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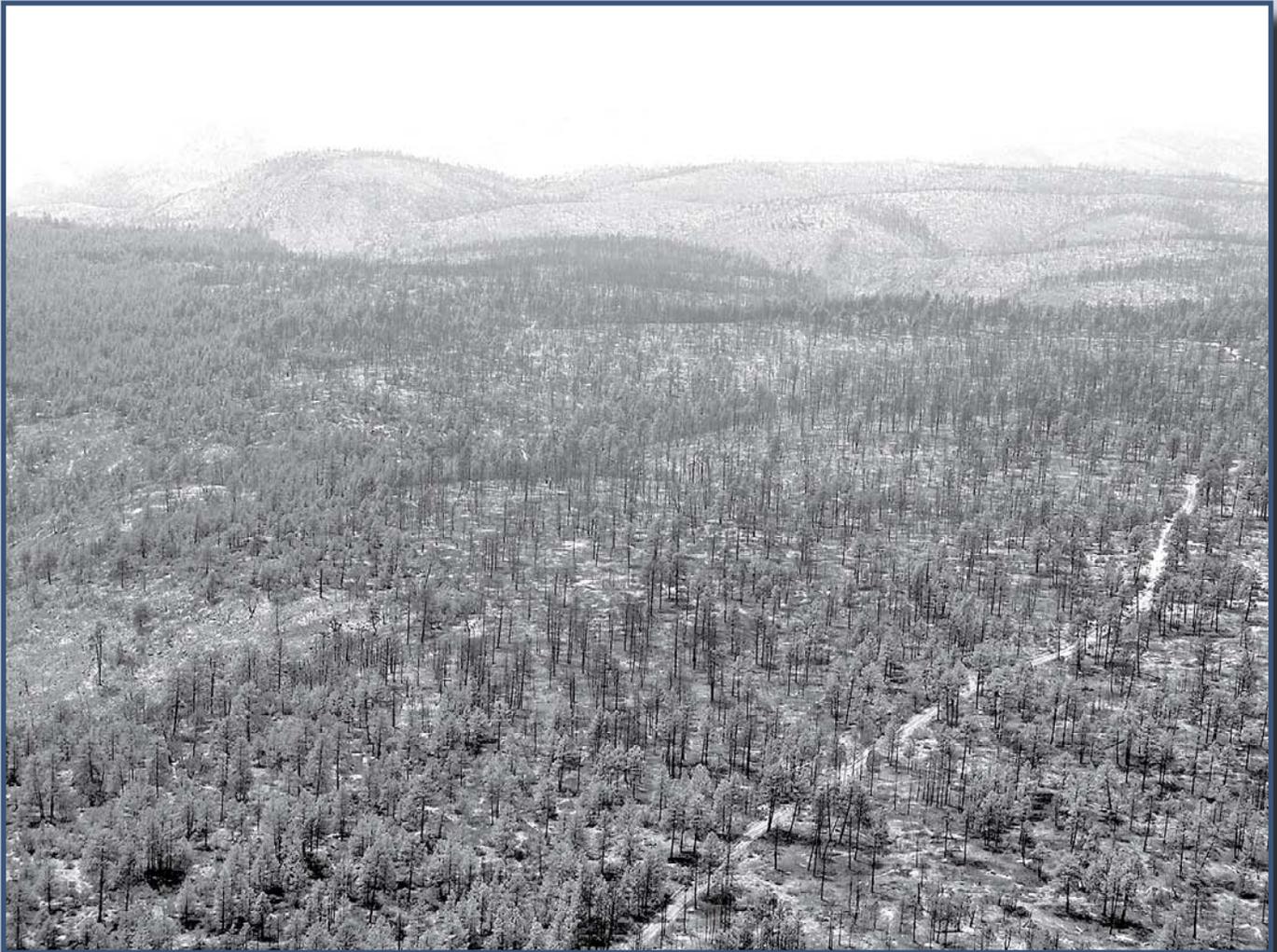
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Historical Wildfire Impacts on Ponderosa Pine Tree Overstories: An Arizona Case Study

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Abstract

The Rodeo-Chediski Wildfire—the largest in Arizona’s history—damaged or destroyed ecosystem resources and disrupted ecosystem functioning in a largely mosaic pattern throughout the ponderosa pine (*Pinus ponderosa*) forests exposed to the burn. Impacts of this wildfire on tree overstories were studied for 5 years (2002 to 2007) on two watersheds in the area burned. One watershed was burned by a high severity (stand-replacing) fire, while the other watershed was burned by a low severity (stand-modifying) fire. In this paper, we focus on the effects of the wildfire on stand structures, post-fire mortality of fire-damaged trees, and stocking of tree reproduction. We also present a fire severity classification system based on the fire-damaged tree crowns and a retrospective description of fire behavior on the two burned watersheds.

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Introduction

The Rodeo-Chediski Wildfire of 2002—the largest in Arizona’s history—damaged or destroyed valuable ecosystem resources and disrupted crucial ecosystem functioning in a largely mosaic pattern throughout the ponderosa pine forests. Once a source of material for primary wood products, these forests currently provide watershed protection, wildlife habitats, and sites for recreational activities. We were presented with a unique opportunity to study the impacts of this wildfire on ponderosa pine tree overstories and stocking of tree reproduction on two watersheds in the burn area (Ffolliott and Neary 2003). Because one of the watersheds was exposed to a high severity (stand-replacing) fire and the other watershed to a low severity (stand-modifying) fire, it was possible to make comparisons of the effects of differing fire severities on tree overstories and stocking of tree production.

Study Objectives

The primary objectives of the 5-year (2002 to 2007) study were to:

- determine the initial impacts of the wildfire on stand structures;
- determine post-fire mortality of fire-damaged trees; and
- describe the impacts of the wildfire on stocking of tree reproduction.

Other objectives were to:

- develop a fire severity classification system based on fire damage to tree crowns and
- retrospectively describe the fire behavior on the burned watersheds from evaluations of fire severity.

We initiated the study shortly after the cessation of the Rodeo-Chediski Wildfire and continued until salvage cutting and fuel reduction treatments were imposed on one of the watersheds studied. Similar treatments were imposed on a larger scale within the ponderosa pine forests on the portion of the Apache-Sitgreaves National Forest burned by the wildfire.

