Contributions of Silviculture to Watershed Experiments in Arizona's Ponderosa Pine Forests: A Historical Review

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Silvicultural studies on the Fort Valley Experimental Forest, the oldest experimental forest in the United States, have been the basis for planning and implementing watershed management experiments in ponderosa pine (*Pinus ponderosa*) forests. The primary purpose of these experiments had been to evaluate the potentials for increasing streamflow volumes while maintaining or improving other ecosystem-based, multiple-resource values. Knowledge gained from these experiments has provided today's managers with a better appreciation of the past management of Arizona's ponderosa pine forests. The effects of applying silvicultural treatments formulated largely from studies on the Fort Valley Experimental Forest and effects of these treatments on forest structures are reviewed in a historical context in this paper.

Silvicultural Prescriptions for the Management of Ponderosa Pine Watersheds

Water has been and remains critically limited in the southwestern region. In response to diminishing supplies and increasing demands for water in the late 1950s, a group of public- and private-sector entities formed the Arizona Watershed Program with the goal of increasing streamflow volumes from upstream watersheds by implementing silvicultural treatments that held promise in achieving this goal at the time (Ffolliott 1999, Fox et al. 2000). Leading up to the organization of this collaborative program, George Barr, an economist at the University of Arizona, and a team of watershed management specialists were commissioned to evaluate the possibilities of enhancing streamflow volumes from watersheds in the state (Barr 1956). Literature reviews and on-site examinations of watershed conditions and management opportunities by Barr and his team concluded that vegetation management might increase streamflow volumes while maintaining other watershed-based values.

It was further concluded by Barr's team that silvicultural treatments on watersheds in high-elevation forests such as ponderosa pine forests had the greatest potentials for increasing streamflow volumes. However, because little information relating to these potentials was available at the time of the Barr study, a research program was initiated as a component of the Arizona Watershed Program. Its purpose was to evaluate the effects of applying prescribed silvicultural treatments to increase streamflow volumes from selected watersheds before implementing large-scale, operational management practices in these forests (Baker 1999, Fox et al. 2000). Among the silvicultural treatments to be considered were clearcutting tree overstories to create openings of varying shapes and sizes, thinning tree overstories to specified densities, and combining clearcutting and thinning treatments.

Research Protocols

One of the more important sites for the proposed research program was Beaver Creek, located in the Coconino National Forest south of Flagstaff. Research at Beaver Creek involved collaboration among U.S. Forest Service scientists and other partners in the Arizona Watershed Program (Baker 1999). Watershed studies were also undertaken at Castle Creek in the Apache-Sitrgeaves National Forest of eastern Arizona (Gottfried et al. 1999). The paired-watershed approach was applied in analyzing these experiments (Brooks et al. 2013).

With the recent, extended drought in the Southwest, there has been renewed interest in using silvicultural treatments to increase water yields from forested watersheds (Neary et al. 2008, Poff and Neary 2008). Silvicultural treatments imposed on watersheds in the ponderosa pine forests of Beaver Creek and a watershed at Castle Creek are reviewed to illustrate the contributions of silviculture in the management of southwestern ponderosa pine watersheds to increase streamflow volumes. Silvicultural studies on the Fort Valley Experimental Forest were not duplicated but provided the foundation for the watershed treatments (Gottfried et al. 2008).

Clearcutting of Tree Overstories

Beaver Creek Watershed 12 is a 425-acre watershed that was clearcut in 1966-1967 to evaluate effects of this "most drastic" of silvicultural treatments on streamflow volumes and other resource values (Baker 1986, 1999). The pre-treatment overstory consisted largely of ponderosa pine trees with intermingling Gambel oak (*Quercus gambelii*) and alligator juniper (*Juniperus deppeana*) trees. Annual precipitation in the ponderosa pine forests on

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Beaver Creek, when the watershed experiments were imposed, ranged from 20 to 25 inches, occurring in a bi-modal pattern with almost equal amounts in the winter and summer months (Baker 1999). Winter precipitation, often snowfall, was the major source of streamflow with only a small portion of summer rains converted into streamflow. Topography of Beaver Creek is characterized by flat, rolling mesas with intermingling mountainous terrain and varying slope and aspect combinations. Basalt and cinders are the parent materials of soils on the watershed. Forage for livestock and habitats for wildlife were found on the watershed before clearcutting.

