# ASSESSMENT OF TIMBER RESOURCES AND LOGGING HISTORY OF THE VALLES CALDERA NATIONAL PRESERVE [1] [2]

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## SUMMARY

The purpose of this research is to describe the history of timber harvest in the 89,000 acre Valles Caldera National Preserve in the Jemez Mountains of northern New Mexico. Logging was arguably the most extensive and ecologically significant twentieth century human modification to forests now enclosed by the Preserve. This research synthesizes various forms of harvest records, timber cruise data, airphotos, maps, and other forestry data to create a cohesive and spatially explicit narrative of logging history. There were three distinct eras of harvest between 1935 and 2000. From 1935 to 1962 easily accessible, lower elevation ponderosa pine and mixed conifer stands were heavily harvested. Clear-cutting took place at most elevations and affected nearly all stand types from 1963 to 1972. After a brief moratorium, harvesting resumed in 1980 and continued until the 2000 creation of the Preserve. We created GIS coverages of each harvesting era (including 1980-1991 and 1992-2000 coverages for the most recent era). Comparison of timber data from 1978 and 1998 demonstrates a broad trend of increase in volume and volume per area of all major species in all areas of the Preserve, though relative rates of increase vary spatially and by species. We created a coarse map of potential old-growth areas that generally agrees with other data on unharvested stands. A stand-level inventory of the Preserve is necessary to evaluate current forest characteristics on a scale comparable to the scale of (1) the effects of logging and logging roads on vegetation and other ecosystem components and (2) future forest treatments. Future timber harvests in the form of small diameter thinning holds promise as an appropriate treatment for reducing fuel load and improving ecological and aesthetic value.

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# INTRODUCTION

While plant ecologists have long recognized the importance of abiotic factors—climate, topography, substrate—in structuring vegetation patterns, it is clear that past land uses and disturbance history are also important determinants of species composition, biodiversity and community pattern, even in landscapes that outwardly appear "natural." For much of the first half of the twentieth century, the results of both natural and anthropogenic disturbances were seen as little more than ephemeral departures from relatively stable climax communities (Clements 1915). Persistent or irreversible changes in plant community structure or composition following disturbances were largely regarded as rare incidents that only occurred following exceptional events or particularly extreme disturbances (e.g., severe erosion following forest removal and poor agricultural practices). Even in some contemporary ecological studies examining landscape-level mosaics of ecosystem patterns, transitions among land use and land cover types are treated as predictable processes governed largely by the rates of disturbance and recovery.

Recent research, however, has helped to reveal the persistence of disturbance legacies and demonstrated that while contemporary patterns of species and ecosystems are clearly structured by abiotic conditions, they may also bear the marks of past land use and disturbances. For example, while natural reforestation of agricultural lands in New England over the past 150 years has created a predominantly forested landscape (Foster 2002), compositional differences between the vegetation of primary and post-agricultural secondary forests indicate that the distribution patterns for many plant species still reflect the open, agricultural environment of the nineteenth century (Bellemare et al. 2002).

At a time when the needs of renewable resource utilization (e.g., timber harvesting) must be balanced against the various other functions that forested habitats provide, it is important not only to have reliable information on the potential economic value of forests but also to understand how historical factors have shaped current forest conditions and how future management actions may influence forest structure, composition and function. In the Southwest, forests have experienced considerable changes during the last century as a result of land use policies that encouraged economically profitable resource extraction without also encouraging ecologically-minded long-term sustainability. This historical context of change is relevant to the current and future management of valued resources. The initiation of large-scale commercial logging in the Southwest accompanying EuroAmerican settlement is one example of a significant land use change that has had substantial ramifications for forest management.

**Impacts of Tree Harvesting and Associated Roads**

Logging can have significant, long-term ecological consequences (Barnes et al. 1998), but specific effects of tree harvest and associated activities such as road construction vary widely as a function of the techniques used to harvest (e.g., clear cutting, selection logging) and regenerate (e.g., seeding, seed tree retention) an area. Large-scale timber harvest is a disturbance affecting forest pattern and process from the scale of an individual tree to that of an entire ecosystem. Logging eliminates old growth and reduces habitat for certain species. Harvesting only large diameter merchantable timber—"high grading"— or targeting particular timber species affects stand composition, modifies interspecies resource competition, and alters the availability of seed sources for new establishment. These changes in pattern in turn affect the elements and mechanisms of ecological functioning, including vegetation, wildlife, soil, surface and groundwater, and microclimate. Removal of significant quantities of biomass from a forest affects nutrient and water cycling. Logging may also alter the landscape's natural heterogeneity and reduce the structural complexity of stands, including the variety of stand structural attributes that are present in natural forests in an area (e.g., the stand age and size class structure, presence of standing snags and downed woody debris, variation in canopy gap structure, vertical heterogeneity associated with different canopy layers) and how these features are arranged across a landscape (i.e., spatial heterogeneity).

In addition to the direct effects of logging, the construction of logging roads has important consequences for landscape configuration. Roads are known to have a wide range of associated effects on biodiversity and ecological processes (Baker and Knight 2000), including roadside vegetation and animals as well as water, sediment and chemical fluxes (Forman and Alexander 1998, Forman 2003). Trombulak and Frissel (2000) identified seven general ways that roads affect terrestrial and aquatic ecosystems: (1) mortality from road construction, (2) mortality from collision with vehicles, (3) modification of animal behavior, (4) disruption of the physical environment, (5) alteration of the chemical environment, (6) facilitation of the spread of exotic species, and (7) changes in human use of land and water. A comprehensive examination of logging effects must thus acknowledge the effects of road construction.

**Purpose and Objectives of this Study**

The primary purpose of this study is to investigate and document logging history in Valles Caldera National Preserve (VCNP), which is located in northern New Mexico's Jemez Mountains. The VCNP, previously known as the Baca Location #1 land grant (Baca), is an area of considerable natural, scenic, historic, and cultural value that has a legacy of human use and modification. Logging practices in this landscape may in fact have caused the most extensive and most ecologically significant vegetation changes of the twentieth century, and the cumulative effects of logging, grazing, and fire suppression have created challenges for current management of the area.

The VCNP's organic act (Valles Caldera Preservation Act, Public Law 206-248, 2000) mandates the protection and preservation of the biological, cultural, economic, and aesthetic integrity of the landscape. To protect and preserve resources for the future, understanding past land uses and their impacts is essential. Many questions about the effect of logging on the flora, fauna, hydrology, soils, and ecosystem functioning remain as yet unanswered in the VCNP. A prerequisite to focused research on logging effects is a spatially-explicit reconstruction and analysis of the timber harvesting that has occurred on the preserve. Currently, there is no comprehensive ecologically-oriented synthesis of the numerous and disparate sources of information about the VCNP's logging history. This research fills this information gap. The following questions direct this investigation:

1. What is the logging history of the VCNP?
    a. Where and when did logging occur?
    b. What type of logging occurred?
2. How has logging changed the structure of forests?
    a. What is the current status of merchantable timber?
    b. How have timber volume and species composition changed over time?
3. How might future harvests affect the forests?
    a. What specific recommendations can be made about future forest inventory and mapping that would assist forest management?
    b. What general recommendations can be derived for future timber management from knowledge of past harvests?

We address these questions by qualitatively and quantitatively synthesizing multiple historical and field data sources into a spatially-explicit reconstruction of logging events. This history will be valuable to two audiences. First, it will inform VCNP management decisions by providing a historical and spatial perspective on logging occurrence. Second, it will contribute to future research aimed at understanding the effects of human impacts on the environmental, economic, and social components of the VCNP landscape by describing available data sets and summarizing their uses and limitations.

# STUDY AREA

## Administrative History and Status

The Valles Caldera National Preserve, located near the town of Los Alamos in northern New Mexico, is a national experiment in natural resource management. Previously known as the Baca Location #1 or Baca Ranch (and informally referred to as the Valle Grande, after its most prominent feature), the tract has remained largely intact as a single parcel since its granting by the New Mexico Territory to Luis Maria Cabeza de Vaca in 1860 (Martin 2003). The original parcel was 40,181 ha (99,289 ac); the current parcel is approximately 36,000 ha (88,950 ac), or just under 90% of the original land area (Martin 2003). It is located within a diverse administrative setting that includes not only private lands but also areas managed by the U.S. Forest Service, National Park Service, Department of Energy, State of New Mexico, and local tribal governments (Fig. 1).

## Physical Setting

The central landform of the Jemez Mountains is the Valles Caldera, a collapsed magma chamber that spans approximately 25 km (15.5 mi) and encloses multiple resurgent lava domes that formed after the chamber's collapse *ca.* 1.2 million years ago (Goff et al. 1996) (Fig. 2). The physical landscape of the dormant caldera is characterized by forested domes and uplands (about three quarters of the land area) separated by grassland *valles* ('valle' is a Spanish term meaning a treeless depression, similar to the English term 'valley'). Elevation varies from 2440 m (7930 ft) at the outflow of the Jemez River's East Fork to 3430 m (11,254 ft) on Redondo Peak, the highest dome in the caldera. Uplands are underlain by volcanic flows and tuff while valles contain alluvial deposits (Smith et al. 1970). Forest soils are andisols, alfisols, and inceptisols while grassland soils are mollisols (Muldavin and Tonne 2003). The caldera interior is a single watershed unit draining out a breach in the caldera wall to the Jemez River's San Diego Canyon, southwest of the VCNP.