Rodeo-Chediski Wildfire

The Rodeo-Chediski wildfire damaged or destroyed ecosystem resources and disrupted the ecological functioning on much of the 467,066 acres impacted by the burn (Ffolliott and Neary 2003, Gottfried and others 2003). Intermingling chaparral shrub communities and pinyon-juniper woodlands at lower elevations and ponderosa pine forests at high elevations were located within the burned area. The wildfire was caused by two human ignitions that merged into one inferno. The Rodeo Fire was started by an arsonist on June 18, while the Chediski Fire was ignited as a signal fire by a stranded motorist on June 20. The two fires merged on June 26 to become the Rodeo-Chediski Wildfire. The combined wildfires were contained on July 7 at a suppression (firefighting) cost of about \$50 million. However, the estimated costs associated with property losses; losses of ecosystem, anthropological, and cultural resources; and post-fire rehabilitation efforts increased the costs of the wildfire to over \$150 million.

The wildfire impacted 280,992 acres on the Fort Apache Reservation, 167,215 acres on the Apache-Sitgreaves National Forest, and 10,667 acres on the Tonto National Forest. The remaining area burned was on private land. About ½ of the total area burned by the Rodeo-Chediski Wildfire experienced a high severity fire, other areas burned at a low to medium severity fire, and still other areas were largely unburned according to a Burned Area Emergency Rehabilitation (BAER) report and fire severity map (<http://www.fs.fed.us/r3/asnf>) prepared shortly after containment of the wildfire. A mosaic of areas burned at varying fire severities within intermingling unburned areas resulted (fig. 1). Post-fire rehabilitation efforts, including establishment of water bars, wattles, k-rails, and aerial seeding and mulching of herbaceous plants to mitigate that anticipated accelerated post-fire soil erosion, began immediately after the fire was extinguished and it was declared safe for people to enter the burned area and initiate rehabilitation.



Figure 1. A mosaic burning pattern of varying fire severities within intermingling unburned areas resulted from the Rodeo-Chediski Wildfire.

Study Areas

The study areas were two watersheds established in 1972 and 1973 along Stermer Ridge on the Apache-Sitgreaves National Forest at the headwaters of the Little Colorado River. These watersheds were instrumented as a cooperative endeavor of the School of Natural Resources, University of Arizona, Tucson, and the Rocky Mountain Research Station, U.S. Forest Service, to obtain baseline information on watersheds located in ponderosa pine forests on sedimentary soils (Ffolliott and Baker 1977). Situated about 8 miles southwest of Heber, Arizona, the Stermer Ridge Watersheds, 60 acres each, were established to complement the results obtained from “experimental watersheds” located in ponderosa pine forests on basaltic soils. The information obtained on the Stermer Ridge Watersheds facilitated comparisons of ecological and hydrologic characteristics between the forests on the two parent materials.

The two watersheds are characterized by flat topographies, with few slopes exceeding 10 percent. Elevations range from 6,800 to 7,000 ft. Cretaceous undivided material with a mineralogy that is similar to that of the Coconino sandstone formation lies beneath the watersheds. Soils derived from this parent material have been classified in the McVickers series with fine, sandy loam surface textures (Hendricks 1985). The watersheds receive about 20 to 25 inches of annual precipitation. Nearly 65 percent of this precipitation falls from October to April, much of it as snow, with the remainder coming mostly in high-intensity (monsoon) rainstorms from July to early September. However, the southwestern United States was experiencing drought conditions at the time of the Rodeo-Chediski Wildfire, a condition that continued throughout the evaluations presented in this paper. Annual precipitation in this drought period averaged less than 16 inches. Results of these post-fire evaluations, therefore, must be considered within context of these conditions. Over 90 percent of the ephemeral streamflow originating on the Stermer Ridge Watersheds occurs as a result of prolonged winter rains or snowmelt-runoff events in the spring. Discharge rates of the streamflow are generally low with minimal sediment concentrations. Summer storms rarely produce significant streamflow.

Before the wildfire, tree overstories on the two watersheds were largely uneven-aged stands of cutover ponderosa pine trees. Merchantable timber had been harvested several times before the Rodeo-Chediski Wildfire occurred. The last timber harvest in the early 1960s removed about 45 percent of the sawtimber trees by group selection. Intermingling Gambel oak (*Quercus gambelii*) and scattered alligator juniper (*Juniperus deppeana*) trees were also found on the watersheds.

Principle grasses and grass-like plants were muttongrass (*Poa fendleriana*), blue grama (*Bouteloua gracilis*), squirreltail (*Elymus elymoides*), black dropseed (*Sporobolus interruptus*), and sedge (*Carex* spp.). The main forbs and half-shrubs included showy aster (*Aster commutatus*), showy goldeneye (*Heliomeris multiflora*), western ragweed (*Ambrosia psilostachya*), and broom snakeweed (*Gutierrezia sarothrae*). Shrubs in addition to the shrub-form of Gambel oak included Fendler’s ceanothus (*Ceanothus fendleri*) and New Mexican locust (*Robinia neomexicana*).

The Stermer Ridge Watersheds were “moth-balled” in late 1977 after completion of the earlier baseline studies. However, the control sections (3-ft H-flumes) were left in place in anticipation of future use. Such a use presented itself with the occurrence of the Rodeo-Chediski Wildfire. Following the

fire, the control sections were refurbished and re-instrumented with water level recorders. A weather station on the site was also re-established. Thirty sample plots that had been installed on each watershed to measure ecological and hydrologic parameters in the earlier studies were relocated to provide a sampling basis to evaluate the impacts of the wildfire on the ponderosa pine tree overstories and stocking of tree reproduction.

Classification of Fire Severity

A classification system that relates fire severity to the soil-resource response to burning (Hungerford 1996) was the basis for classifying severity of the Rodeo-Chediski Wildfire at the sample plots on the watersheds immediately following burning. Hungerford's system of classifying fire severity is:

- No fire.
- Low fire severity—low soil heating or light ground char occurring where litter is scorched, charred, or consumed, while the duff is left largely intact although it can be charred on the surface. Woody debris accumulations are charred or partially consumed. Mineral soil is not changed. Soil temperatures at 0.5 inch are less than 125°F. Lethal (fatal) temperatures for soil organisms occur to depths of 0.5 inch. The lethal temperatures for most soil organisms range upward to 212°F (DeBano and others 1998).
- Moderate fire severity—moderate soil heating or moderate ground char occurring where the litter is consumed and the duff is deeply charred or consumed. Woody debris is mostly consumed except for logs that are deeply charred. Underlying mineral soil is not visually altered. Soil temperatures at 0.5 inch can reach 212 to 392°F. Lethal temperatures for soil organisms occur down to depths of 1.2 to 2.0 inches.
- High fire severity—high soil heating or deep ground char occurring where the duff is completely consumed and the top of the mineral soil is visibly reddish or orange. Color of the soil below 0.5 inch is darker or charred from organic material. The char layer can extend to a depth of 4 inches or more. Logs can be deeply charred or consumed and deep ground char can occur under slash concentrations or burned-out logs. Soil texture in the surface layers is changed and fusion evidenced by clinkers can be observed. All shrub stems, if present, are consumed and only the charred remains of larger shrubs are visible. Soil temperatures at 0.5 inch are greater than 485°F. Lethal temperatures for soil organisms occur to depths of 3.5 to 6.4 inches.