Silvicultural Prescription

Once all of the trees in the overstory were cut, merchantable wood was removed from the watershed and transported to a sawmill in Flagstaff for processing. Non-merchantable wood and residual logging slash were piled in parallel windrows that were aligned perpendicular to the stream channel to facilitate a more efficient transport of overland flows of water to the channel. Post-treatment Gambel oak and alligator juniper sprouting were not controlled because of existing herbicide-use restrictions. Artificial regeneration was not part of the prescribed treatment.

Streamflow Response

Annual streamflow volumes following the clearcutting treatment increased an average with standard error of 1.7±0.2 inches (29.9±3.1%) for seven years (Baker 1986). Parenthetically, inches of annual increase in streamflow volumes are calculated from the total cubic feet of streamflow water prorated on a watersheds area. The increase in streamflow volumes on Watershed 12 was attributed mostly to a decrease in the water loss by transpiration (Brown et al. 1974, Baker 1986, Baker and Ffolliott 1999). Greater overland flows of water also resulted from melting snowpacks because of the reduction in soil-moisture deficits. Additionally, the windrows trapped snowfall on the lee sides of the windrows in the winter and then delayed snowmelt-runoff until the ambient temperature increased enough to rapidly melt the snow (Baker 1983). As a result of the alignment of the windrows, more of the snowmelt-runoff reached the stream channels. Vegetation had recovered within 7 years of the clearcutting treatment to where soil-water depletion was essentially the same as found beneath the pre-treatment forest cover. Annual sediment yields in the post-treatment streamflow ranged from 0.01 to 27 tons/acre annually with the highest value occurring after a historical rainstorm and hydrologic event in 1970 (Thorud and Ffolliott 1973). Changes in the concentrations of chemical constituents were inconsequential.

Impacts on Forest Structure

Clearcutting removed the watershed from timber production although it is improbable that timber production would become a focus of management in ponderosa pine forests in the future (Ffolliott 2008). However, post-treatment Gambel oak and alligator sprouts provided firewood for local inhabitants in the short-term. Stocking of natural regeneration (ponderosa pine seedlings) decreased from 65% before clearcutting to nearly 15% three years after the treatment. Only 5% of the watershed was stocked with ponderosa pine seedlings that had germinated since the treatment at this time. Stocking conditions remained relatively constant at this low level for 23 years following the clearing treatment (Ffolliott and Gottfried 1991). It is even unlikely, therefore, that the watershed could be considered for future timber production without artificial regeneration. Studies at Fort Valley had indicated that it was necessary to initiate artificial regeneration soon after clearcutting to minimize the problems of competing vegetation (Schubert 1974; Schubert et al. 1970). As mentioned earlier, artificial regeneration was not prescribed as part of the treatment.

Achieving goals other than timber production remained on the watershed. Increases in the production of forage plants following the clearcutting treatment increased forage production and, therefore, the possibilities of maintaining livestock grazing in the short-term (Baker and Ffolliott 1999). But, the post-treatment production of forage will decline if a competing forest cover should become re-established on the watershed (Bojorquez-Tapia et al. 1990). Impacts of the treatment on wildlife habitats can be estimated from the literature. Mule deer (*Odocoileus hemionus*) and elk (*Cervus elaphus*) should benefit from the edge-effect (ecotone) that was created between the clearcut area and adjacent uncut forest (Patton 1974) along the boundary of the watershed. However, the interior of the clearcut area was probably too far away from protective cover to be used regularly by these species (Ffolliott et al. 1977). The numerous post-treatment Gambel oak sprouts become a source of browse for mule deer (Ffolliott and Gottfried 1991, Reynolds et al. 1970). Key components of the habitat for Abert's squirrel (*Sciurus aberti*), specifically feeding and nesting trees for the squirrel (Ffolliott and Patton 1978, Patton 1975b, respectively), were eliminated by the treatment. Protective cover was furnished for cottontail (*Silvilagus auduboni*) by the windrows (Costa et al. 1976) until the windrows were later made available to firewood gatherers. It has been assumed that foliage-gleaning birds, birds whose nests are supported by trees, and birds that nest in cavities of standing dead trees declined in numbers while birds that scavenge for food on the ground were less affected by the treatment (Szaro and Balda 1979).