## Climate

The nearest climate station to the VCNP with a reasonably long period of record is in the town of Los Alamos, 20 km east of and 300 m below the lowest point in the caldera, although climate observations are currently being collected within the caldera. The regional climate is characterized by a summer monsoonal precipitation pattern, with July and August convective monsoon rains contributing nearly 40% of the annual Los Alamos precipitation average of 475 mm (data from the National Climatic Data Center; Fig. 3). Because of its higher elevation, annual precipitation is greater in the caldera than at the Los Alamos climate station (as evidenced by vegetation types) and snowfall is much greater, especially on the domes and caldera rim (Allen 1989). Mean Los Alamos

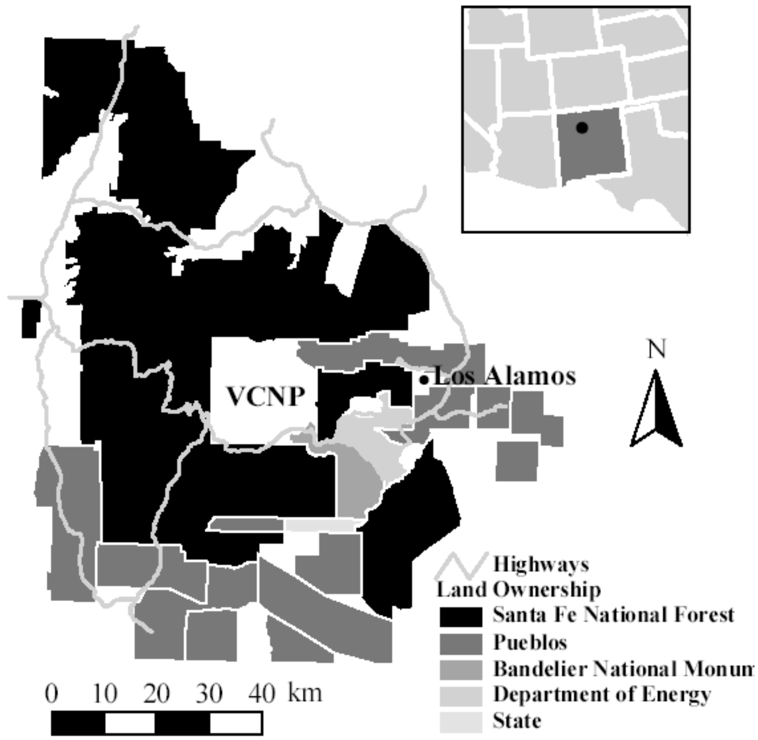


**Figure 1. Location of the Valles Caldera National Preserve and major landowners in the Jemez Mountains ecosystem.**

temperatures range from -2°C to 20°C, although the actual temperatures in the caldera are appreciably lower (Muldavin and Tonne 2003) and decrease with increasing elevation and proximity to cold air drainages (J.D. Coop, unpub. data).

## Vegetation

The Jemez Mountains are located at the southern margin of the Southern Rocky Mountains ecoregion (Neeley et al. 2001). Elevation and slope aspect are the primary gradients across which local forest vegetation varies (Koski et al., in prep.) (Fig. 4), as is generally the case throughout the Southwest (Dick-Peddie 1993, Brown 1994). Ponderosa pine (*Pinus ponderosa*) is the major forest species in stands below 2740 m (9000 ft) that ring the valles, except on some north-facing slopes where blue spruce (*Picea pungens*) has recently gained importance (Hogan and Allen 1999, Muldavin and Tonne 2003). Below 3050m (10,000 ft), mixed conifer forests containing combinations of ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), quaking aspen (*Populus tremuloides*) and limber pine (*Pinus flexilis*) are predominant. Spruce-fir

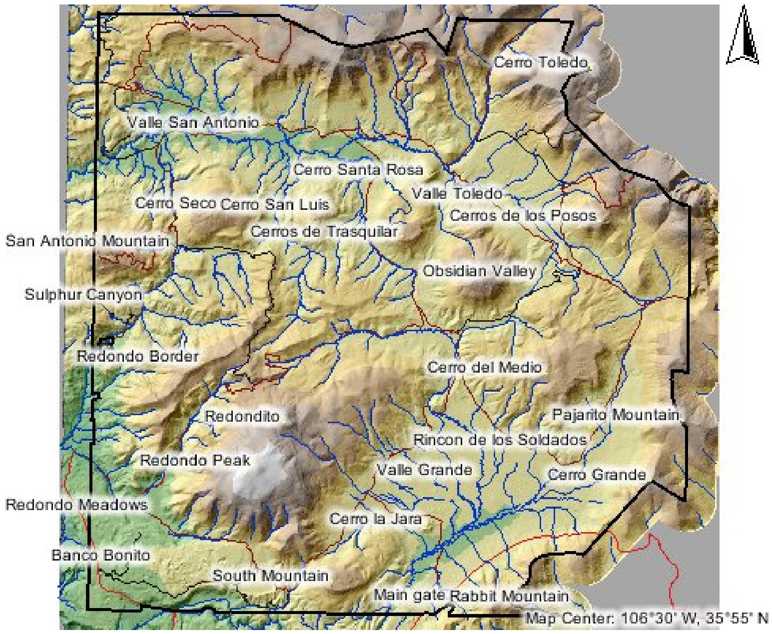


**Figure 2. Primary topographic features within Valles Caldera National Preserve. The east-west and north-south extents of the preserve are both ca. 20km. Map generated using the interactive mapping framework at www.vallescaldera.gov.**

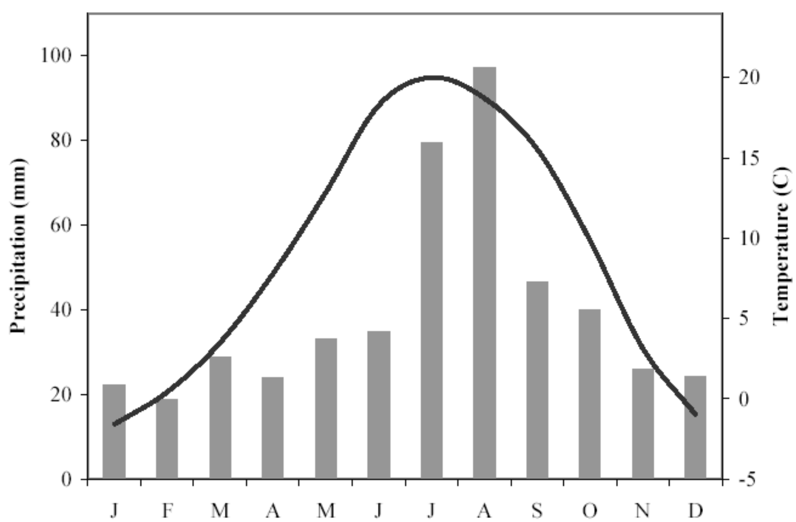


**Figure 3. Total monthly precipitation (bars) and average monthly temperature (line) for Los Alamos, New Mexico (station 295084), 1951-2000 (data from the National Climatic Data Center).**

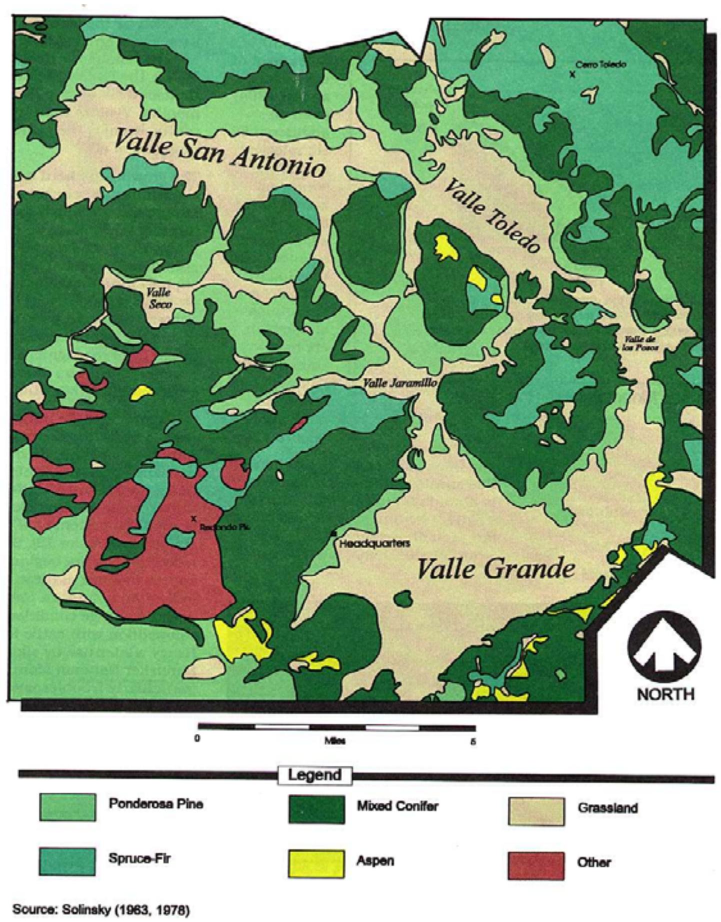


**Figure 4. Generalized map of vegetation communities within Valles Caldera National Preserve (from USFS 1993).**

forests dominated by Engelmann spruce (*Picea engelmannii*) and corkbark fir (*A. lasiocarpa* var. *arizonica*) occupy the highest elevations and north-facing slopes on the domes above 2740 m (9000 ft). Aspen stands occur throughout the preserve, especially in disturbed (logged or burned) areas (Muldavin and Tonne 2003). Soil characteristics, cold air drainage, hydrology, fire and grazing contribute to the maintenance of the grasslands that span the valles in the enclosed caldera (Allen 1989), although there is evidence of woody species encroachment (especially by *Pinus ponderosa* and *P. pungens*) into these low elevation grasslands. High elevation grasslands that were historically maintained at least in part by fire also occur on upper, south-facing slopes in the mixed conifer and spruce-fir zones (Allen 1989). Specific forest associations and their characteristic flora are described by Muldavin and Tonne (2003).

## Ecological Disturbances

Ecological disturbances are natural or anthropogenic events that disrupt vegetation structure and change the nature or availability of limited vital resources—light, nutrients and water (White and Pickett 1985). Disturbances are relatively discrete events, but, over time, they act as processes with a regime of describable characteristics such as spatial extent, spatial distribution, frequency, and magnitude (Turner et al. 2001). The “strength” of a disturbance can be judged in terms of the event itself (intensity of a particular event) or in its ecological consequences (severity of disturbance effects) (Sousa 1984). Disturbances often exhibit spatial variability with respect to intensity, even within an individual disturbance event (e.g., Farris et al., in press), and spatial patterns of response or recovery after a disturbance are often closely related to the spatial distribution of event intensity.

