover." These and other early descriptions agree with Pearson's (1923, p. 38) statement that "rarely does [ponderosa pine] crown cover reach more than 30%, and usually not over 25%." Recent research also found low canopy coverage by trees of presettlement origin, with ranges of 17% (Covington and Sackett 1986) to 22% (White 1985) of the surface area for lightly harvested and unharvested basalt soil sites near Flagstaff, Arizona.

In general, old-growth (presettlement) ponderosa pine trees in the pine/bunchgrass type on basalt soils follow the pattern of trees of different ages aggregated into groups of usually less than an acre. According to Woolsey (1911, p. 24), "The typical western yellow pine forest of the Southwest is a pure parklike stand made up of scattered groups from 2 to 20 trees, usually connected by scattering individuals. Openings are frequent and vary greatly in size." Spatial analyses of presettlement trees support this pattern. For example, a contiguous quadrat analysis of data from two study areas in the White Mountains of east-central Arizona determined that presettlement trees were aggregated into groups ranging from 0.16 to 0.32 acre (Cooper 1960). Cooper's 1961 analysis had similar results (0.15–0.35 acre). In another study in the G.A. Pearson Natural Area near Flagstaff (White 1985), the nearest neighbor method showed that presettlement tree groups ranged from 3 to 44 stems within a group, with group size varying from 0.05 to 0.70 acre. Moore et al. (1993) obtained similar results in the same general area—maximum variance (clumpiness) around 0.16 acre with a range of 0.08 to 0.64.

In contrast to conventional wisdom, White (1985) concluded that each presettlement tree group was uneven-aged: "Ages of stems within a group were also variable, with the most homogeneous group having a range of 33 years and the least homogeneous group having a range of 268 years." Although Cooper earlier concluded (1960, 1961) that presettlement trees in this area were in even-aged groups, he presently believes that even-agedness in presettlement times was rare (pers. commun., C.F. Cooper, San Diego State University, San Diego, California, 1992). Isolated even-agedness occurs within groups due to windthrows and other microsite disturbances. In general, seedling establishment was infrequent in presettlement times, with up to three or four decades between regeneration events (White 1985, Savage 1989).

For the southwestern ponderosa pine type, therefore, data suggest that pattern at several scales. Trees may be even-aged at the individual-tree level (2–5 trees originating from the same spot). At the group level, trees are all-aged with sporadic regeneration (White 1985). At the landscape level (several to thousands of square miles), however, several studies have shown that synchronous regeneration correlated with favorable climatic oscillations such as the La Niña (Kerr 1988, Savage 1989, Swetnam 1990). Thus confusion about whether southwestern presettlement pine forests were all-aged or even-aged may be, in part, a matter of scale. Madany and West (1983) discussed the regeneration effects of extended heavy grazing and fire suppression in southern Utah. They suggested that ponderosa pine seedling survival was probably greater in the early 1900s than in presettlement days because of less competition from grasses (through grazing) and reduced thinning effects from fires.

Moir and Dieterich (1988) stressed the role of presettlement fire regimes in directing succession toward old-growth development and reducing fuel loading so large trees could survive wildfires; they stated that most of the old-growth in southwestern ponderosa pine forests has deteriorated because recurrent natural fires have been suppressed. Their 11-stage model of succession (from open meadow to landscapes dominated by dead snags) may be a bit misleading. Several analyses of tree ages indicated that succession proceeds more on an individual tree basis rather than on a stand basis (White 1985).

Postsettlement changes are not unique to the Southwest. Studies in Utah (Madany and West 1983, Stein 1987); Montana (Gruell et al. 1982, Keane et al. 1990); Idaho (Barrett 1988, Steele et al. 1986); Oregon (Dickman 1978); Washington (Weaver 1959); and California (van Wagtendonk 1985, Laudenslayer et al. 1989) suggested that increased tree density, fuel loading, and crown fires are common consequences of fire exclusion throughout the range of the ponderosa pine type (Kilgore 1981). Therefore, although many questions remain regarding the ecological and multiresource implications of postsettlement changes, there is wide consensus that today's ponderosa pine forests are radically different from those present before Euro-American settlement.