Thinning of Tree Overstories

A thinning treatment based on individual groups of ponderosa pine trees was implemented on the 298-acre Beaver Creek Watershed 17 in 1969. Thinning studies at Fort Valley specified high post-thinning basal-area levels of 80 to 120 ft^2/acre and even higher levels in some cases (Krauch 1949, Pearson 1950, Gaines and Kotok 1954, Myers and Martin 1963, Myers 1967). However, information on the response of ponderosa pine stands thinned to lower basal-area levels was also needed to manage ponderosa pine stands. Obtaining such information was a purpose of the watershed treatment in addition to evaluating the effects of a "heavy thinning treatment" on streamflow volumes. Similar to all of the Beaver Creek watersheds, Watershed 17 provided livestock forage and habitats for wildlife.

Silvicultural Prescription

Overstory trees on the watershed were commercially harvested by group selection with the remaining groups of ponderosa pine trees thinned uniformly to a basal area level of 25 ft^2/acre, a density level that was less than the "general guideline" of 80 ft^2/acre prescribed by managers at the time of the treatment (Schubert 1974). However, the thinning level was above the density level where windthrow of residual trees might occur (Ffolliott et al. 2000). All of the trees 25 inches in d.b.h. and larger and all dead standing trees were cut. Poor-risk trees, trees with dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum*) infections, and trees of poor form were also cut if their removal did not significantly reduce the targeted basal area level. It was then decided which of four size-classes of trees would dominate the thinned stand. These size of classes (classified by 2-inch d.b.h. intervals) were saplings (less than 4 inches in d.b.h.), poles (4 to 10 inches in d.b.h.), small sawtimber (12 to 18 inches in d.b.h.), and larger sawtimber (20 inches in d.b.h. and larger). Dominance was based on the size-class of trees that occupied the largest proportion of the stand. With the exception of den trees, Gambel oak trees larger than 15 inches in d.b.h. were removed and all of the alligator juniper trees originally present on the watershed were cut leaving a residual average of about 20 ft^2/acre of basal area in trees 7 inches d.b.h. and larger. Smaller trees satisfied the prescribed basal area level. Non-merchantable wood and residual slash were piled in windrows in a manner similar to that on Watershed 12. Artificial regeneration was not prescribed.

Streamflow Response

Annual streamflow volumes increases averaging 1.6±0.2 inches persisted for 10 years following the thinning treatment. These increases ranged from 10 to 30% above the predicted streamflow volume had on the watershed remained untreated (Brown et al. 1974, Baker 1986, Baker and Ffolliott 1999). The streamflow response was considered to be the result of both reduced transpiration losses and increased "runoff efficiency" of overland flows of water to the stream channel. It was apparent that the windrows created by the treatment influenced snowpack accumulation and melt patterns in a manner similar to that observed on Watershed 12. Annual sediment yields following the thinning treatment ranged from 0.03 to 0.32 tons/acre (Brown et al. 1974). Changes in the chemical constituents entrained in the post-treatment streamflow volumes were insignificant or inconsistent.

Impacts on Forest Structure

The thinning treatment resulted in the anticipated reduction in the number of trees, basal area, and volume per acre. However, an inventory conducted 25 years following the treatment indicated while the basal area and volume of the residual trees increased on a per acre basis, the number of trees remained the same (Ffolliott et al. 2000). These post-treatment trends were similar to those reported in earlier thinning studies at Fort Valley by Ronco et al. (1985), Schubert (1974, 1971), Myers (1967) Myers and Martin (1963), Gaines and Kotok (1954), and Pearson (1950). Stocking of natural regeneration was reduced from over 50% before the treatment to less than 2% immediately by the treatment. This initial loss of regeneration was temporary as nearly 40% of the watershed was re-stocked with ponderosa pine seedlings within 10 years of the treatment (Ffolliott et al. 2000). The scarified soil-surface caused by the treatment apparently provided a "favorable bed" for germination of the abundance of seeds dispersed 1 and 3 years following the treatment. Stocking at this time was about 15% higher than that observed 23 years following the clearcutting treatment on Watershed 12 (Ffolliott and Gottfried 1991).