Logging, wildfire (both lightning- and human-caused), herbivory by wild and domesticated animals, and forest pest outbreaks are the principal disturbances influencing vegetation pattern and process in VCNP. Human activities over the last one hundred fifty years have significantly modified prehistoric disturbance regime characteristics and introduced novel disturbances. Fire and native ungulate herbivory are indigenous disturbances while timber harvesting and domesticated animal grazing are novel at the landscape scale. The relevance of other forest disturbances to research on logging is that the legacies of one disturbance may interact with the characteristics of a subsequent disturbance (Madany and West 1983, Keane et al. 2002). Thus, it is important to view logging—its practice and its effects—as a disturbance in its wider ecological context.

### *Natural Disturbance Regimes in the VCNP*

Fire is a keystone natural disturbance process whose regimes have been altered by fire exclusion policies throughout the Southwest (Covington and Moore 1994). Fire has been a regular phenomenon in the Jemez Mountains for at least the last 8000 years (Brunner Jass 1999) and prior to Euro-American settlement, fire was the dominant large scale disturbance on the forested landscape (Allen 1989). Frequent, low severity surface fires at lower elevation once maintained old, open-structure pine stands. Fire at higher elevations may have been less frequent but still maintained patchy grasslands on the caldera rim (Allen 1989) and aspen stands where fire burned with higher intensity (Margolis et al. 2001). Swetnam and Baisan (1996) report mean fire intervals for ponderosa pine and mixed conifer fire history sites (ranging from 10 to 100 ha in size) in the Jemez Mountains ranging between 4.5 and 25.2 years. Some of these sites are also reported by Touchan et al (1996) as having mean fire intervals between 5.0 and 18.9 years.

Although Puebloan peoples have populated northern New Mexico for many centuries, their influence on fire occurrence and severity in the Jemez Mountains is perceived to have been localized and minimal (Allen 2002). On the other hand, Euro-American settlement of the Jemez, beginning in earnest in the late nineteenth century, profoundly altered the regimes of fire and other processes in substantive ways that Puebloan land uses had not. The fire regime changes discussed below are the result of Euro-American influence while Puebloan influences are considered part of the pre-Euro-American regime.

Numerous forest pests inhabit the forests of the Jemez Mountains. Recent surveys have detected damage by western spruce budworm (affecting Douglas-fir, true firs, and spruce), spruce beetle (spruce), western roundheaded pine beetle (ponderosa pine), and aspen defoliators (aspen) (USFS 2002). Tree ring records indicate recurrent outbreaks of spruce budworm (Swetnam and Lynch 1993) and tent caterpillar (Margolis et al. 2001). Logging and insect populations can have synergistic effects on one another; for example, untreated logging slash can initiate insect outbreaks or increase their severity.

Other minor disturbances affect VCNP forests but are not expressly discussed here. Documented examples include mistletoe infestations and windthrow (NMSF records). Because of its increased occurrence in association with logging, windthrow is worthy of management consideration and is discussed later in this paper. Some discrete climate fluctuations may also be considered as disturbances. Interdecadal climate oscillation can have significant direct ecological effects (Allen and Breshears 1998, Swetnam and Betancourt 1998) as well as synergistic effects on other disturbances and deserve management consideration but are not discussed here.

*Anthropogenic Disturbance Alterations*

The combination of the introduction of grazing animals and the active suppression of fire prompted long-term changes in the vegetation mosaic of VCNP. Domesticated animal grazing accompanied Euro-American expansion into the frontier West in the eighteenth and nineteenth centuries. The removal of fuel connectivity through grazing is widely seen as an initial cause of wildfire cessation in fire-adapted ecosystems in the Southwest (Madany and West 1983, Savage and Swetnam 1990, Touchan et al. 1995).

Historical grazing records (Scurlock 1981) indicate that intense sheep grazing began in the late 1800s in the grasslands and forests of the Jemez. This coincides with a sudden cessation of fire scars on trees in the caldera around 1879 (Morino et al. 1998) and by 1893 throughout the Jemez (Touchan et al. 1996). The fire exclusion policy that characterized twentieth century land management perpetuated the grazing-induced fire interruption and accentuated the deviation of forest structure, composition and function from their historic range of variability in the Southwest (Covington and Moore 1994, Brown et al. 2000).

During the first decades of the 20th century, the replacement of sheep grazing by less intensive cattle grazing (Scurlock 1981) permitted some tree establishment but still prevented fire spread by limiting herbaceous fuel production. Livestock grazing continues to the present day under the multiple-use mandate of the Valles Caldera Preservation Act (106th Congress 2000). Recent increases in the elk population have severely curbed tree establishment, especially of aspen (Allen 1998, Krantz 2001). This constant pressure of elk herbivory continues to affect both fire spread and post-logging aspen regeneration and is of specific management concern (Valles Caldera Trust 2003).

**Logging History**

Researchers have acknowledged logging as an important ecological disturbance in VCNP (Allen 1989, Martin 2003, Muldavin and Tonne 2003) (Fig. 5), but much is still to be learned about logging's effects on the pattern and process of this landscape. Three distinct eras of harvest, described in detail by Martin (2003), define the logging history of the Baca, each characterized by methods and approaches that reflect the technological, political, and economic context of the period. Harvest method, spatial extent, and species composition of harvest are important determinants of the ecological consequences of logging operations, and each of these determinants is uniquely identified in each logging event. A description of the historical sequence of logging episodes in the caldera helps to elucidate some broad patterns of logging as an anthropogenic disturbance regime—its timing, spatial occurrence, and fluctuating intensity—and aid in the interpretation of logging effects.

**Pre-1935**. Small timber firms began commercial logging operations in the Jemez Mountains in the late 1800s (Martin 2003). Limited by access, these operations easily reached ponderosa pine stands around the village of Ponderosa, in the Cañon de San Diego Grant, south of the Baca (Glover 1990). Harvesting within the Baca, if there was any, was relatively insignificant.

**1935-1962**. The Civilian Conservation Corps built a road through Ponderosa and across the Valle Grande in 1935 that provided access to the caldera for subsequent truck-based logging operations (Glover 1990, Martin 2003). Glover (1990) estimates the pre-1935 timber potential at 400-500 million board-feet and Martin (2003) reports that in a deed dated July, 1935, 42 thousand board-feet[3] had already been harvested.

[3] Martin (2003, p. 86) presumably misinterprets "mbf," common notation for "thousand board-feet," as "million board-feet." Forty-two million board-feet would have been one tenth of the Baca's timber, not a feasible single season harvest. Martin also miscites chapter reference #6 (Glover 1990) instead of #5 (1935 deed from Redondo Development to Robert Anderson, Jr.).

**Figure 5. Logged areas within: (top) a high elevation spruce-fir forest on a west facing slope of Redondito, and (bottom) a low elevation ponderosa pine stand along the margins of Valle Grande.**

The New Mexico Timber and Lumber Company (hereafter NMT, later named the New Mexico Timber Company) bought the timber rights to the Baca from the Redondo Development Company in 1935, commenced logging, and oversaw logging operations from then until 1972. From 1935 to 1962, the ponderosa pine stands of the Baca were "high-graded", with the best ponderosa pine sawlogs greater than twelve inches in diameter being harvested from the lower elevations, save for a few seed trees per acre (Martin 2003). Approximately 10,380 ha (25,641 ac; 38% of forested area) were harvested using light to heavy selection cutting in the southwest corner on the Banco Bonito lava flow, the northern and eastern rims (Garita and north of Valle Toledo), and around the base of Cerro del Medio, Cerros del Abrigo, and Cerros de Trasquilar (USFS 1993). Before chainsaw technology became pervasive, crosscut saws were used to fall timber. Logs were skidded by horses to decks where trucks waited to haul the logs to the mill. Toward the end of the era, middle elevation mixed conifer stands were harvested as roads and technology improved.

**1963-1972**. Improved technology and roads enabled clear-cutting of all species and sizes on approximately 4700 ha (10,589 ac; 16% of forested area) of the Baca from 1963 to 1972 (USFS 1993, Martin 2003). During this era, NMT employed jammer logging, a cable logging system where a mechanical cable winch hauled logs directly from the stump to roadside collection points. At the Baca, the trees were then were taken to the mill by truck and large slash piles were left in place of trees (USFS 1993, Martin 2003). Regulatory changes and a new pulpwood mill in Arizona further aided intensive harvesting during this period. Legal action halted NMT and its intensive logging methods in 1972 (Martin 2003).

Jammer logging was supported by a dense network of thousands of kilometers of new, contour-paralleling roads, sometimes less than 300 ft (90 m) apart, spiraling up the forested domes of the Baca (Fig. 6) (Allen 1989). The roads permitted logging of steep and high elevation slopes and contributed to fragmentation of the remaining forest areas. Lack of conservation practices caused severe soil and water quality damage as well as aesthetic depreciation of the landscape. These unsustainable practices still affect the biological, economic, and aesthetic qualities of today's forests (Fig. 7).

**1980-2000.** From 1980 until the sale of the Baca to the US government in 2000, logging proceeded at a more conservative pace under the guidance of the New Mexico State Forestry Office. Approximately 1100 ha (2,739 ac, 4% of forested area) were harvested between 1980 and 1992 (USFS 1993). Most harvests employed selection cutting and were guided by conservation-minded guidelines established by the State (New Mexico State Forestry 1990). Selection cutting harvests a portion of mature trees, usually the largest and highest quality individuals of the most valuable species. The proportion of trees harvested varied widely. Some patch cutting took place (a patch is a small clearcut). Logging was carried out in many areas of the Baca

**Figure 6. VCNP road network (based on Allen 1989). Most major roads (thicker lines) were built during the first logging era (1935-1962) to facilitate harvest of easily accessible stands near valles. Most minor roads (thinner lines) were built during the second logging period (1963-1972) to facilitate clearcutting.**

**Figure 7. Logging roads are still visible throughout the VCNP.**

including the Cerros del Abrigo, Cerro del Medio (much of which had been previously harvested), and the Sierra de los Valles on the eastern caldera rim (USFS 1993).

**Summary**

The Valles Caldera is a heterogeneous mosaic of vegetation types that reflects the influences of abiotic factors, namely climate, topography, and substrate, and ecological processes of disturbance, primarily fire, grazing, and logging. The patterns created by these conditions and events will shape these forests for centuries to come, and conversely, the forests will shape the regimes of natural and anthropogenic disturbance. The human impact on the VCNP landscape is indelible and logging practices are arguably the most extensive, most severe, and most ecologically significant disturbance of the twentieth century. A spatial perspective on the history and effects of logging is imperative if the multiple ecological, economic, and aesthetic values of the VCNP are to be effectively managed.