Study Site

A 16,200-acre experimental watershed in Bar-M Canyon (one of the Beaver Creek watersheds approximately 25 miles south of Flagstaff) encompassed the study area. Although Bar-M Canyon was lightly harvested at the turn of the century and again in the late 1940s, it is relatively undisturbed by logging. Since ponderosa pine decomposition rates are extremely slow in the Southwest, stumps and downed logs from the late 1800s are still evident so the Bar-M watershed provided an opportunity to study pre-

G.A. Pearson

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G.A. Pearson

Figure 1. Photographic time series (clockwise from top: 1909, 1949, 1990) from the Pearson Natural Area, Fort Valley Experimental Forest, Coconino National Forest, Arizona.

and postsettlement vegetation structure and patterns.

The Bar-M watershed contains a gently rolling landscape dissected by many steep canyons. Elevations range from 6,360 to 7,710 feet. Plots were located between 6,800 and 7,200 feet. The underlying bedrock consists of igneous rocks of volcanic origin. The soils are mostly silty clays and silty clay loams less than 2.6 feet deep. Average annual precipitation is 25 inches; 64% of the precipitation falls during the winter (October through April) and 32% falls during the summer, particularly in July and August (Brown et al. 1974).

The forests are predominantly ponderosa pine, with a mixture of Gambel oak *(Quercus gambelii)* and alligator juniper *(Juniperus deppeana)*. The understory grasses consist primarily of mutton bluegrass *(Poa fendleriana)*, black dropseed *(Sporobolus interruptus)*, blue grama *(Bouteloua gracilis)*, and bottlebrush squirreltail *(Sitanion hysterix)*. Forbs include showy aster *(Aster commutatus)*, spreading fleabane *(Erigeron divergens)*, showy goldeneye *(Viguiera multiflora)*, western ragweed *(Ambrosia psilostachya)*, and snakeweed *(Gutierrezia* spp.). The shrubs are primarily New Mexican locust *(Robinia neomexicana)*, Gambel oak, and Oregon grape *(Berberis repens)* (Brown et al. 1974). Plant nomenclature follows Kearney and Peebles (1964).

Field Procedures

For the stratified systematic sampling procedure, areas were stratified by soil type and topography using the USDA Forest Service Region 3 Terrestrial Ecosystem Survey (USDA Forest Service 1986). The Terrestrial Ecosystem (TE) map unit 582 was sampled since it was the most common soil-slope-vegetation unit in the watershed (Typic Argiboroll and Mollic Eutroboralf; low sun cold, with ponderosa pine and Gambel oak as the dominant trees, 0–15% slope). This map unit represents approximately one-fourth of the watershed.

Seventy 0.62-acre plots were systematically located within unit 582. Plot size was selected to incorporate the patchy nature of ponderosa pine and for spatial analysis in subsequent studies. On 62 of these plots, only the presettlement trees were sampled (using dbh and bark criteria). Working at a study area similar to Bar-M, White (1985) determined statistically that the majority of presettlement ponderosa pine would be greater than 14.6" dbh, and that smaller presettlement trees would have "yellow bark." This latter criterion is based on the observation that, in the Southwest, ponderosa pine bark changes from black to yellow as the tree ages (Pearson 1950). All presettlement trees (live, snags, stumps, and downed logs) on these 62 plots were mapped for location, species, condition, and dbh.

An additional eight 0.62-acre plots were sampled more intensively by gathering both pre- and postsettlement tree data: location, species, condition (live, snags, stumps, and downed logs), size class, and dbh. Ten percent of all trees between 3.9" and 14.6" dbh were randomly selected to determine an approximate date of postsettlement tree establishment. All larger trees were aged, as was any pine with yellow bark. Trees smaller than 3.9" dbh were counted but not aged.