Integrity of the thinned stands should be maintained at low density levels by preventing excessive windthrow. But, it was unlikely that timber production could be sustained on a rotational basis even if timber was later to become a component of forest management (Ffolliott et al. 2000). Managing the watershed for other resources is a more plausible scenario. The observed post-treatment increase in forage production should be sustained for a short time following the thinning treatment (Brown et al. 1974). However, the annual average of 100 lbs/acre of additional herbaceous species (including forage plants) produced after the treatment (Clary 1975) would decline as the density of forest cover increased (Bojorquez-Tapia et al. 1990). Habitats for mule deer and elk were enhanced by the treatment because of the combination of increased forage production with retention of a protective cover of trees. While many of the feeding and nesting trees that are commonly used by Abert's squirrel (Ffolliott and Patton 1978, Patton 1975b, respectively) were retained by the treatment, the interlocking of tree crowns that is necessary for squirrels to escape from predators and other disturbances (Patton 1975a) was lost by the prescribed spacing of the thinned trees. Bird habitats were essentially unchanged (Szaro and Balda 1979) with the exception of habitats for birds nesting in cavities of the standing dead trees that were cut as part of the silvicultural treatment.

Combined Stripcutting and Thinning of Tree Overstories

A combined stripcut-thinning treatment was carried out on the 1,350-acre Beaver Creek Watershed 14 in 1970-1971 to evaluate its effect on streamflow volumes. Cutting tree overstories in strips can increase snowpack accumulation and, in doing so, the amount of water available for streamflow (Gary 1975, Ffolliott et al. 1989, Baker 1999). Thinning of trees in the intervening leave strips can also increase accumulations of snow and, from a silvicultural standpoint, the growth of the residual trees. The effects of such a combined stripcut-thinning treatment on streamflow volumes and other resources were studied on this watershed.

Silvicultural Prescription

Overstory trees were cut in strips 60 feet wide with alternating leave strips 120 feet wide. The stripcuts were oriented in the direction of the land-slope and irregularly shaped for aesthetic purposes. A few trees were left as “spacers” within the stripcuts to break up the cleared continuity of the strips. The intervening leave strips were thinned uniformly to a prescribed basal-area level of 80 ft^2/acre by retaining favoring 12 to 24 inches in d.b.h. that were in short-supply as timber at the time. Trees 25 inches and larger, trees with heavy mistletoe infections, and poor-risk trees were also cut. Gambel oak trees that were larger than 15 inches in d.b.h. were cut in the leave strips unless there was evidence of their use as den trees. All alligator juniper trees were cut regardless of their size. The combined stripcut-thinning treatment eliminated nearly 40% of the pre-treatment total basal area on the watershed. Non-merchantable wood and residual slash were piled in the center of the stripcuts and later burned. Ponderosa pine seedlings were planted in stripcuts on better sites to supplement the natural regeneration that survived the treatment.

Streamflow Response

The hypothesis tested by the combined stripcut-thinning treatment was that streamflow volumes would increase since water loss by transpiration would decrease and the efficiency in transporting overland flows of water to stream channels would increase due to the uphill-downhill orientation of the stripcuts. Increased overland flows were also expected to occur because more snow would accumulate in the stripcuts as a result of reductions in interception losses and a re-distribution of snowfall by wind patterns (Ffolliott et al. 1989). An average annual increase in streamflow volumes of 1.0±0.1 inches (12 to 24%) was observed following the treatment but it lasted for only four years (Brown et al. 1974, Baker 1986, Baker and Ffolliott 1999). The comparatively short duration of increased streamflow was assumed to be caused by the recovery of vegetation in the stripcuts including the growth of planted ponderosa pine seedlings (Ffolliott and Baker 2001). Sediment yields after the combined treatment was implemented were less than those occurring after the clearcutting on Watershed 12 and heavy thinning treatment on Watershed 17. Changes in the concentrations of chemical constituents in the streamflow were largely insignificant.