The act of Congress that converted the privately held Baca into public land (Valles Caldera Preservation Act, Public Law 206-248, 2000) charges the managing body, the Valles Caldera Trust, with a complex responsibility: “to protect and preserve the scientific, scenic, geologic, watershed, fish, wildlife, historic, cultural, and recreational values of the preserve, and to provide for multiple use and sustained yield of renewable resources within the preserve” (Valles Caldera Preservation Act, sec. 104[b], 2000). Four forest management goals drive the Trust’s decisions according to the Comprehensive Management Framework set forth by the Trust (Valles Caldera Trust 2003):

- Reduce forest vulnerability to stand-replacing fire (particularly pine and some mixed conifer stands).
- Restore natural fire regimes.
- Restore aspen regeneration.
- Protect and restore old-growth stands.

VCNP forests are also likely to remain a source of wood products in the future, as they have been in the past. These forests are a resource of significant economic, social, and natural value. The landscape legacies of past logging as well as the potential for future logging in the VCNP are relevant to these management goals.

# METHODS

## Data

For this report, we integrated an array of spatial and non-spatial information to provide a more complete understanding of logging in the VCNP. Data sets used in this analysis span the period of interest, 1935-2000 (Fig. 8), but they differ in content as well as spatial and temporal extent, resolution, and consistency, which has consequences for harvest documentation precision. Each also has sources of error and analytical shortcomings that will be clarified throughout the report. Many of these datasets have not been previously analyzed with current management objectives in mind so this section serves as an introduction to their scope of inference and potential uses.

### *Historical Aerial Photography*

As of July 2004, the Valles Caldera Trust possessed nine sets of unrectified aerial photograph prints (air photos) covering at least part of the preserve (Fig. 9; Table 1). The earliest set was flown in 1935 before large scale commercial logging began, and subsequent sets often coincided with the onset of distinct logging episodes. Two additional sets of recent digital orthophoto quadrangles (DOQs) are available.

### *New Mexico State Forestry records*

In 1970, the State Forestry Division of the New Mexico Energy, Minerals, and Natural Resources Department was charged with supervising timber harvests on non-municipal, non-federal and non-tribal lands in the state. From 1970 until 2000, when the Baca passed into federal jurisdiction, the New Mexico State Forestry Division retained records on timber operations on the Baca (Fig. 10). These records (NMSF records) are now held by the Valles Caldera Trust and contain information on each timber sale in compliance with minimum standards set forth in the Commercial Timber Harvesting Guidelines in the New Mexico Forest Practices Guidelines (current revision is New Mexico State Forestry 2002). There are records for thirteen separate timber sales between 1980 and 2000. No State Forestry records exist for 1970-1980 (legal interruption of logging activity lasted from 1972 until 1980).

Each individual timber sale record should include a harvest method and regeneration plan, periodic commercial harvest field inspection forms accompanied by topographic quadrangles with hand-drawn boundaries of active harvest areas, and letters regarding various stages and permissions of the sale. In actuality, most of these sale records do not contain all of these elements. Maps are incomplete and most show the boundaries of cutblocks (entire areas for which harvest is permitted) rather than the actual harvested areas, which may be significantly smaller, especially since much post-1980 logging was selective and more patchy in nature than earlier harvests.

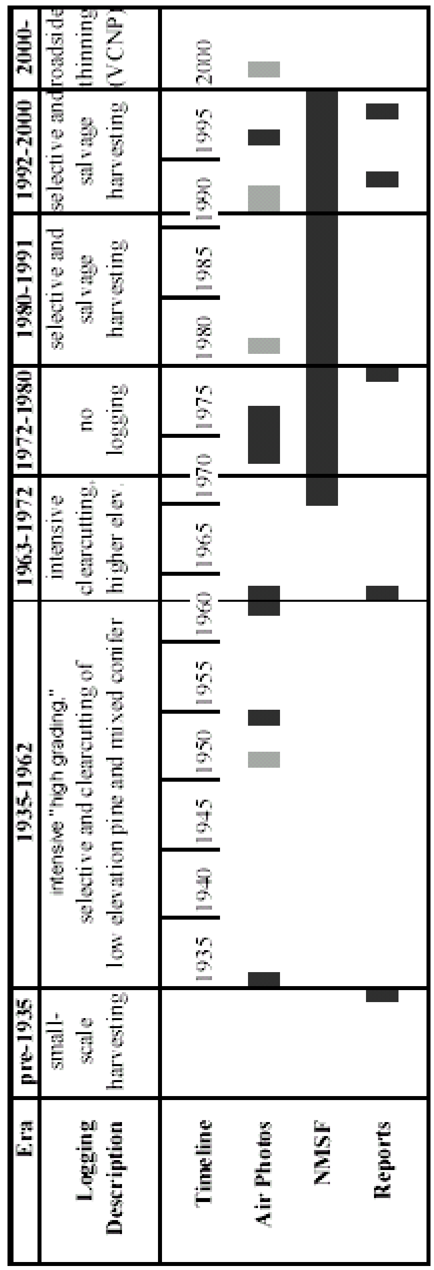


**Figure 8. Data sets relevant to the logging history of the VCNP. Each data set is displayed during its year(s) of observation. Dark shaded data sets were used in this research.**

**Table 1. Airphoto sets covering the VCNP. Five print sets and one digital set of airphotos were scanned (300 dpi) and used in this analysis. The methods of interpretation do not require orthorectification. Only every other photograph was scanned in sets which overlap in coverage by 60%.**

| YEAR | TYPE | SCALE | USED | COVERAGE |
|---|---|---|---|---|
| 1935 | grayscale | 1:31,680 | yes | full |
| 1951 | grayscale | 1:15,840 | | partial |
| 1954 | grayscale | 1:54,000 | yes | full |
| 1962-3 | grayscale | 1:15,480 | yes | full |
| 1973-6 | grayscale | 1:15,480 | yes | full |
| c. 1975 | grayscale, color | 1:15,480 | yes | partial |
| 1981 | grayscale | 1:24,000 | | full |
| c. 1991 | color infrared | 1:40,000 | | full |
| 1992 | color | 1:15,480 | | partial |
| DOQ 1996 | grayscale | 1:12,000 | yes | full |
| DOQ 2001 | color | 1:12,000 | | full |

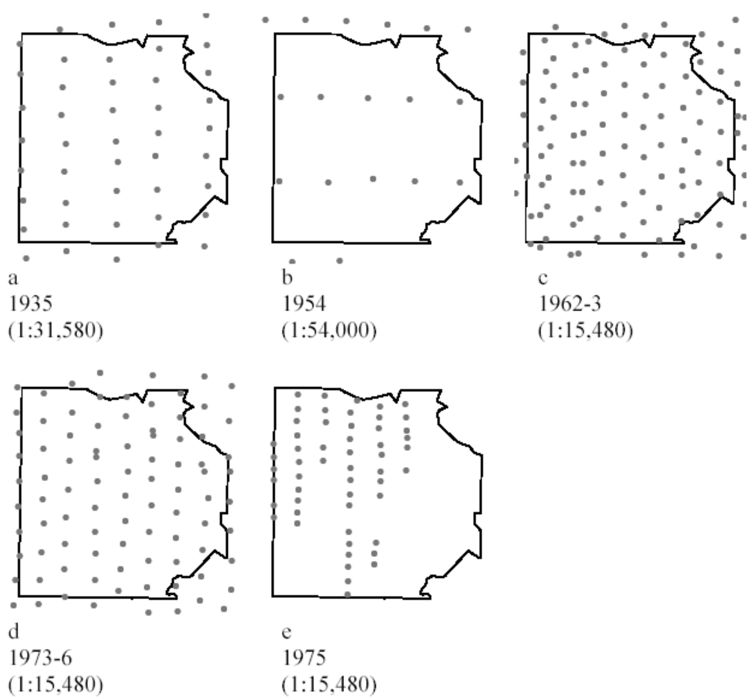


**Figure 9. Spatial coverage of aerial photograph sets used in this analysis. Points show the geographic centers of photographs.**

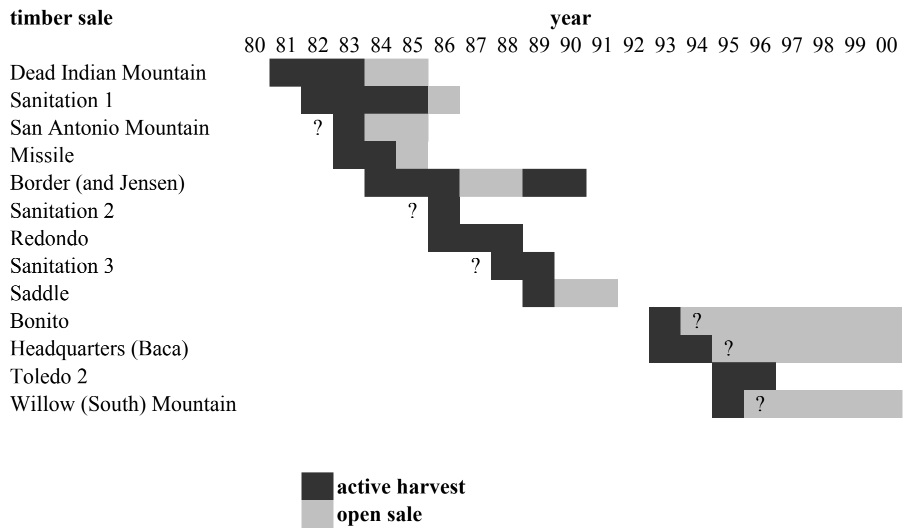


**Figure 10. Timeline of New Mexico State Forestry timber sale records on the Baca, 1980-2000. Dark shading indicates dates of active harvest; light shading indicates approximate dates of an open timber sale. Incomplete records (indicated in part by question marks surrounding active harvests) limit the accuracy of this figure in displaying the full span of each sale.**

Regeneration plans, which explain harvest method and composition of harvest, are incomplete or missing for most sales. Estimates of timber harvest volumes are rare and inconsistently reported.