The classifications of the fire severity at the sample plots were extended to a watershed-basis by determining the respective percentage of the total areas of the two Stermer Ridge Watersheds that were burned at low, moderate, and high fired severities (Neary and others 2005; Ryan and Noste 1985; Wells and others 1979) as follows:

- No burning.
- Low severity fire—less than 2 percent of the area experienced a high severity fire, less than 15 percent burned moderately, and the remainder of the area was burned at a low severity or was unburned.
- Moderate severity fire—less than 10 percent of the area exposed to a high severity fire, over 15 percent burned moderately, and the remainder of the area burned at low severity or was unburned.

- High severity fire—more than 10 percent of the area burned at high severity, more than 80 percent moderately burned or burned at high severity, and the remainder of the area burned at low severity.

The extrapolations of Hungerford's fire severity classification system to a watershed basis indicated that one of the Stermer Ridge Watersheds was burned by a high severity (stand-replacing) fire, while the other watershed was burned by a low severity (stand-modifying) fire. A classification system that relates fire severity to the damage to trees crowns was developed later in this study to further classify fire severities on the watersheds (see following). Interpretations of Hungerford's system and this second classification system were used to describe in more detail fire behavior on the burned watersheds.

Study Protocols

Initial Impacts of the Wildfire on Stand Structures

We reconstructed the pre-fire stand structures of the ponderosa pine trees on the Stermer Ridge Watersheds to provide a reference to determine the initial impacts of the Rodeo-Chediski Wildfire on the stand structures. Two approaches were undertaken in obtaining these reconstructions.

One approach was to tally trees 6 inches in diameter (dbh) and larger at the sample plots shortly after the cessation of the wildfire—both alive and killed outright by the fire—by point sampling (Avery and Burkhart 2002) with a basal area factor of 25. (The 6-inch dbh class included trees 5.0 to 6.9 inches, the 8-inch dbh class included trees 7.0 to 8.9 inches, and so forth.) Trees less than 6 inches in dbh (saplings) were excluded from these tallies because the clumped distributions of these smaller trees in southwestern ponderosa pine forests (fig. 2) could introduce a bias in the reconstruction process. When these smaller trees are tallied by point sampling and then expanded to a per acre basis (Ffolliott 1965), either too large or too small numbers are frequently obtained and thus cause this (unknown) bias in the constructions of stand structures.

The reconstruction of pre-fire stand structures obtained by point sampling also included tallies of burned-out root cavities representing trees completely consumed by the wildfire. We obtained estimates of the dbh of the pre-fire trees “occupying” these cavities from interpretations of earlier relationships for estimating dbh of standing trees from stump diameters (Myers 1963a). Diameters of the root cavities were assumed to approximate the stump diameters of the pre-fire trees in obtaining these estimates.

The second approach to reconstructing the pre-fire stand structures involved a series of sequential computer-simulated stand-table projections from 1977, when the two watersheds were “moth-balled,” to a time immediately before the Rodeo-Chediski Wildfire. For this purpose, we used a simplified version of TRAS (Timber Resource Analysis System), a widely used computer program for obtaining projections of the forest resources in the United States (Alig and others 1982; Larson and Goforth 1970), at the time when the earlier baseline studies on the Stermer Ridge Watersheds began. Results of the simulated stand-table projections were then compared to the reconstructions of the stand structures obtained by point sampling inventorying to verify the “correctness” of the reconstructions obtained by point sampling.



Figure 2. Clumped distributions of trees less than 6 inches in dbh (saplings) are common in southwestern ponderosa pine forests.

The reconstructions obtained by point sampling techniques and those simulated by the simplified version of TAS were similar in their respective tree distributions with the exception of minor discrepancies (less than 15 percent) in the numbers of trees in the 6-to-10 inch dbh classes. Fewer numbers of trees in these smaller dbh classes were estimated by the point sampling than by the computer simulations. Nevertheless, based on the similarities between the tree distributions of the other dbh classes, we concluded that the reconstructed stand structures based on the point sampling represented an “acceptable depiction” of the pre-fire ponderosa pine tree overstories on the Stermer Ridge Watersheds and, therefore, formed the basis for analyzing the initial impacts of the Rodeo-Chediski Wildfire on stand structures.

The pre-fire stand structures were summarized by 2-inch dbh classes in terms of the number of trees per acre (stand tables), basal area per acre, and cubic-foot volume per acre (stock tables) for analyses purposes. We used a volume table based on recoverable cubic-foot volumes in ponderosa pine stands (Ffolliott and others 1971) to construct the stock tables because this table was the basis for obtaining volume estimates in the earlier baseline studies on the Stermer Ridge Watersheds. Consistency was necessary in evaluating the impacts of the wildfire on tree overstories.

Post-Fire Mortality of Fire-Damaged Trees

Immediately after the wildfire, trees tallied on the sample plots and initially surviving the Rodeo-Chediski Wildfire were classified in terms of their relative crown and bole damage as follows:

- Crown (foliage and terminal bud) damage
- No crown damage
- Less than 1/3 of the crown killed or severely scorched
- Between 1/3 to 2/3 of the crown killed or severely scorched
- More than 2/3 of the crown killed or severely scorched
- Bole (cambium) damage
- No damage
- Less than 1/3 of the bole circumference charred
- Between 1/3 and 2/3 of the bole circumference charred
- More than 2/3 of the bole circumference charred

Similar criteria were used to classify fire damage and predict post-fire mortality of ponderosa pine trees in other studies (Fowler and Sieg 2004). Later in the study, we determined that the incorporation of bole damage within the classification of tree damage, based solely on fire-damage to tree crowns, did not significantly change the annual observations of post-fire mortality of fire-damaged trees on the Stermer Ridge Watersheds from 2002 through 2006. We assumed that the impacts of the Rodeo-Chediski Wildfire on tree mortality had been “fully expressed” by this time. To complicate these annual observations, however, it was unknown whether a fire-damaged tree on the watershed burned by the high severity fire had died before initiation of the salvage cutting and fuel reduction treatments in late 2005 and was then cut as part of these treatments. Salvage cutting and fuel reduction treatments were not conducted on the watershed burned by the low severity fire and, therefore, this complication was moot.