Impacts on Forest Structure

The treatment eliminated most of the trees in the stripcuts while retaining a mosaic of even-aged stands comprised largely of trees 8 to 18 inches in d.b.h. in the leave strips. The number of trees, basal area, and volume per acre of residual trees in the leave strip increased in the initial 25-year post-treatment period as expected (Ffolliott and Baker 2001). However, this finding differed somewhat from the results obtained in thinning experiments at Fort Valley where little or no initial increase in basal area and volume per acre was observed following thinning but individual trees grew faster once they were released (Krauch 1949, Pearson 1950, Gaines and Kotok 1954, Myers and Martin 1963). Pearson (1950) believed that the results at Fort Valley were related to the low residual stocking of trees and high mortality of trees in the virgin and cutover stands that were thinned. It should be mentioned that trends similar to those reported at Fort Valley were observed after the thinning treatment on Watershed 17. Almost 20% of Watershed 14 was stocked with natural regeneration before the treatment was implemented (Ffolliott and Baker 2001). This level of stocking was similar to, or less than, stocking conditions in ponderosa pine forests elsewhere on Beaver Creek (Ffolliott and Gottfried 1991, Ffolliott et al. 2000). Stocking on the watershed was reduced by the combined stripcutting-thinning treatment with less than 12% of the leave strips stocked shortly after the treatment was completed in 1971; stocking in the stripcuts at this time was unknown. The loss of stocking in the leave strips was caused by felling and skidding of trees marked for thinning. Stocking in these strips has remained largely unchanged since. Stocking of stripcuts that had been planted with ponderosa pine seedlings to supplement the natural regeneration was about 45% in 1996 while stocking in the stripcuts that were not planted was 12%, a level that was similar to the stocking of the leave strips at this time.

Ponderosa pine stands in the leave strips should be sustained with the growth of residual trees likely to increase. However, planting of additional ponderosa pine seedlings in the stripcuts will be necessary if a forest cover is to be re-established or, alternatively, other strips are cut to replace the original stripcuts in the rotational cycle of management envisioned when the combined stripcut-thinning treatment was planned (Brown et al. 1974). The increases in forage production in the stripcuts and leave strips following the treatment were anticipated to continue but at a lowering level of production with increases in forest cover (Bojorquez-Tapia et al. 1990). Mule deer and elk habitats were improved with the increase in forage production, retention of a protective cover in the leave strips, and the ecotone created between the cut and leave strips (Patton 1974). Habitat for Abert's squirrel was lost in the stripcut while it was retained at a lower quality in the leave strips for reasons that were similar to those following the thinning treatment on Watershed 17. Availability of food and cover for bird populations was mostly unchanged on a watershed-basis by the combined treatment (Szaro and Balda 1979).

Timber Harvesting and Thinning Tree Overstories

The Castle Creek watersheds, south of Alpine, are part of a group of experimental watersheds in ponderosa pine, mixed conifer, and mountain grassland on the Apache-Sitgreaves National Forest (Gottfried et al. 1999). These watersheds were established to investigate effects of vegetative management practices on streamflow volumes based on the "best thinking" of U.S. Forest Service managers at the time the treatments were implemented (Rich 1972, Rich and Thompson 1974). As one component of this research effort, a combined treatment of harvesting timber and thinning of the remaining overstories to place trees in the "best growing condition" possible, was imposed in the ponderosa pine forest on the 900-acre West Fork of Castle Creek in 1965-1966. The silvicultural purpose of this treatment was to initiate movement of the original uneven-aged structure of the forest to an even-aged form of management. West Fork is higher in elevation than the Beaver Creek watersheds, and, therefore, annual precipitation is greater, ranging from 27 to 30 inches. Precipitation occurs in a bi-module pattern of seasonal distribution similar to Beaver Creek (Baker 1999). Ponderosa pine trees dominated the overstory before the treatment was implemented with an intermediate understory of scattered Gambel oak trees. Mixed-conifer tree species occurred on moist north-facing slopes and along stream channels. Topography and soils are similar to those found on the Beaver Creek watersheds. Forage for livestock and habitats for wildlife are other watershed values.