*Timber Reports*

There are several Baca-era reports that hold specific analytical interest. Two logging reports by Frank and Dean Solinsky, Consulting Foresters (Solinsky 1963, 1979) were commissioned, but to the best of our knowledge, only the 1979 report is extant (now held by the Valles Caldera Trust). This report and accompanying map integrated a review of the 1963 report and other reports, an examination of airphotos, and additional field reconnaissance into a summary of timber on the Baca as of 1978. The field data collection methods used to evaluate timber volume were not clear from the report, which quantitatively described timber volume (calculated from basal area and height) by species for each of eight geographic strata (geographic units of measurement and analysis; Fig. 11a) and for unharvested and harvested areas (Table 2). Species examined included ponderosa pine, Douglas-fir, spruce, and white fir over ten inches (25 cm) in diameter and aspen over 6 inches (13 cm) in diameter. The report did not present tallies of numbers of trees nor did it partition the data by tree size.

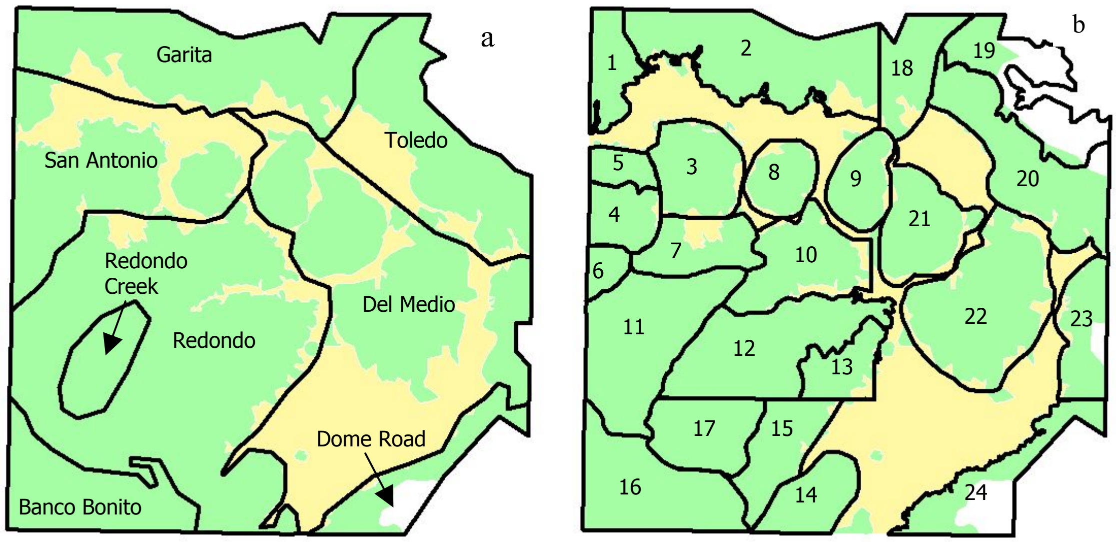


**Figure 11. Geographic strata used in the: (a) 1979 Solinsky Report, and (b) 1998 Keel timber cruise. Forest area is green; grassland area is in yellow.**

In the early 1990's, interest in federal purchase of the Baca prompted the US Forest Service to contract a survey of the natural and cultural resources of the Ranch (USFS 1993). This report contains general harvest information and summary statistics that are mostly summarized from the Solinsky reports.

Finally, in 1998, Keel and Associates Timber Cruising and Appraisals Company was commissioned to conduct a "timber cruise" or survey of merchantable timber on the property (Keel 1998, now held by Valles Caldera Trust). The cruise measured the species, diameter, and height of 2,889 trees at 922 plots in 24 strata using the Bitterlich variable plot method (Grosenbaugh 1952) (Figs. 11b and 12; Table 3). The strata in this cruise were larger than a typical management compartment, ranging from 647 to 6,527 acres with a mean of 2,615 acres (261 to 2,641 ha with a mean of 1,058 ha), and did not correspond with those defined by Solinsky (1979). The cruisers recorded pine, Douglas-fir, spruce, white fir, and corkbark fir over nine inches (23 cm) in diameter. The cruisers also (inconsistently) recorded some occurrences of logging. Keel used the National Timber Cruising Program, NATCRS (USFS 1994), to compile merchantable timber summary reports of volume and number of trees by strata and by species (plot n = 875, 740 of which are non-zero). We used their field cruise tally sheets (Fig. 13), the NATCRS output (digital text file), the report text, and topographic quadrangles annotated with plot locations to conduct additional analyses of the Keel data set.

**Table 2. Summary of 1978 raw volume data from Solinsky (1979) in thousand board-feet of trees >10 in (>25 cm) (aspen >6 in (>13 cm)). Locations are shown in Figure 11a.**

| | area | | volume (thousand board-feet) by species | | | | | total | |
|---|---|---|---|---|---|---|---|---|---|
| | | | pond. | Doug. | | white | | | |
| Timber Type | ha | ac | pine | fir | spruce | fir | aspen | conifer | all |
| **Redondo** | | | | | | | | | |
| unharv. conifer | 3,259 | 8,052 | 11,877 | 23,775 | 14,924 | 8,009 | 1,580 | 58,585 | 60,165 |
| harvested conifer | 3,796 | 9,381 | 5,209 | 1,345 | 116 | 744 | 300 | 7,414 | 7,714 |
| aspen | 614 | 1,518 | | | | | 1,980 | 0 | 1,980 |
| non-commercial | 1,433 | 3,541 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 962 | 2,377 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 10,064 | 24,869 | 17,086 | 25,120 | 15,040 | 8,753 | 3,860 | 65,999 | 69,859 |
| **Redondo Creek** | | | | | | | | | |
| unharv. conifer | 181 | 448 | 173 | 1,258 | 973 | 249 | 30 | 2,653 | 2,683 |
| harvested conifer | 81 | 200 | 36 | 215 | 18 | 54 | 50 | 323 | 373 |
| aspen | 159 | 393 | 0 | 0 | 0 | 0 | 510 | 0 | 510 |
| non-commercial | 371 | 917 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 792 | 1,958 | 209 | 1,473 | 991 | 303 | 590 | 2,976 | 3,566 |
| **San Antonio** | | | | | | | | | |
| unharv. conifer | 1,508 | 3,726 | 3,970 | 7,936 | 3,607 | 2,813 | 630 | 18,326 | 18,956 |
| harvested conifer | 1,008 | 2,490 | 807 | 502 | 1,847 | 224 | 440 | 3,380 | 3,820 |
| aspen | 206 | 510 | 0 | 0 | 0 | 0 | 670 | 0 | 670 |
| non-commercial | 206 | 510 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 1,129 | 2,790 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 4,057 | 10,026 | 4,777 | 8,438 | 5,454 | 3,037 | 1,740 | 21,706 | 23,446 |
| **Garita** | | | | | | | | | |
| unharv. conifer | 146 | 360 | 45 | 1,491 | 989 | 149 | 70 | 2,674 | 2,744 |
| harvested conifer | 2,975 | 7,352 | 5,019 | 225 | 769 | 146 | 200 | 6,159 | 6,359 |
| aspen | 276 | 682 | 0 | 0 | 0 | 0 | 890 | 0 | 890 |
| non-commercial | 3,397 | 8,394 | 5,064 | 1,716 | 1,758 | 295 | 1,160 | 8,833 | 9,993 |
| grassland | 1,157 | 2,860 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 5,198 | 12,844 | 5,064 | 1,716 | 1,758 | 295 | 1,160 | 8,833 | 9,993 |
| **Toledo** | | | | | | | | | |
| unharv. conifer | 380 | 940 | 44 | 2,980 | 2,190 | 485 | 100 | 5,699 | 5,799 |
| harvested conifer | 2,677 | 6,616 | 1,444 | 360 | 576 | 72 | 250 | 2,452 | 2,702 |
| aspen | 581 | 1,436 | 0 | 0 | 0 | 0 | 1,870 | 0 | 1,870 |
| non-commercial | 871 | 2,153 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 1,084 | 2,679 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 5,594 | 13,824 | 1,488 | 3,340 | 2,766 | 557 | 2,220 | 8,151 | 10,371 |

**(Table 2 - continued)**

| | area | | volume (thousand board-feet) by species | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | pond. | Doug. | | white | | total | |
| Timber Type | ha | ac | pine | fir | spruce | fir | aspen | conifer | all |
| **Del Medio** | | | | | | | | | |
| unharv. conifer | 694 | 1,716 | 1,073 | 5,418 | 4,703 | 1,178 | 340 | 12,372 | 12,712 |
| harvested conifer | 3,340 | 8,253 | 3,335 | 1,805 | 1,945 | 1,764 | 630 | 8,849 | 9,479 |
| aspen | 390 | 963 | 0 | 0 | 0 | 0 | 1,260 | 0 | 1,260 |
| non-commercial | 390 | 963 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 4,992 | 12,334 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 9,805 | 24,229 | 4,408 | 7,223 | 6,648 | 2,942 | 2,230 | 21,221 | 23,451 |
| | | | | | | | | | |
| **Dome Road** | | | | | | | | | |
| unharv. conifer | 811 | 2,003 | 2,013 | 5,938 | 4,193 | 1,806 | 380 | 13,950 | 14,330 |
| harvested conifer | 236 | 584 | 1,026 | 415 | 305 | 437 | 100 | 2,183 | 2,283 |
| aspen | 69 | 171 | 0 | 0 | 0 | 0 | 220 | 0 | 220 |
| non-commercial | 69 | 170 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 36 | 90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 1,221 | 3,018 | 3,039 | 6,353 | 4,498 | 2,243 | 700 | 16,133 | 16,833 |
| | | | | | | | | | |
| **Banco Bonito** | | | | | | | | | |
| unharv. conifer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| harvested conifer | 1,769 | 4,371 | 11,375 | 195 | 0 | 0 | 0 | 11,570 | 11,570 |
| aspen | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| non-commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | 61 | 150 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total | 1,830 | 4,521 | 11,375 | 195 | 0 | 0 | 0 | 11,570 | 11,570 |
| | | | | | | | | | |
| **BACA TOTAL** | | | | | | | | | |
| unharv. conifer | | 17,245 | 19,195 | 48,796 | 31,579 | 14,689 | 114,259 | 3,130 | 117,389 |
| harvested conifer | | 39,247 | 28,251 | 5,062 | 5,576 | 3,441 | 42,330 | 1,970 | 44,300 |
| total conifer | | 56,492 | 47,446 | 53,858 | 37,155 | 18,130 | 156,589 | 5,100 | 161,689 |
| aspen | | 5,673 | 0 | 0 | 0 | 0 | 0 | 7,400 | 7,400 |
| total timber | | 62,165 | 47,446 | 53,858 | 37,155 | 18,130 | 156,589 | 12,500 | 169,089 |
| non-commercial | | 9,844 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| grassland | | 23,280 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| total non-timber | | 33,124 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Total** | | 95,289 | 47,446 | 53,858 | 37,155 | 18,130 | 156,589 | 12,500 | 169,089 |