Stocking of Tree Reproduction

To determine the initial impact of the fire on the stocking rates, stocking of tree reproduction was tallied on mil-acre plots centered over the sample plots on the watersheds immediately following the cessation of the wildfire. A mil-acre plot was considered stocked with reproduction if at least one plantlet was tallied; otherwise, the plot was considered not stocked. Stocking was then recorded in 2004 and 2006, 2 and 4 years after the fire, respectively, to assess longer term stocking conditions.

Fire Severity Classification System Based on Crown-Damaged Trees

The fire severity classification system based on the effects of burning on tree crowns was developed using post-fire mortality observations of the crown-damaged ponderosa pine trees. Bole damage was not incorporated into this system (see previous). All of the tallied trees were considered in these observations.

Fire Behavior on the Stermer Ridge Watersheds

We used two approaches to retrospectively estimate the behavior of the Rodeo-Chediski Wildfire at the sample plots on the two watersheds. One approach indicated the severity of a surface fire to the soil-resource response (Hungerford's 1996 classification system). The second approach indicated the severity of a crown fire to the damage of the fire to tree crowns (see previous).

With respect to the second approach, differentiating crown scorching caused by the heat of a surface fire from the damage caused by a crown fire advancing from one tree to another tree independent of a surface fire (McPherson and others 1990) proved difficult. Instead, we used the general term "crown damage" when referring to the fire damage of tree crowns.

Using both approaches, fire severities determined at the sample plots on the Stermer Ridge Watersheds were extrapolated to a watershed-basis (Neary and others 2005; Ryan and Noste 1985; Wells and others 1979) to characterize the respective fire behavior patterns on the watersheds.

Results and Discussion

Initial Impacts of the Wildfire on Stand Structures

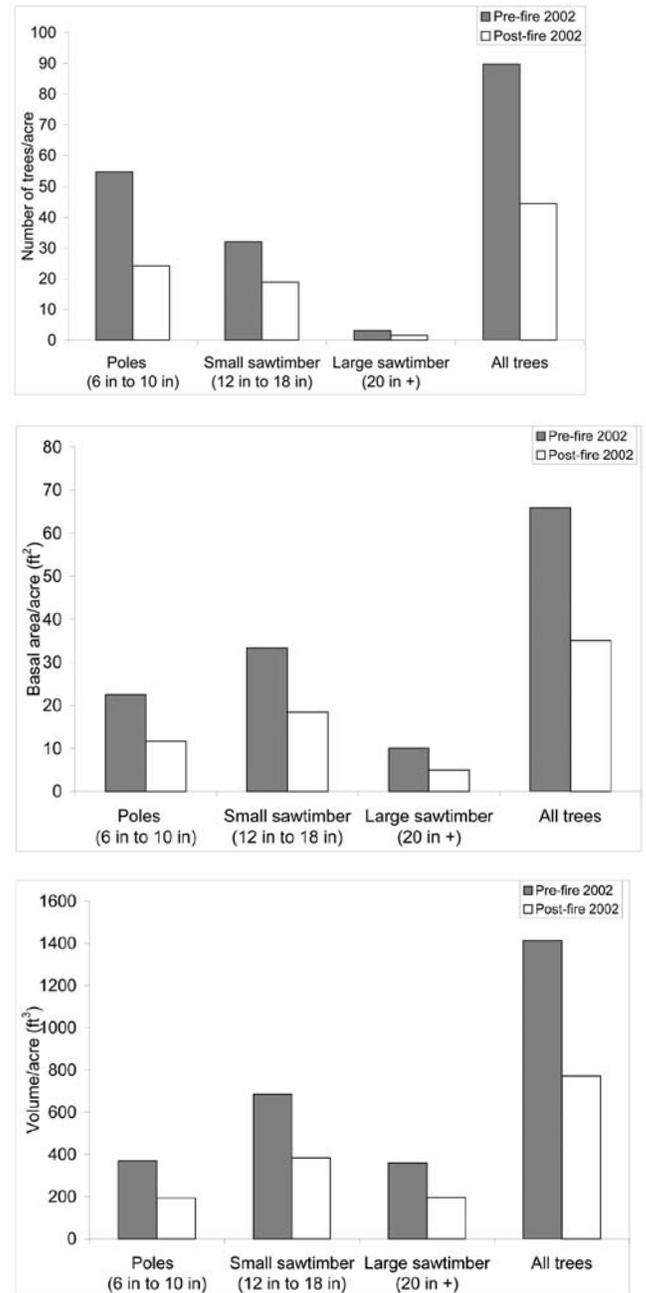
As expected, initial impacts of the Rodeo-Chediski Wildfire on the stand structures of ponderosa pine trees were more pronounced on the watershed experiencing the high severity fire than on the watershed burned by the low severity fire. The initial impacts for selected tree classes and all of the ponderosa pine trees on the two watersheds are shown in figures 3 and 4, respectively. Tree classes coincide with the categories of Smith and others (2004) for poles (at least 6 inches dbh, but smaller than sawtimber) and sawtimber (12 inches dbh and larger). The sawtimber class was further separated into small sawtimber (up to 18 inches dbh) and large sawtimber (20 inches dbh and larger). Small sawtimber trees (often called blackjacks) have dark bark and relatively rapid stem taper, while large sawtimber trees (yellow pine) have yellowish bark and less stem taper (Myers 1963b; Pearson 1950; Schubert 1974). Trees in these two sawtimber classes are often tallied separately in timber inventories and other mensurational work in the region.

High severity fire

Nearly 50 percent of the pre-fire ponderosa pine trees on the watershed burned by a high severity fire (90 trees/acre) were killed outright by the burn (fig. 3). We observed higher mortality in the poles than in the sawtimber classes, a frequent finding following high severity fires in western montane forests (Arno 2000). Almost 55 percent of the poles suffered mortality, while slightly less than 35 percent of the trees in the sawtimber classes were killed. However, all of the trees surviving the initial impact of the wildfire were severely damaged by the burn, with at least 2/3 of their crowns consumed or heavily scorched by burning. Many of these crown-damaged trees died within 2 years of the fire (see following).