Silvicultural Prescription

The timber harvesting operations involved clearcutting one-sixth of West Fork in irregular blocks (openings) that were fitted to conform to the existing stands of mostly over-mature and unneeded tree size-classes. The remaining five-sixths of the watershed were thinned uniformly to remove high-risk and over-mature trees, mature trees where necessary to release crop trees, poorly formed trees, and trees infected with dwarf mistletoe (Gottfried and DeBano 1990, Gottfried et al. 1999). This treatment "mimicked" a shelterwood system of silviculture at a growing stock level of about 60 ft^2/acre. The idea was also to simulate "commercial timber management" by initiating a 120-year rotation period with a 20-year cutting cycle. This management model was based largely on the results of earlier studies at Fort Valley and later proposed by Schubert (1974) to produce the "highest possible" sustained yield of high-quality trees. Nearly 50% of the original basal area of 135 ft^2/acre on the watershed was removed by the timber harvesting and thinning treatment. Ponderosa pine seedlings were planted in the harvested blocks to achieve adequate regeneration.

Streamflow Response

Increases in streamflow volumes on West Fork remained stable at 0.5 inches (about 30%) for more than 20 years after implementing this treatment (Gottfried and DeBano 1990). These increases were attributed to reduced evapotranspiration rates and increased snowpack accumulations (Rich 1972, Rich and Thompson 1974, Gottfried and DeBano 1990). It was also likely that the increases in streamflow volumes were due to the roots of newly established trees not fully occupying the soil mantle. Other factors included the height differences between residual trees surrounding the cut blocks and regeneration in these openings causing aerodynamic conditions that favored increased snowpack accumulations (Gottfried et al. 1999, Gottfried and Ffolliott 2009).

Impacts on Forest Structure

The post-treatment stand structure on West Fork closely resembled the initial stages of a balanced even-aged condition (Rich and Thompson 1974, Gottfried et al. 1999). Silvicultural studies at Fort Valley indicated that a balanced even-aged stand structure has a greater "timber-productivity potential" than an unbalanced stand structure (Pearson 1950, Schubert 1974). Timber production is not the main component of forest management at this time. Changes in the stocking of natural regeneration as a result of the treatment were unknown. However, even with the emphasis on the Four Forest Restoration Initiative in Arizona (U.S. Forest Service 2010), which features thinning and stand reductions, timber production is still an important consideration of forest management planning. Changes in the overall stocking of natural tree regeneration as a result of the Castle Creek treatment were unknown but many of the openings were subsequently planted with ponderosa pine seedlings.

Since timber production is not a focus of forest management, at the present time, management of ponderosa pine forests is furnishing other ecosystem-based, multiple-use benefits on the watershed (Gottfried et al. 1999). The timber harvesting and thinning treatment should benefit livestock production because of anticipated increases in the production of forage plants (Bojorquez-Tapia et al. 1990). Interspersion of the clearcut blocks with thinned tree overstories should provide "excellent" habitat conditions for mule deer and elk (Patton 1974). Abert's squirrel habitat was eliminated on the one-sixth of West Fork where timber was harvested while it was largely sustained on the remainder of the watersheds. A study of changes in bird population after timber harvesting in a nearby mixed conifer forest (Franzblau 1977) suggests that some bird populations benefitted from the treatment while the effects on other birds were largely inconsequential or detrimental.

Summary

Silvicultural treatments implemented on watersheds in the ponderosa pine forests of Beaver and Castle Creeks to increase streamflow volumes were imposed following general agreement among collaborators in the original Arizona Watershed Program. Findings from silvicultural studies on the Fort Valley Experimental Forest played a key role in preparing the prescriptions for these treatments. It was found that streamflow volumes increased at Beaver Creek for seven to ten years, respectively, when the tree overstories on Watershed 12 were clearcut and the tree overstories on Watershed 17 were thinned. A combined stripcut-thinning treatment on Watershed 14 and a timber harvesting-thinning treatment on the West Fork of Castle Creek represented a combination of these silvicultural practices. The increased streamflow volumes observed on these watersheds were attributed to reductions in evapotranspiration rates and redistributions of snowfall with differential melting of the accumulated snowpack improving increased overland flows of water. Impacts of these experiments on forest structures were what would be expected by applying the silvicultural prescriptions tested. Depending on the opening characteristics and magnitudes of the reductions in the densities of tree overstories, all of the treatments were beneficial to livestock and wildlife. Knowledge gained from these keystone watershed experiments should provide today's managers with a better appreciation of the contributions of silviculture to the past management of Arizona's ponderosa pine forests.

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