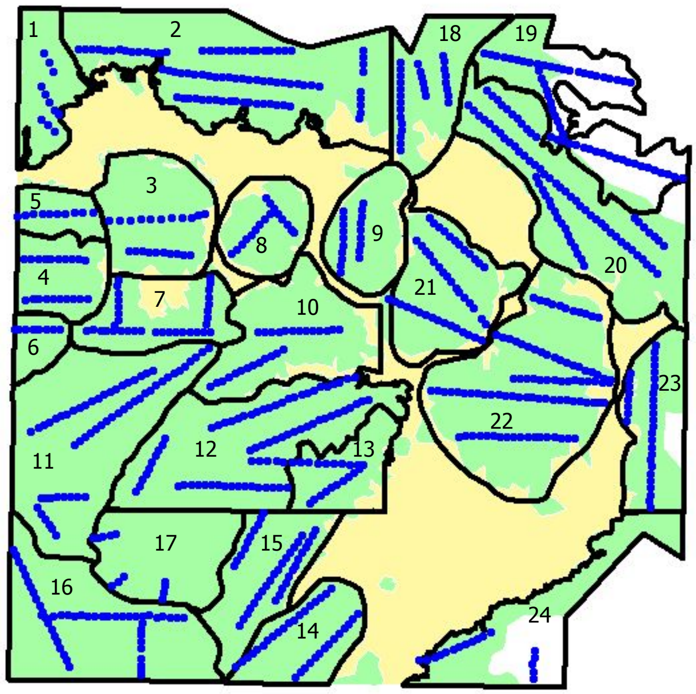


**Figure 12. Plot locations from 1998 Keel timber cruise (n = 922) with strata outlined and numbered (Keel 1998).**

A brief description of the Bitterlich method of timber estimation is provided here for clarity and to benefit researchers who may wish to use this data in the future. The Bitterlich method of "variable radius plot" or "plotless" cruising has been used by American foresters for over half a century (Grosenbaugh 1952). Traditional fixed plot-based methods sample trees proportional to their frequency per fixed unit area. Variable plot methods sample trees proportional to their size. The plot radius is not fixed in size but rather varies with the diameter of each measured tree (a sampling point is still termed a "plot"). A cruiser stands at a point (the equivalent of a plot center) and rotates a fixed-angle gauge around that point, tallying the number of trees whose diameter at breast height is greater than the angle projected by the sighting device. The critical angle of the sighting device determines its basal area factor (BAF). Multiplying the observed tree number by the BAF equals the basal area per unit area. Through standard equations, basal area is converted to timber volume. Each tree carries equal weight in computing basal area per unit area (Bell and Dilworth 1988).

The Bitterlich method is relatively fast since no plot or tree measurements are necessary, but it is inferior for density calculation (Lindsey et al. 1958), and a single sample point is a poor estimate of stand properties so many points must be aggregated to assess stand characteristics. A single BAF should be used for a given forest (Bell and

**Table 3. Summary of plot information for the 1998 Keel timber cruise (Keel 1998).**

| Stratum | Area Hectares | Area Acres | Plots used | Total plots | BAF |
|---|---|---|---|---|---|
| 1 | 673 | 1,663 | 10 | 10 | 20 |
| 2 | 1,983 | 4,901 | 79 | 79 | 20 |
| 3 | 990 | 2,447 | 21 | 21 | 20 |
| 4 | 546 | 1,349 | 20 | 20 | 30 |
| 5 | 380 | 939 | 10 | 10 | 20 |
| 6 | 262 | 647 | 8 | 8 | 20 |
| 7 | 713 | 1,761 | 35 | 35 | 20 |
| 8 | 575 | 1,421 | 17 | 17 | 30 |
| 9 | 460 | 1,137 | 19 | 19 | 30 |
| 10 | 1,007 | 2,489 | 26 | 26 | 20 |
| 11 | 2,045 | 5,053 | 60 | 60 | 30 |
| 12 | 1,832 | 4,527 | 75 | 86 | 20 |
| 13 | 577 | 1,427 | 19 | 30 | 20 |
| 14 | 821 | 2,028 | 33 | 33 | 20 |
| 15 | 980 | 2,421 | 43 | 43 | 20 |
| 16 | 1,670 | 4,127 | 51 | 52 | 20 |
| 17 | 836 | 2,066 | 12 | 12 | 20 |
| 18 | 799 | 1,974 | 28 | 28 | 30 |
| 19 | 896 | 2,215 | 55 | 55 | 20 |
| 20 | 1,343 | 3,318 | 72 | 72 | 30 |
| 21 | 1,325 | 3,274 | 45 | 45 | 20 |
| 22 | 2,641 | 6,527 | 87 | 108 | 20 |
| 23 | 761 | 1,880 | 33 | 33 | 30 |
| 24 | 1,278 | 3,157 | 17 | 20 | 20 |
| | | | | | |
| Totals | 25,394 | 62,748 | 875 | 922 | - |

USDA-Forest Service

| SALE CRUISE TALLY SHEET (Ref: FSH 2409.24-R-3) CARD TYPE 3 | Cruiser: WIRTZ | Date: 7/26/98 |
|---|---|---|
| NF | Dist. | samp. size 20 — unit num. 021 |
| Cruise Name Cari 7 & 7 | | (10-12) |

| plot 1 tree number | Ct. Pt. | species | DBH | total height | class | code | COUNT 3P KPI estimated vol/ht. | % seen defect | ult. Pole or Pulp length | clear face | ht. first live limb | out only | % slope | grown rat. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14-17 | 18 | 19-20 | 21-23 | 24-26 | 27 | 28 | 29-31 | 33-34 | 38-40 | 41 | 43-44 | 45 | 47-48 | 50 |
| | 4 | DF | 144 | 065 | | | | | | | | | | |
| | 5 | DF | 118 | 062 | | | | | | | | | | |
| | 6 | DF | 163 | 067 | | | | | | | | | | |
| FP | | | | | | | 0 | | | | | | | |
| ASPEN | | | | | | | 2 | | | | | | | |
| | | (10 chs to PLOT 8 @ 118°) | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| PLOT | 8 | | | | | | | | | | | | 34 | |
| | 1 | DF | 207 | 060 | | | | | | | | | | |
| | 2 | WF | 134 | 048 | | | | | | | | | | |
| | 3 | WF | 146 | 054 | | | | | | | | | | |
| | 4 | DF | 110 | 041 | | | | | | | | | | |
| | 5 | DF | 093 | 033 | | | | | | | | | | |
| FP | | | | | | | 1 | | | | | | | |
| ASPEN | | | | | | | 0 | | | | | | | |
| | | (10 chs to PLOT 9 @ 118°) | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| PLOT | 9 | | | | | | | | | | | | 32 | |
| | 1 | DF | 148 | 049 | | | | | | | | | | |
| | 2 | DF | 148 | 058 | | | | | | | | | | |
| | 3 | WF | 254 | 120 | | | | | | | | | | |
| FP | | | | | | | 0 | | | | | | | |
| ASPEN | | | | | | | 1 | | | | | | | |
| | | (10 chs to PLOT 10 @ 118°) | | | | | | | | | | | | |
| | | | | | | | | | | | | | | |
| PLOT | 10 | | | | | | | | | | | | 40 | |
| | 1 | WF | 307 | 082 | | | | | | | | | | |
| | 2 | LP | 240 | 090 | | | | | | | | | | |

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**Figure 13. Sample timber cruise datasheet from the 1998 Keel survey.**

Dilworth 1988) because alternating BAFs causes bias arising primarily from points with low tree counts (Iles and Wilson 1988). A suitable BAF can be determined by dividing the estimated basal area per acre by the desired tree count. Average minimum tree count per plot should generally exceed four trees; when plots range between four and twelve trees per plot, efficiency and statistical confidence are both maximized (Iles and Wilson 1988).

Data from the 1998 timber cruise did not always meet the optimal characteristics for the Bitterlich method described above, making rigorous analyses problematic. Different BAFs were employed, and less than four trees per plot were recorded at more than half of the survey points (Fig. 14; Table 4). Recent logging could account for low tree number on some plots but cannot explain the consistently low tree numbers. In

**Table 4. Frequency of tree numbers recorded at individual survey points in the 1998 Keel timber cruise (Keel 1998).**

| # Trees Recorded | Frequency | Percent |
|---|---|---|
| 0 | 135 | 15% |
| 1 | 115 | 13% |
| 2 | 153 | 17% |
| 3 | 103 | 12% |
| 4 | 119 | 14% |
| 5 | 80 | 9% |
| 6 | 66 | 8% |
| 7 | 41 | 5% |
| 8 | 19 | 2% |
| 9 | 18 | 2% |
| 10 | 12 | 1% |
| 11 | 5 | 1% |
| 12 | 6 | 1% |
| 13 | 3 | 0% |
| Total | 875 | 100% |

addition, since this data set was acquired by variable plot surveying techniques, it is not directly comparable to the stand structural data in other fixed plot-based field data sets collected in the VCNP. Inferences derived from its analysis are limited by the data's lack of precision.