Tree rings of all presettlement trees on the eight intensive plots were used to determine total age. All rings to the year of Euro-American settlement (1867 in Bar-M) were counted and measured to determine diameter of each tree at that date and average annual growth since settlement. If the tree was a stump, year of death was determined from logging records; then a regression equation was used to calculate dbh from the stump diameter. For snag or downed material, the year of death was estimated from the tree's condition class (Thomas 1979, Maser et al. 1979, Cunningham et al. 1980, Rogers et al. 1984) and presettlement diameter was determined.

Simulation Models

To understand the trajectory of forest structure over time, data from the eight intensive plots were linked to the ECOSIM (Rogers et al. 1984) multiresource forest growth-and-yield simulation model. The results were used to project temporal changes in multiresource characteristics from 1867 to 1987, and from 1987 through 2027 (40 years from the sampling date).

The growth-and-yield ECOSIM model is based on the FREP/STEMS model (Belcher 1981, Brand 1981) calibrated with continuous forest inventory data from Arizona and New Mexico. The water yield model was based on the Baker-Kovner model (Brown et al. 1974) in which streamflow is a function of winter precipitation, aspect, slope, and tree density. For herbage production a modification of Clary's (1978) model was used, where herbage is a function of annual precipitation, tree density, and range site class. Forest floor accumulation was estimated as the difference between litterfall (calculated from tree density and canopy biomass) and litter decomposition using Fogel and Cromack's (1977) estimates for ponderosa pine decomposition rates. Near-view scenic beauty was estimated using equations developed by Daniel and Boster (1976) and Schroeder and Daniel (1981). An index of scenic beauty was calculated as a function of the number of large (greater than 16" dbh) and mid-sized (5"–16" dbh) trees, quantity of logging slash, amount of herbage, and number of shrubs.

Each simulation run consisted of entering the dbh of all presettlement trees (live trees, snags, downed trees, and stumps) by diameter class as stand conditions in 1867 for each of the eight intensive plots. Then, based on the regeneration events inferred from the age distribution of the postsettlement trees, trees were entered into the group or stand at appropriate intervals in simulated time. To simulate the logging event in the late 1940s, the harvest simulation component of ECOSIM was applied to harvest trees of dbh equal to that of the stumps present on each plot.

The output from these computer runs was a series of tables (1867–2027) that quantitatively estimated changes in forest density in southwestern ponderosa pine since settlement. From the results, we drew inferences about temporal changes in multiresource conditions since Euro-American settlement and forecasted future trends (in the absence of fire or other major disturbances).

The simulation initialized in 1867 included:

- tree density (number and dbh of trees present on each intensive plot in 1867);
- a site index of 75 (base age 100), the site index for TE map unit 582;
- a range (forage) rating factor of 9, based on the forage production potential for unit 582 (this index varies from 0 for poor range sites to 12 for the best sites);
- fuel loading of 0.1 ton/acre of fermentation plus humus layers and 0.1 ton/acre of litter layer on the forest floor.

This is based on the fuel loading data from Covington and Sackett's (1986) two-year-interval prescribed burning plots in ponderosa pine forests and the assumption that tree canopy covered approximately 20% of the surface (White 1985, Covington and Sackett 1986); and

- an average annual precipitation of 25" and average winter precipitation of 16.9". This is the 22-year average for the ponderosa pine watersheds in the Beaver Creek drainage (Campbell and Ryan 1982). Precipitation was held constant throughout the simulation.

To simulate the establishment of postsettlement trees, ponderosa pine seedlings and oak seedlings equal to the density of postsettlement trees on each plot were entered in 1904, the date for the beginning of a 26-year wet climatic cycle in northern Arizona (Schubert 1974). These seedlings were specified to take between 15 and 40 years to reach 0.5" dbh, the size at which they are entered ("ingrowth") into the tree stand table for growth simulation. As with the rest of this analysis, regeneration was modeled as a simple (and proportional) deterministic process. Trees were similarly entered into the tree stand tables for each plot between 1919 and 1944. Thus postsettlement trees that were seedlings in 1898, 1900, 1904, 1907, and so on would not reach 0.5" dbh until after 1919; and the last major postsettlement cohort (1924) would not reach this size until 1944.