About 45 percent of the basal area and cubic-foot volume of ponderosa pine trees before the wildfire (66 ft² of basal area/acre and 1,414 ft³ of cubic-foot

Figure 3. Initial impacts of the Rodeo-Chediski Wildfire on the stand structure of ponderosa pine trees on the Stermer Ridge Watershed burned by a high severity fire in terms of number of trees/acre (top), basal area (ft²/acre) (middle), and volume (ft³/acre) (bottom). Scales of the Y-axis are unique for each graph.



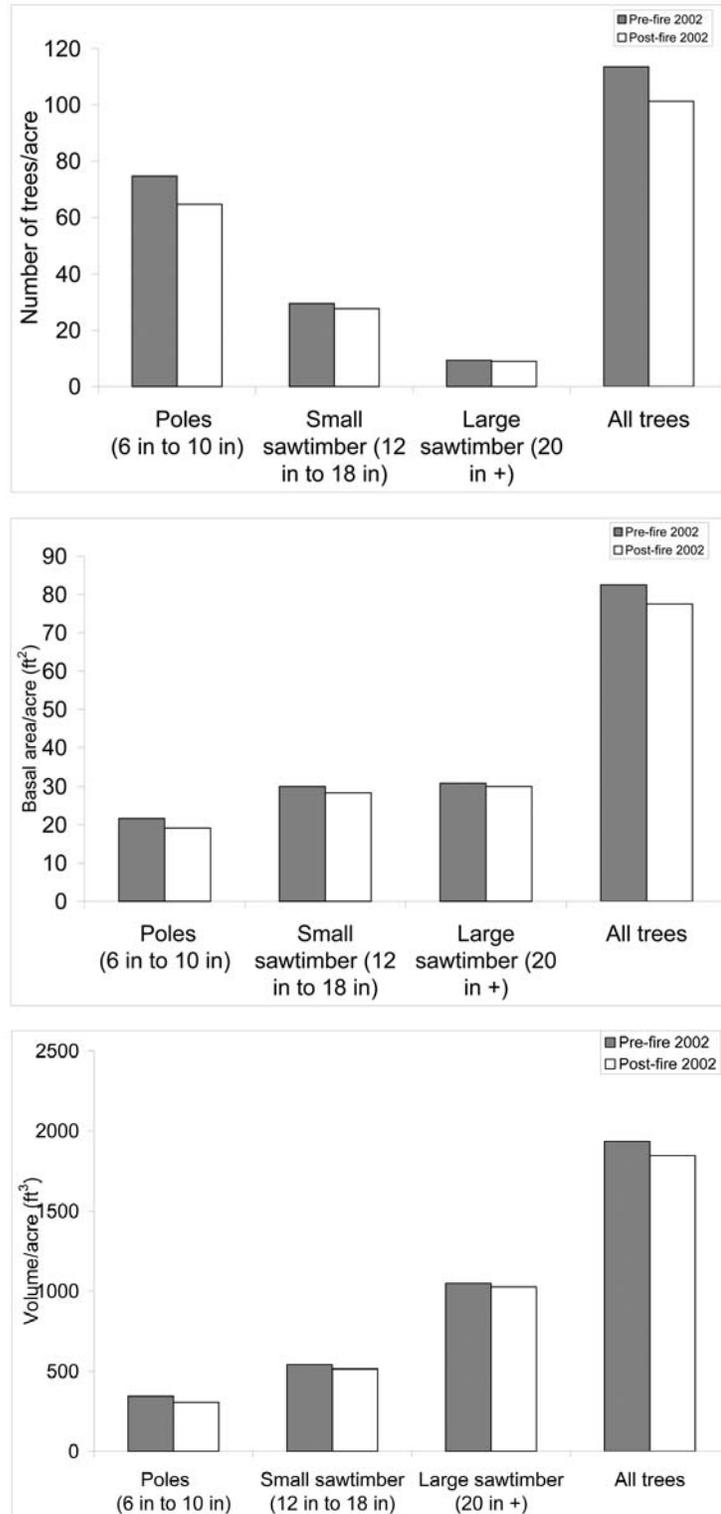
volume/acre, respectively) were initially lost in the burning event. The largest loss in basal area occurred in large sawtimber. Poles suffered the largest loss in cubic-foot volume.

The number of pre-fire Gambel oak trees (6.5 trees/acre) was less than generally found in southwestern ponderosa pine forests (Smith and others 2004). Almost 90 percent of these trees suffered complete crown kill. However, basal sprouting was observed on most of the trees within a year of the fire, indicating that they had not been root-killed by the burn. While none were tallied on the sample plots, it was noted that most of the scattered alligator juniper trees on this watershed were either killed by the fire or experienced severe crown damage. Only limited post-fire basal-sprouting of alligator juniper was observed.

Low severity fire

Only 17 percent of the pre-fire ponderosa pine trees on the watershed exposed to a low severity fire (113.5 trees/acre) were killed directly by the fire (fig. 4). The largest mortality, comparatively speaking, occurred in poles, with 20 percent of the trees lost. Mortality in the sawtimber classes was less than 10 percent. Of the 83 percent of the trees surviving the fire, 70 percent were undamaged by the burn, while about 30 percent experienced only minimal crown damage.

Figure 4. Initial impacts of the Rodeo-Chediski Wildfire on the stand structure of ponderosa pine trees on the Stermer Ridge Watershed burned by a low severity fire in terms of number of trees/acre (top), basal area (ft^2/acre) (middle), and volume (ft^3/acre) (bottom). Scales of the Y-axis are unique for each graph.



Basal area and cubic-foot volume losses of ponderosa pine trees were also minimal. A loss of only 5 percent occurred in both the pre-fire basal area (80 ft²/acre) and cubic-foot volume (nearly 1,950 ft³/acre). Poles suffered the largest loss of almost 10 percent in both basal area and cubic-foot volume. Large sawtimber lost only 2 percent of its original volume.

Nearly all of the pre-fire Gambel oak and alligator juniper trees (a combined average of only 7.5 trees/acre) survived the wildfire with little or no fire damage to their crowns. Less than 15 percent of the Gambel oak exhibited severe crown damage and many of these trees sprouted within 2 years of the fire. None of the alligator juniper observed was damaged.