*Complementary Data*

Field reconnaissance was used to verify locations of some harvested areas, but we did not systematically field-check the logging boundaries digitized from paper maps or airphotos. We were also unsuccessful in relocating monuments (e.g., wooden stakes, flagging) at Keel timber cruise reference points, presumably because they had decayed, been removed, or had not been precisely located on cruise maps. We did, however, collect plot-based data on forest structure and composition from 70 stands in unlogged and selectively logged areas (Koski et al., in prep.). These data allowed us to spot-check mapped locations of logging activity. Muldavin and Tonne (2003) similarly located more than 200 vegetation plots throughout the VCNP, although specific data collected at each point varied from relatively detailed plot information to GPS-referenced spot checks of dominant vegetation type. The Valles Caldera Trust also provided supporting GIS digital data layers, including land ownership, roads, hypsography, hydrology, and remotely sensed vegetation, that aided in the creation of the logging data sets.

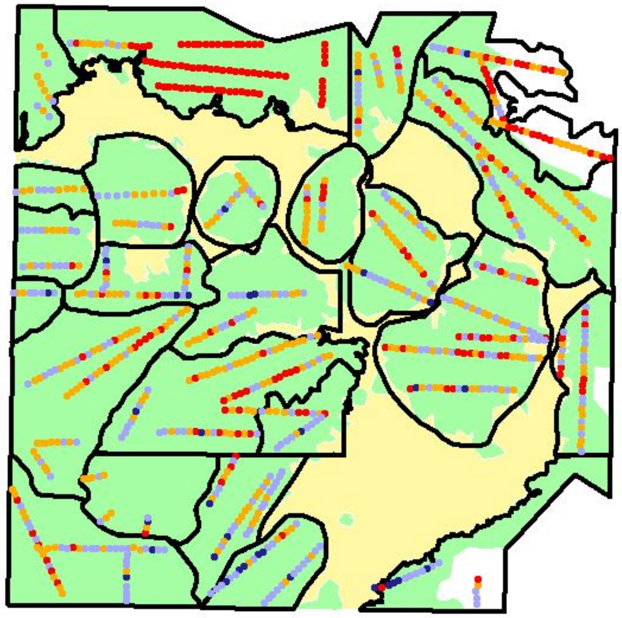


**Figure 14. Frequency of trees recorded at each plot (n = 740, 80% of total plots) in the 1998 Keel timber cruise (Keel 1998). Red plots had no recorded trees, orange plots had 1-3 recorded trees, light blue plots had 4-8 recorded trees, and navy blue plots had 9-13 recorded trees.**

**Data Analysis**

We calculated summary harvest statistics for each relevant data set. Raw data from Solinsky (1979) and Keel (1998) were translated into spreadsheet format to facilitate these analyses and future use by managers and researchers. Similarly, the resulting spatial datasets are available to facilitate future studies by managers and researchers.

*GIS Logging Database*

Digital spatial data layers of logging history were created using ArcView™ v3.3 by digitizing on top of the 1996 DOQ and 1993 DRG base maps. The resulting digitized layers were then converted to ArcGIS™ v8.2 coverages. Polygons were partitioned into coverages by era of occurrence: 1935-1962, 1963-1972, 1980-1991, and 1992-2000. The two primary data sources used for digitizing harvest boundaries were aerial photographs and State Forestry maps. The area of interest extended beyond the VCNP boundary into Santa Clara Pueblo in the northeast.

Five sets of airphotos obtained from the Valles Caldera Trust were scanned for use in digitizing logged areas (Fig. 9). A sixth set of 1998 digital orthophotos was used as a base map and aided in digitization of more recent harvests. Photographs of the same location taken on different dates were compared to identify boundaries of logging activity. The photos were the primary source for logging activity identification during the period 1937-1962, and, in many cases, it was relatively easy to identify harvest boundaries based on textural contrast between heavily cut and adjacent uncut stands (Fig. 15). Due to regrowth of advanced reproduction and lateral in-filling of the canopy opening by surrounding trees, the boundaries of selection cuts were much more difficult to identify (Fig. 16). These boundaries were digitized based on all available data sets and the judgment of the digitizer.

In addition to the airphotos, records from New Mexico State Forestry, which contain maps of logging boundaries sketched by hand on topographic quadrangles, were used to identify logging activity from 1970-2000. These maps have greater temporal precision but less spatial accuracy and precision than airphotos, and in many cases, only the sale and block boundaries were delineated on NMSF maps. A block is a subunit of a sale, and logging operations generally progressed block by block. In most cases only a portion of each block was harvested, but the majority of maps did not indicate the harvested area, just the block boundary (Fig. 17). Airphotos were used wherever possible to confirm NMSF logging boundaries, but many boundaries could not be resolved at a finer resolution than the block.

The GIS roads coverage was also useful for digitizing precise harvest boundaries since many of the roads, especially those built in 1963-1972 era, were built for the express purpose of facilitating logging. Maps and notes from the timber reports as well as field reconnaissance served to enhance the quality of the data. For example, timber cruise data (Keel 1998) sporadically mentioned evidence of past logging, or absence of such evidence, within a plot (Fig. 18). While mention of logging at a location that other sources did not identify as a logged area was taken as valid evidence of logging activity, no mention of logging at a timber cruise plot was not taken as an indication that logging did not occur there.

*Current Timber Estimates*

Timber volume data is essential for effective implementation of timber management practices. The 1998 timber cruise data were used as the most current estimate for timber on the VCNP, and timber volume, volume per area, number of trees, and trees per area were calculated by species and by stratum. Presence of the five reported species in timber cruise plots was collated into plot frequencies from NATCRS output.

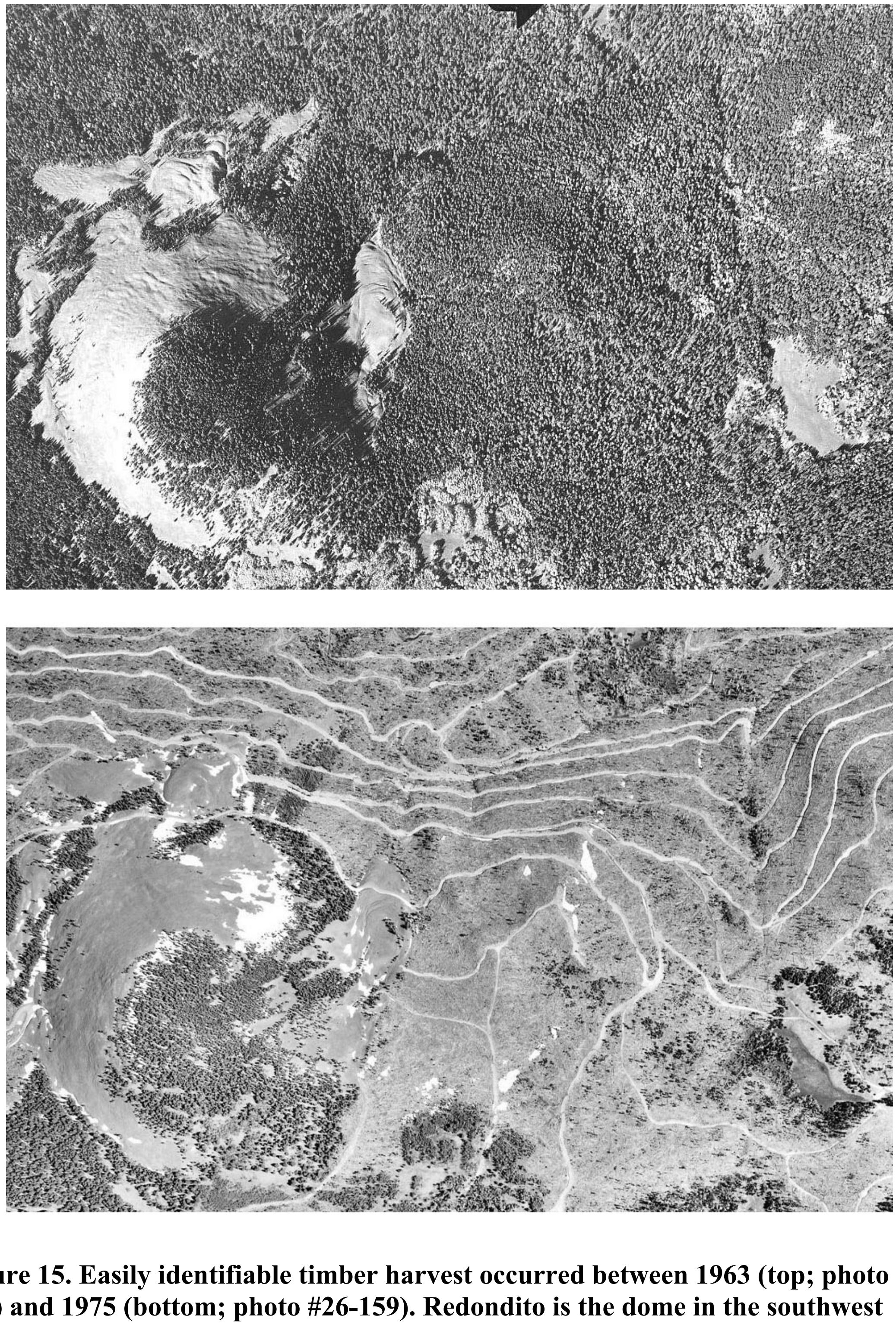


**Figure 15. Easily identifiable timber harvest occurred between 1963 (top; photo #11-104) and 1975 (bottom; photo #26-159). Redondito is the dome in the southwest quadrant. Photo width is approximately 1.8 km.**

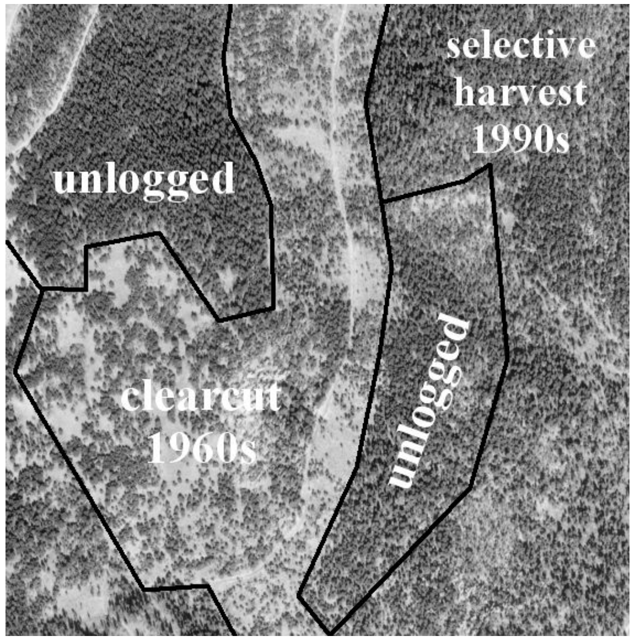



**Figure 16. Example of variations in boundary contrasts between stands of differing harvest history. The contrast between unlogged and clearcut areas and even between selectively harvested and clearcut stands was often clearly visible. The contrast between selectively harvested and unharvested stands was often less apparent and sometimes impossible to discern on photographs.**