Mortality in ECOSIM is simulated stochastically as a function of tree diameter. Regressions developed from continuous forest inventory data relate mortality to tree diameter, then a uniform random number is generated for each tree represented by the subject tree. If the mortality rate is greater than the random number, then that tree is removed from the tree list and enters a snag list. A locally calibrated snag fall model moves snags from standing to downed and dead woody material and then to a log decomposition model that simulates decay of that ecosystem component (Rogers et al. 1984).

To estimate changes in wildlife habitat characteristics since 1867, the output for tree density by diameter class was used to classify the simulated stand into vegetation structural stages (Thomas 1979). Then the Forest Service Southwest Region's wildlife technical report for forest planning (Byford et al. 1984) was used to determine the change in relative habitat value for individual species from 1867 to the present.

To simulate the harvesting that occurred in the late 1940s, ECOSIM's harvesting algorithm was used to "remove" presettlement trees that are currently stumps from the tree list of live trees for simulated year 1950.

Table 1. Present-day species composition on eight intensive plots, Bar-M Canyon.

Species	Percent
Ponderosa pine	
Presettlement[1]	2.0
Postsettlement[2]	89.0
Gambel oak	
Presettlement	0.2
Postsettlement	7.4
Alligator juniper (postsettlement)	1.3
Total	99.9

[1] 120 years or older, including live trees, stumps, snags, and downed logs.
[2] Less than 120 years old including seedling, sapling, pole-sized, and small sawlog classes as well as stumps, snags, and downed logs.

Projected Tree Data

On the intensive (n=8) plots, presettlement trees (pine and oak) on the watershed represented only 2.2% of the tree density (trees/acre), contributed approximately 19 stems/acre, and had a basal area of approximately 65 square feet/acre *(table 1, 2).* The density of presettlement trees for all 70 plots was 23 trees/acre, with a range of 21 to 24.

Table 2. Average density and basal area (live and dead trees) on eight intensive plots, Bar-M Canyon.

Class	Density	Basal area
	trees/ac	*ft^2/ac*
Presettlement pine (live)	12.1	37.0
Presettlement pine (stumps, snags, downed trees)	5.3	26.0
Postsettlement pine (live)	757.0	120.0
Postsettlement pine (stumps, snags, downed trees)	1.4	0.6
Presettlement oak (stumps)	1.4	2.0
Postsettlement oak	62.8	14.0
Alligator juniper (seedlings below breast height)	11.1	—
Total	851.1	199.6

Postsettlement trees represented 97.7% of tree density, or 832 stems/acre, and had a basal area of approximately 134.6 square feet/acre *(table 1, 2).* Of the postsettlement trees, ponderosa pine represented the largest proportion with 758 stems/acre (89%) and basal area of 120.6 square feel/acre (60%). Trees less than 4" dbh made up 59% of the stems on the TE unit sampled. Data for both pre- and postsettlement trees represented snags, downed trees, and stumps as well as live trees.

Simulation Model Projections

The projections provided an estimation of the trajectory of ponderosa pine forest conditions over time in the study area. Increases in tree density through 1987 caused an estimated decrease in average herbage production of approximately 1,000 pounds/acre, a 90% reduction *(table 3).* Stream flow was estimated to have declined by 1.8", a 26% reduction, while near-view esthetics (as estimated by a scenic beauty index) declined from a high of 109 in 1867 to −1.5 in 1987. On the other hand, this same increase in tree density caused an estimated increase in average timber volume from 2,263 board feet/acre in 1867 to 7,225 in 1987, despite the decline due to harvesting in the late 1940s (simulated in year 1950). At the same time, forest floor and herbaceous fuel loads were estimated to have increased from an average of less than 1 ton/acre in 1867 to more than 19 in 1987. Vertical diversity, fuel ladder continuity as estimated by vegetation structural stage *(table 4),* and forest floor fuel loading *(table 3)* also increased substantially.