Other studies on the impacts of wildfire on stand structures

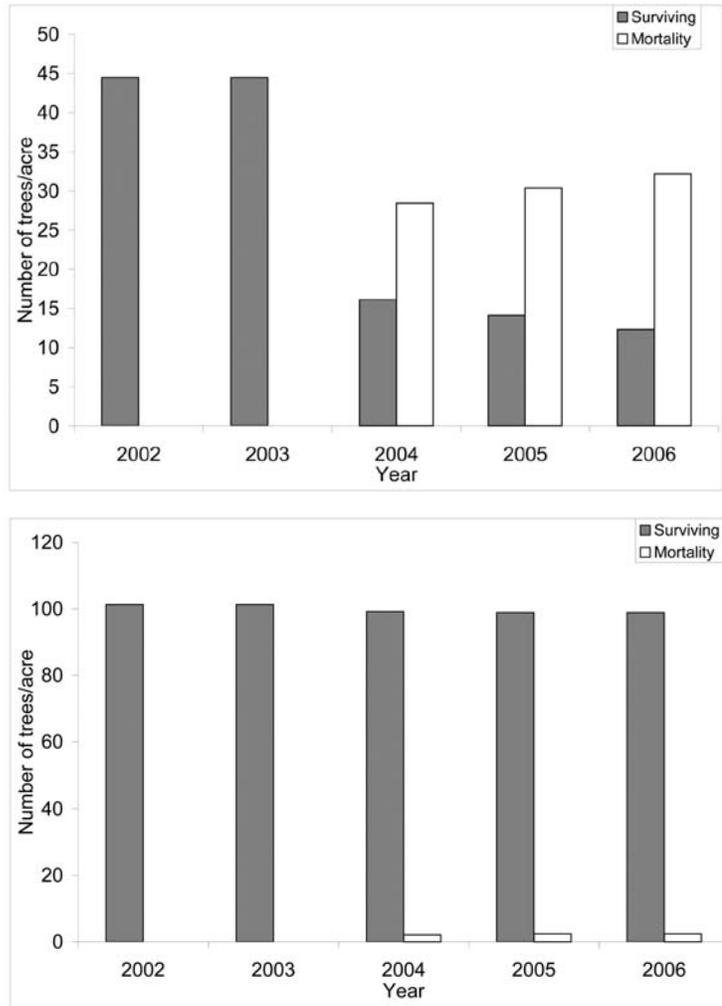
Approximately 800 acres of a ponderosa pine forest north of Flagstaff, Arizona, were burned by a wildfire in early May 1967. Included within the burned area were two pastures on the Wild Bill Experimental Range (Pearson and Jameson 1967). One of the burned pastures had been thinned to a basal area level of approximately 20 ft²/acre before the fire, while the other unthinned pasture contained a pre-fire basal area of 135 ft²/acre. The crown fire essentially eliminated the forest stand in the unthinned pasture by reducing the basal area to less than 5 ft²/acre (Pearson and others 1972). In comparison, there was no significant reduction in tree density in the thinned pasture. While some of boles of some of the trees in the thinned pasture were scorched, their crowns were (apparently) not damaged to the extent that significant post-fire mortality occurred. Pearson and others (1972) thought that growth of most of the ponderosa pine trees surviving the wildfire but experiencing crown damage would likely be reduced.

The impacts of the Rattle Burn of May 1972 on the tree overstories in a ponderosa pine forest located 20 miles southwest of Flagstaff, Arizona, were evaluated on three watersheds that were severely burned, moderately burned, and unburned (Campbell and others 1977). (The basis for classifying the fire severity on the watersheds was not specified by these authors, but it was not the classification system of Hungerford [1996] that evolved later.) Nearly 2/3 of the ponderosa pine trees on the severely burned watershed were killed outright by the burn, while 1/4 of the trees on the moderately burned watershed were destroyed. Mortality of trees on these two burned watersheds was greatest in trees less than 12 inches in dbh. Campbell and others (1977) concluded that growth of the ponderosa pine trees surviving the burn would be reduced (to an unknown extent) because of their severe crown damage. However, the post-fire growth of these trees was not studied.

Post-Fire Mortality of Fire-Damaged Pine Trees

Not surprisingly, the post-fire mortality of ponderosa pine trees initially surviving the wildfire was greater on the Stermer Ridge Watershed burned by the high severity fire than on the watershed exposed to the low severity fire. Mortality of the fire-damaged trees was observed on both watersheds in the second year after the wildfire (fig. 5). It is possible, however, that some of the trees that had died by this time were “physiologically dead” before mortality became apparent. Standing trees initially killed by the fire also started to fall to the ground in 2004.

Figure 5. Post-fire mortality of ponderosa pine trees initially surviving the Rodeo-Chediski Wildfire on the Stermer Ridge Watershed burned by a high severity fire (top) and low severity fire (bottom) in terms trees/acre. Scales of the Y-axis are unique for each graph.



High severity fire

Almost 2/3 of the ponderosa pine trees on the watershed exposed to a high severity fire and apparently surviving the burn (44.5 trees/acre) were dead by 2004, 2 years after the wildfire (fig. 5). Continuing rates of additional mortality of about 5 percent annually were observed through 2006. The post-fire mortality of poles and sawtimber closely paralleled the mortality observed for all of the trees combined. However, these estimates of mortality were confounded by initiation of salvage cutting and fuel reduction treatments in late 2005 and continuing into 2006. Severely damaged trees 12 inches in dbh and larger with “merchantable value,” but not expected to survive, were harvested in the salvage cutting (fig. 6). Smaller trees were also cut to reduce post-fire loadings of flammable fuels.

About 65 percent of the basal area of ponderosa pine trees initially surviving the fire (35 ft²/acre) was lost by 2004. Post-fire loss of cubic-foot volume in the surviving trees (775 ft³/acre) was also 65 percent at this time. Post-fire losses of basal area in all ponderosa pine trees totaled 70 percent by 2006, while the total cubic-foot volume losses of all trees at this time ranged from 60 to 70 percent.

Gambel oak and alligator trees were too few in number to adequately analyze mortality and losses in basal area and volume on either of the Stermer Ridge Watersheds.



Figure 6. An unknown volume of trees was harvested in the salvage cutting on the watershed burned by a high severity fire. These trees were eventually chipped to provide fuel for the generation of electricity for nearby towns.

Low severity fire

Less than 3 percent of the ponderosa pine trees surviving the initial impacts of the wildfire on the watershed burned by a low severity fire (101.4 trees/acre) had died by 2004 (fig. 5). Minimal additional increases in annual mortality rates of 1 percent were then observed through 2006. Most of the post-fire mortality was concentrated in large sawtimber with severe crown damage. The post-fire mortality of trees on this watershed was similar to that reported by O'Brien (2002) for unburned Arizona ponderosa pine forests.

Losses of basal area and cubic-foot volume were also minimal. Only 5 percent of the nearly 75 ft² of basal area per acre in trees surviving the fire was lost to the burn by 2006, while about 10 percent of the 1,850 ft³/acre of volume had been lost by this time. These respective losses were concentrated in large sawtimber trees with severe crown damage.