The vegetation structural stage analysis *(table 4)* indicated that the simulated plots changed from a grass-forb structural stage (with too few trees for classification as timber) in the late 1800s, to a seedling-

Table 3. Mean changes in multiresource characteristics of ponderosa pine (standard errors in parentheses) on eight plots, as simulated by ECOSIM.[1]

Simulated date	Basal area	Fuel loading	Herbage production	Stream flow	Scenic beauty index	Timber volume
	ft^2/ac	*t/ac*	*lbs/ac*	*in.*		*bd ft/ac*
1867	17 (4)	0.9 (0.2)	1,134 (119)	6.9 (.06)	109 (15)	2,263 (941)
1887	23 (5)	2.1 (0.4)	1,000 (123)	6.8 (.08)	95 (15)	3,361 (1113)
1907	30 (6)	3.1 (0.6)	856 (125)	6.7 (.11)	85 (14)	4,788 (1268)
1927	38 (7)	4.0 (0.7)	571 (84)	6.6 (.13)	61 (11)	6,560 (1437)
1947	60 (6)	6.5 (0.6)	134 (9)	6.1 (.15)	34 (6)	8,699 (1660)
1967	85 (7)	11.7 (0.5)	124 (12)	5.6 (.16)	27 (4)	5,980 (1274)
1987	154 (14)	19.0 (1.1)	114 (2)	5.1 (.16)	–1.5 (6)	7,225 (1590)
2007	234 (20)	30.1 (2.2)	112 (0)	4.8 (.14)	–19.5 (8)	8,719 (1808)
2027	306 (22)	42.0 (2.9)	112 (0)	4.7 (0.0)	–28.3 (10)	12,887 (2148)

[1] These results differ somewhat from results presented at a 1992 workshop (Covington and Moore 1992). The 1992 results were based on simulation analysis of a single plot using average conditions; the data in this table came from eight plots simulated individually.

dominated stage after the turn of the century, then to mature timber, and finally to old-growth trees growing over dense saplings and poles from the 1960s on.

These changes in vegetation since 1867 indicated a shift from a foraging habitat that favors grassland species (pronghorn antelope, grasshoppers, bluebirds, turkeys) to one favoring species that prefer higher tree densities (Abert squirrel, porcupine, bark beetle, pygmy nuthatch). Canopy cover had, of course, increased for all species. In sum, the shift in tree density favored species dependent on closed forest conditions at the expense of those that require some portion of their habitat in the grass/forb stage. Gruell et al. (1982) noted similar changes in wildlife habitat for ponderosa pine/Douglas-fir forests in western Montana.

Under the assumption that no substantial tree mortality (e.g., crown fire or bark beetle epidemics) or intensive forest management occurs between 1987 and 2027, many of these trends are predicted to continue. Basal area will increase to 306 square feet/acre, forest floor fuel loading will increase to 42 tons/acre, and timber volume will increase to almost 13,000 board feet/acre *(table 3)*. Scenic beauty will continue to decline, but herbage production *(table 3)* and streamflow will not be further reduced as they are now near their minimum levels. Of course, the assumptions of no substantial tree mortality and no intensive harvesting are not likely to occur (given current trends) and are addressed below.

Table 4. Changes in vegetation structural stage (VSS) for simulated southwestern ponderosa pine plots over time (after Appendix III, Byford et al. 1984).

Simulated date	VSS
1867	Grass/forb
1887	Grass/forb
1907	Seedling
1927	Mature timber/seedling
1947	Mature timber/seedling
1967	Mature timber/sapling-pole
1987	Old-growth/sapling-pole
2007	Old-growth/sapling-pole

Discussion

Ponderosa pine forests on basaltic soils near Flagstaff, Arizona, were much more open and parklike than they are today. The dominant tree species are the same; however, the density of trees (especially ponderosa pine) has drastically increased. Presettlement ponderosa pine forests on sites similar to the ones in this study probably contained larger diameter trees averaging 19–24 trees/acre. Today, the forest at Bar-M Canyon has approximately 843 trees/acre (851 including dead trees), consisting primarily of trees less than 4" dbh.

Establishment of ponderosa pine seedlings in presettlement times was infrequent because of frequent low-intensity fires, competition from bunchgrasses, and climate. Successful regeneration occurred locally, especially when mineral soil was exposed (Schubert 1974, White 1985). Fire exclusion, logging (which exposed mineral soil for pine seedling establishment), grazing, and key climatic events all contributed to abundant pine regeneration after the turn of the century (Arnold 1950, Pearson 1950, Cooper 1960, Schubert 1974). The abundant regeneration has become dense thickets of pine, which accounts for most of the individuals in the present-day forests of Bar-M Canyon. This change in age structure and density over the past 120 years has contributed to corresponding changes in multiresource yields and conditions.

Simulation results *(table 3)* are consistent with other lines of evidence for vegetation and resource change. The simulated tree density of 19 trees/acre and 4,788 board feet/acre in 1907 are consistent with Lieberg et al. (1904), who reported approximately 3,000 board feet/acre for T17N R8E, which includes the majority of the Bar-M study area. The simulated density of 154 square feet/acre in 1987 is consistent with the 1987–88 inventory of the eight intensive plots, which averaged 171 square feet/acre in live trees. The decline in herbage from 856 pounds/acre in 1907 to 134 pounds/acre in 1947 agrees with Arnold's (1950) results, which documented a similar decline for grass cover density in northern Arizona ponderosa pine. Streamflow for Bar-M Canyon, which has been monitored since 1958 by the USDA Forest Service and the School of Forestry, Northern Arizona University, varies widely with precipitation. The average streamflow from 1958 to 1986 was 5.9 inches; the simulation model predicted 6.1" in 1947, 5.6" in 1967, and 5.1" in 1987 under an unvarying simulated winter precipitation regime of 16.9".

Increases in tree density and forest floor fuels contributed to the more frequent large crown fires in southwestern ponderosa pine (Barrows 1978). Before settlement, fire behavior in southwestern ponderosa forests in this study area would have been classified as open timber over grass, fuel model 2—characterized by fast-moving fires with low flame heights (Anderson 1982). Today's forests are classified as fuel model 9, closed timber. Under severe conditions crown fires are highly probable in this type, with high rates of spread (300–600 chains/hour) and flame heights of 80–150 feet (Rothermel 1991). Fire simulation studies of ponderosa pine and related forest types (van Wagtendonk 1985, Keane et al. 1990) are consistent with these conclusions.

Furthermore, increased tree density is responsible for decreased growth rates (Sutherland 1983) and hence decreased vigor (Waring 1983), which increases susceptibility to bark beetle attack (Sartwell 1971, Sartwell and Stevens 1975) and other agents of mortality. Numerous studies have demonstrated that the mortality of ponderosa pine increases with both diameter and stand density (McTague 1990). A trend toward increasing rates of mortality, especially of the largest and oldest presettlement trees, is supported by an analysis of Pearson Natural Area data (Avery et al. 1976).

Thus the increase in tree density following Euro-American settlement has resulted in a major increase in forest canopy cover and vertical diversity within the tree canopies and a striking decrease in herbage production. These results are consistent with studies in the northern Rocky Mountains (Gruell et al. 1982, Keane et al. 1990) and California (van Wagtendonk 1985, Laudenslayer et al. 1989).

Management Implications

Disruptions of natural disturbance regimes coupled with postsettlement anthropogenic disturbances have led to forest and woodland conditions that bear little resemblance to natural conditions. Thus old-growth definitions and management objectives based solely on current stand structure may not be compatible with the conservation goal of preserving species diversity by providing the habitats in which species have evolved. In fact, before settlement, none of the plots sampled at Bar-M would satisfy all of the current minimum criteria for basal area, canopy closure, and number of trees per acre (in some cases) under the present old-growth definition (USDA Forest Service 1992).