Other studies on post-fire mortality of ponderosa pine trees

In their analysis of post-fire mortality of ponderosa pine trees in the western regions of the United States, Fowler and Sieg (2004) found that most of the studies they reviewed reported that observations of mortality were made one or more times in the initial 3 years following a fire. Mortality was observed over a longer period of time in only one of these studies. Lynch (1959) observed ponderosa pine tree mortality for 8 years following a wildfire on the Colville Indian Reservation in eastern Washington. He concluded that mortality in this

period was related largely to the percent of tree crowns burned or scorched. Trees with more than 50 percent crown injury suffered the most mortality. Lynch further stated that virtually all of the mortality occurred in the initial 2 years following the fire. A similar pattern of tree mortality occurred on the Stermer Ridge Watershed burned by a high severity fire.

Stocking of Tree Reproduction

On both of the Stermer Ridge Watersheds, stocking of ponderosa pine reproduction after the Rodeo-Chediski Wildfire was insufficient to sustain the ponderosa pine forests into the future at a level of stocking considered necessary by Pearson (1950), Schubert (1974), Schmidt (1988), and other silviculturalists. However, it is important to note that the southwestern United States was experiencing a prolonged drought throughout this study—a condition that likely impacted successful natural reproduction of ponderosa pine trees. This natural reproduction in the southwestern region is episodic in occurrence (Pearson 1950; Schubert 1974; Teclé and Hamre 1989) and must be considered in this assessment of post-fire stocking conditions.

Gambel oak basal sprouts were tallied on one of the mil-acre plots on the watershed burned by a high severity fire in 2004 and thereafter. There was no stocking of Gambel oak sprouts on the watershed exposed to a low severity fire. No post-fire stocking of alligator juniper reproduction was observed on the mil-acre plots of either of the watersheds.

High severity fire

Only two of the 30 mil-acre plots were stocked with pre-fire ponderosa pine reproduction immediately after the burn. However, at the same time, no plots were stocked with post-fire ponderosa pine seedlings, a finding that was unexpected because of the large number of newly germinated seedlings on the watersheds shortly after the wildfire. The numerous cones containing sound seeds that had fallen to the ground in late summer of 2002 (after the Rodeo-Chediski Wildfire) suggested that it might be a “good seed year” for the establishment of ponderosa pine reproduction. But, since none of the mil-acre plots were stocked with either pre- or post-fire seedlings in 2004 or 2006, the post-fire conditions on the watershed did not appear to be conducive to sustaining the survival of these seedlings. Impacts of rodent activity that might affect the stocking conditions were not observed.

Low severity fire

Over 1/2 of the 30 mil-acre plots were stocked with pre-fire ponderosa pine seedlings immediately following the cessation of the wildfire, some of which had been severely scorched by the fire. Many of these plantlets were suffering from the prevailing drought conditions and as a consequence, appeared unlikely to survive at the time. Therefore, it was not surprising that pre-fire ponderosa pine reproduction was tallied on only two of the plots in 2004 and none of the plots in 2006. No plots were stocked with post-fire ponderosa pine seedlings after the wildfire. We concluded that even though the post-fire needle fall was minimal, the fire might not have consumed enough of the litter and duff accumulations for a “favorable” seedbed (Pearson 1950, Schubert 1974) to be created for seeds to successfully germinate. It is likely that the drought also played a role in the lack of post-fire seedlings.

Other studies of post-fire stocking of tree reproduction

Campbell and others (1977) found no post-fire ponderosa pine reproduction following the Rattle Burn in the 3-year evaluation of the impacts of this burn. The effects of this burn on the stocking of tree reproduction were inconclusive, however, because there was no evidence of a large number of established seedlings on unburned sites within the vicinity of the burn.

A comparison of ponderosa pine reproduction on four sites near Flagstaff, Arizona, that had experienced devastating wildfires within 20 years of each other and an unburned site showed a general increase in seedling establishment relative to the unburned site for 20 years following the respective wildfires (Ffolliott and others 1988; Lowe and others 1978). Peak establishment of seedlings occurred within 2 years of the wildfires on all of the burned sites, with the post-fire rate of seedling establishment declining and then leveling off but remaining higher than that observed on the unburned site. To place this time-trend response of post-fire reproduction and initial survival into proper perspective, the 20-year study period coincided with a period of above average annual precipitation in the region.

Fire Severity Classification System Based on Crown-Damaged Trees

From observations of ponderosa pine post-fire mortality on the Stermer Ridge Watersheds, we developed a fire severity classification system based on the effects of the Rodeo-Chediski Wildfire on crown damage to ponderosa pine trees. (Too few Gambel oak and alligator juniper trees were tallied on the watersheds to include these two species the system.) Criteria in this classification system were similar to that in the fire severity classification systems of Dieterich (1979), Herman (1950, 1954), McHugh and Kolb (2003), and other systems reviewed by Fowler and Sieg (2004). Categories of the fire severity classification system developed in this study were:

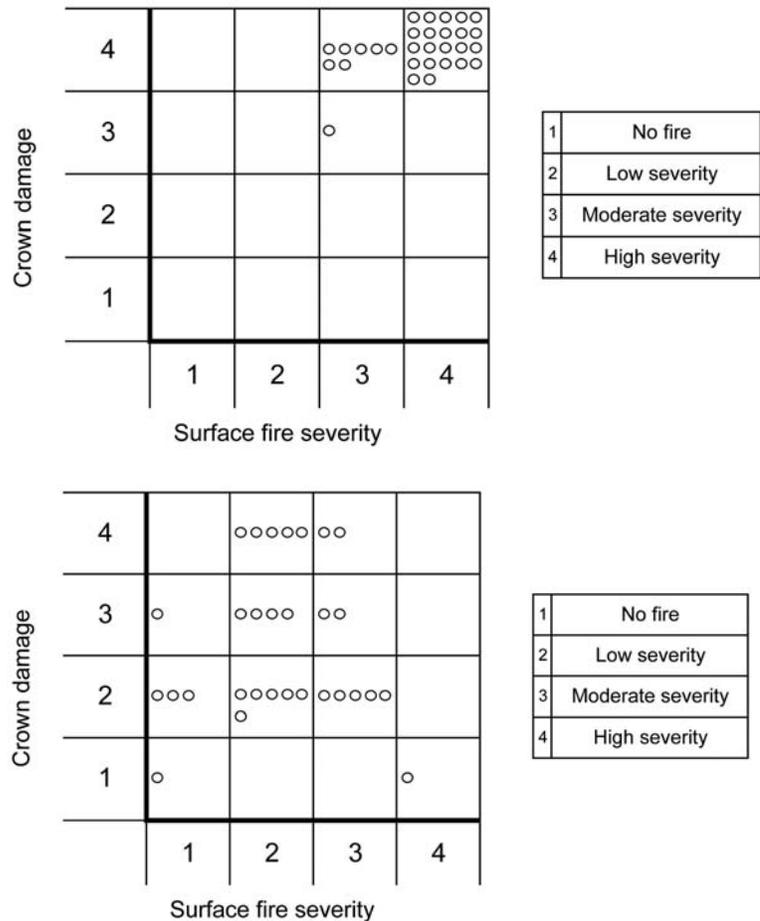
- No fire.
- Low severity fire—less than 15 percent of the trees exhibit crown damage; more than 75 percent of these damaged trees are expected to survive.
- Moderate severity fire—between 15 and 50 percent of the trees exhibit crown damage; 25 to 75 percent of these damaged trees are expected to survive.
- High severity fire—more than 50 percent of the trees exhibit crown damage; less than 25 percent of these damaged trees are expected to survive.