Setting aside old-growth ponderosa pine stands that most closely meet current old-growth definitions may have unexpected consequences. Such stands, whose canopy closures are higher than in presettlement times, are susceptible to crown fire, low tree vigor, and mortality from drought, insects, and diseases. Definitions of old-growth should take into account conditions before Euro-American settlement, particularly the natural fire regime and patchy nature of the forest. In managing for "more nearly natural" old-growth ecosystems (using pre-European settlement conditions as the yardstick), it may be necessary to use thinning from below, manual fuel treatments, or prescribed burning to restore candidate stands.

To restore the forests to more natural conditions, it may be necessary to thin many postsettlement trees, remove heavy fuels, and reintroduce periodic burning.

Research and development is needed to test environmentally sound methods for reducing postsettlement tree densities and fuel loadings—to protect and conserve not only the remaining ancient trees but also the other ecological components and processes in the southwestern ponderosa pine type. It is not certain that remedial management regimes can be developed that are ecologically, economically, and politically acceptable, especially for wilderness and other natural areas. However, this study suggests we have a fairly narrow 15- to 30-year window of opportunity for doing so. Otherwise, less environmentally acceptable processes (crown fires, large insect and disease outbreaks) will not only reduce tree densities and fuel loads but also kill most of the remaining trees of presettlement origin.

Before embarking on widescale restoration, postsettlement changes in ecological conditions must be determined for a broader range of forest and woodland types in the Rocky Mountain and Southwest regions. Then a combination of adaptive resource management (Walters 1986) and process-oriented simulation modeling (e.g., van Wagtendonk 1985, Keane et al. 1990) could design restoration management regimes appropriate for each set of conditions. Simultaneously, small (10- to 100-acre) studies should examine and monitor the ecological effects and practicality of various restoration treatment scenarios. Integrating historical studies, simulation modeling, and management experiments should ensure that wildland management issues in the ponderosa pine type are addressed in a more coherent and ecologically sound manner.

Conclusions

Aldo Leopold admonished the forestry and wildlife professions that if we are serious about restoring ecosystem health and ecological integrity, then we must know what the land was like to begin with. Nonetheless, very little is known about variations in presettlement conditions of ponderosa pine and other ecosystems across the landscape. We need adequate reference points. Clearly, one of those reference points must be the ecological conditions that existed before we overgrazed the land, put out all the fires, and liquidated most of the old-growth trees. The forests of today differ substantially from the natural conditions before Euro-American settlement. These changes in ecosystem structure imply changes in wildlife habitat, water relations, nutrient cycling, soils, forest health, and other resource characteristics.

Structural changes have also shifted the fire regime in ponderosa-dominated ecosystems from frequent, low-intensity surface fires to high-intensity crown fires. Crown fires have created increasingly large openings (1,000–5,000 acres), and dwarf mistletoe control has produced localized smaller openings (10–200 acres). In other areas, logging has resulted in forests that are as open as presettlement forests but lack their large, old trees and native bunchgrass understory. The recent occurrence of larger and larger crown fires may indicate a further shift to a regime characterized by very large (more than 10,000 acres) and destructive crown fires. In fact, these changes, in concert with ongoing global changes in atmospheric CO_2 and climate, imply the need for intensive ecosystem restoration and management to prevent widescale collapse of existing ecological systems, even in wilderness areas (Covington et al., in press).

It is ironic that Leopold, the father of wildlife management and in many ways of ecologically based forestry, spent much of his life fighting with the public over deer irruptions, managing in harmony with nature, and restoring ecosystem health and integrity. Unfortunately, many individuals who now recognize the harmful effects of irruptions of dominant wildlife species in the absence of predators find it difficult to see the analogy to tree irruptions in the absence of fire. JOF

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ABOUT THE AUTHORS

W. Wallace Covington is professor and Margaret M. Moore is associate professor, School of Forestry, Northern Arizona University, Flagstaff 86011.