This system evolved from the observations of post-fire mortality of ponderosa pine trees found only on the two Stermer Ridge Watersheds studied. Applications of the classification system elsewhere, therefore, must be considered within this context.

Fire Behavior on the Stermer Ridge Watersheds

Fire behavior on the Stermer Ridge Watersheds was retrospectively estimated through interpretations of Hungerford's fire severity classification system (Hungerford 1996) and the classification system relating fire severity to the damage to tree crowns. These fire behavior patterns are shown in figure 7.

Figure 7. Severities of surface fire and crown damaged trees on the Stermer Ridge Watershed burned by a high severity surface fire (top) and low severity surface fire (bottom). Each circle in this figure represents about 2 acres on the respective watersheds.



High severity fire

Nearly 75 percent of the watershed burned by a high severity fire, according to Hungerford’s classification system, also experienced a high severity of crown damage to the trees on the area (fig. 7). While about 20 percent of this watershed burned by a surface fire of moderate severity, the trees in this area of the watershed suffered high crown damage. However, the trees on a small area also burned by a moderate severity surface fire experienced only moderate crown damage. No part of the watershed was burned by a low severity fire or escaped the burning event entirely. We suggest, therefore, that much of this watershed burned with a high severity surface fire and most of the trees on the area suffered high severity crown damage. The impacts of the Rodeo-Chediski Wildfire on the stand structure and post-fire tree mortality are indicative of this fire behavior.

Low severity fire

Varying combinations of surface fire and crown damaged trees with intermingling unburned areas depict the mosaic pattern of fire behavior on the watershed defined by Hungerford’s classification system as a low severity fire (fig. 7). Two-thirds of the watershed either escaped the wildfire or burned with a low severity surface fire. Some of the trees on this area escaped crown damage, while other trees suffered crown damage of varying severities. Thirty percent of the watershed was exposed to a moderate severity surface fire, while only a small portion experienced a high severity surface fire. The crown damage

to trees on these latter (combined) areas was variable. The lesser impacts of the Rodeo-Chediski Wildfire on stand structure and post-fire tree mortality are mirrored by this fire behavior pattern.

Conclusions

The Rodeo-Chediski Wildfire impacted the stand structures, post-fire mortality of trees, and stocking of tree reproduction on the Stermer Ridge Watersheds. These impacts were more severe on the watershed burned by a high severity fire than on the watershed experiencing a low severity fire. The results obtained from other studies on the impacts of fire in the ponderosa pine forests of Arizona and, more generally, western montane forests, were reviewed for comparison purposes.

The criteria of the classification system developed in this study that we used to relate crown-damaged trees to post-fire mortality were similar to those of many other classification systems developed to predict the post-fire mortality of ponderosa pine trees. Estimates of the fire behavior on the two Stermer Ridge Watersheds were obtained retrospectively through interpretations of Hungerford's (1996) fire severity classification system that showed the relative severities of a surface fire and the system developed in this study (see previous) relating fire severity to crown damaged trees. A more "comprehensive picture" of the impacts of the Rodeo-Chediski Wildfire was obtained with this combined approach of describing fire behavior patterns.

Management Implications

Large wildfires, such as the Rodeo-Chediski Wildfire, are likely to occur in southwestern ponderosa pine forests into the future because of the large accumulations of flammable fuels, prolonged periods of drought similar to that encountered at the time of this historic wildfire, and increasing access of people into these forests. Managers will need to anticipate the impacts of these large wildfires on the ecological resources and plan rehabilitative measures when possible. Findings of this study on the impacts of the Rodeo-Chediski Wildfire on tree overstories and reproduction of trees should help managers to anticipate the effects of future large-scale wildfires on this forest resource.

As expected and shown in other studies on the effects of fire in southwestern ponderosa pine forests, a significantly larger number of trees were killed outright by the Rodeo-Chediski Wildfire on a watershed experiencing a high severity fire than on a watershed exposed to a low severity fire. There was higher mortality in the pole class of trees less than 12 inches dbh than in the larger sawtimber classes. Post-fire mortality of fire-damaged trees apparently surviving the initial impacts of the burn was also greater on the watershed burned by a high severity fire. (Salving cutting and fuel reduction treatments imposed on this watershed removed the remaining trees.) The limited mortality of trees on the watershed experiencing a low severity fire was similar to that typically encountered in unburned ponderosa pine forests.

As a result of the Rodeo-Chediski Wildfire, conversion of the pre-fire ponderosa pine forest on the watershed experiencing a high severity fire to a landscape of herbaceous plants precludes the re-establishment of a forest in the foreseeable future in the absence of artificial reforestation by planting

of seedlings. Five years after the Rodeo-Chediski Wildfire, stocking of tree reproduction on the watershed burned by a low severity fire was insufficient to sustain the ponderosa pine forest at a stocking level considered necessary by local silviculturalists.

More comprehensive descriptions of fire behavior patterns can be obtained through interpretations of (1) the severities of a surface fire to the soil resources based on the classification system of Hungerford (1996) and (2) the severities of crown damaged trees using the criteria of the classification system developed in this study. It is sometimes unknown if the damage to tree crowns resulted from crown scorching caused by the heat of a surface fire or a crown fire advancing from one tree to another tree independent of a surface fire; however, impacts of a wildfire on stand structure, tree mortality, and reproduction of trees are closely related to descriptions of fire behavior patterns obtained through these combined interpretations of fire severities.

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