*Timber Comparison, 1978-1998*

Information on how timber volume is changing through time, for example as a result of logging operations or post-logging recovery, is also valuable. Unfortunately, such information in the Baca is far from complete. The 1963 Baca timber report (Solinsky 1963), containing old harvested statistics and maps, could not be located. The 1980-2000 New Mexico State Forestry logging records (NMSF records) are not complete enough to precisely identify total harvested volumes during that era. The 1979 timber report (Solinsky 1979) and the 1998 timber cruise (Keel 1998) are relatively thorough, consistent, and complete in their reporting of data. There are, however, issues regarding bias of these data due to differing sampling methodologies (Solinsky's method is unknown; Keel used the variable plot cruising techniques described above), small sample size, and inadequate geographic coverage (see later discussion). Comparison of their volumetric data does at least provide qualitative insights into changes in volume, relative species abundance, and stand density over the past twenty years.

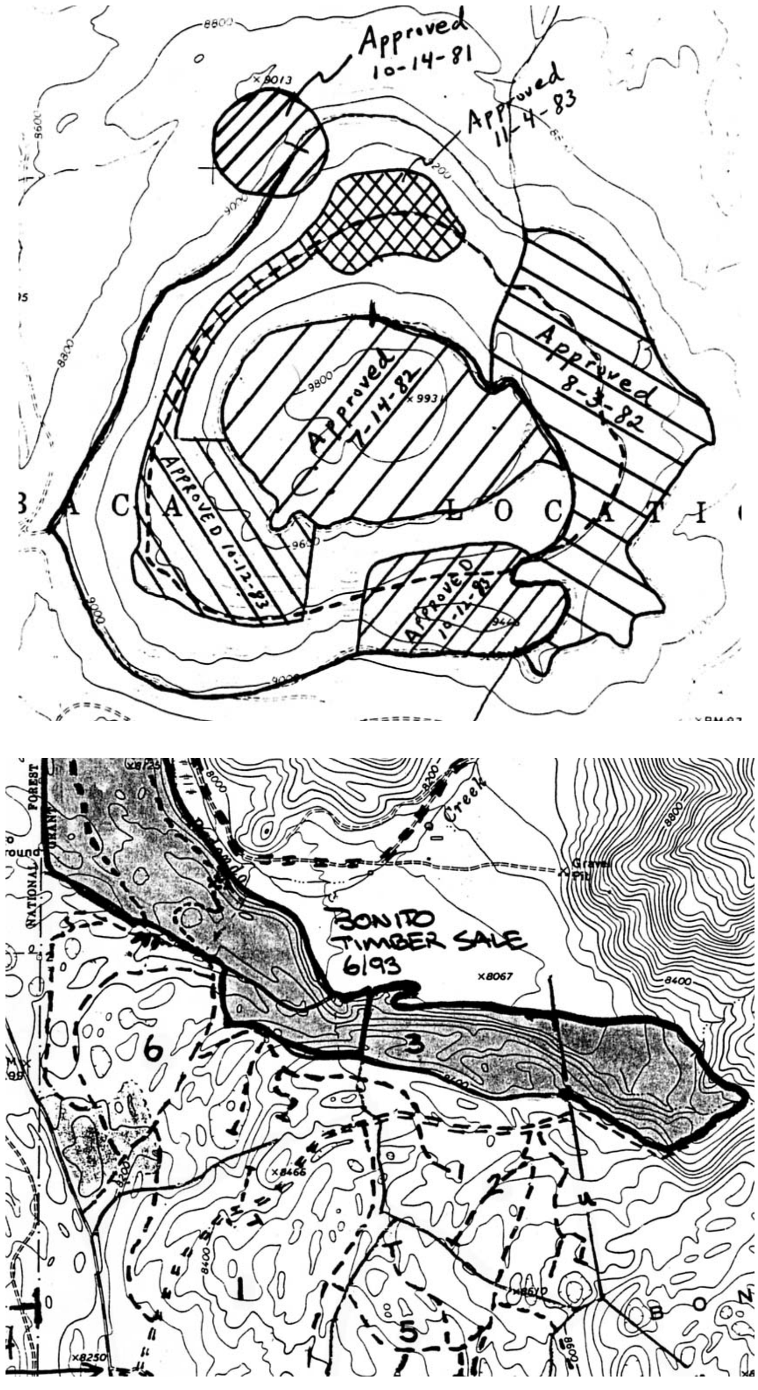



**Figure 17. Examples of New Mexico State Forestry records that have (top) well-delineated harvest zones (Dead Indian Mountain timber sale, 1981-3) and (bottom) poorly-delineated harvest zones showing only sale block boundaries, not actual harvested areas (Bonito timber sale, 1993) (NMSF records).**

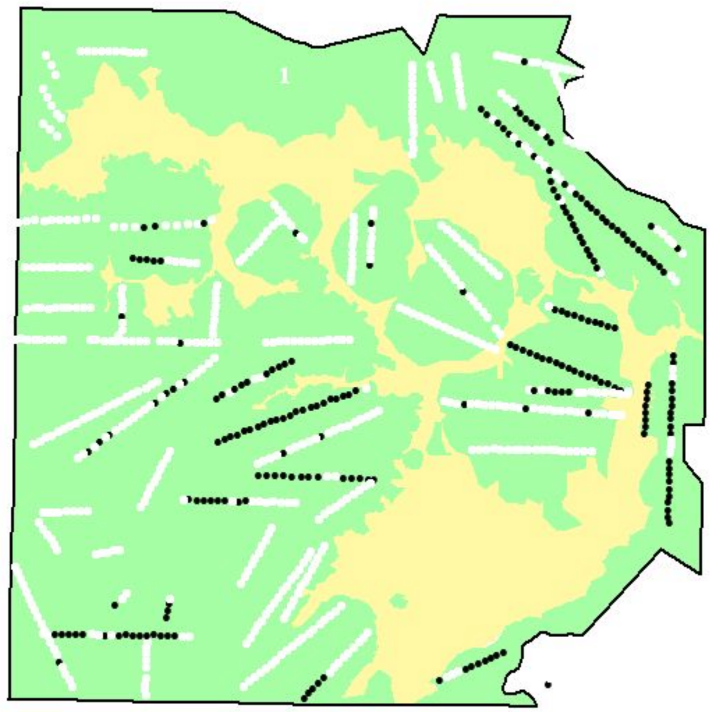


**Figure 18. Mention of logging in 1998 timber cruise field tally sheets. White plots denote plots where no evidence to support or refute past harvest history was given, or where cruisers did not believe prior harvest had taken place. Black plots indicate mention of logging evidence (e.g., stumps).**

Because the geographic strata boundaries of the two timber reports differed, it was necessary to standardize the data sets before comparison. To do so, we combined the geographically dissimilar strata from each report into seven approximately colinear areas (Fig. 19). We aggregated the smaller 1998 strata (n = 24) until their boundaries were relatively coincident with the larger 1978 strata (n = 8). The resulting composite strata names are the same as the 1978 names, with one exception. The 1978 Redondo Creek stratum did not correspond with any of the 1998 strata and is combined with the 1978 Redondo stratum to form the Redondo Complex stratum. The 1978 Redondo Creek stratum was originally part of the Redondo stratum in Solinsky's 1963 report and was separated out only to accommodate the 1973 Geothermal Survey (Pilz et al. 1979).

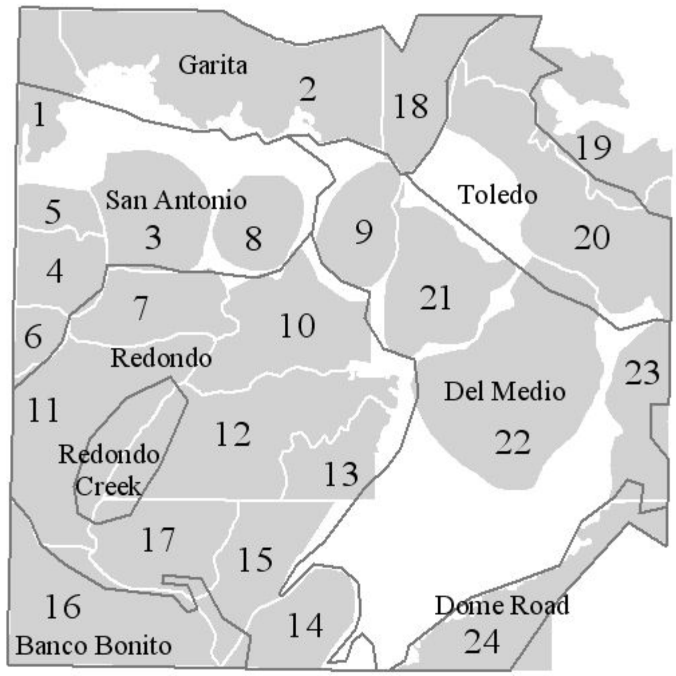



**Figure 19. Overlay of 1979 Solinsky strata (named, outlined polygons, Solinsky 1979) and 1998 Keel timber cruise strata (numbered, shaded polygons, Keel 1998). Redefined harvest strata used in the timber comparison used Solinsky's names, except for Redondo and Redondo Creek, which were combined into the Redondo Complex stratum.**

Some boundary inconsistencies remained, and for these, we combined each indeterminate 1998 stratum with its most closely associated 1978 stratum. The subjective decision of assignment was based upon expert knowledge and field reconnaissance and considered elements including aerial proportion and ecological similarity (using both observed and remotely-sensed vegetation cover). We believe that this method was the most adequate solution possible because it retained strata as entire units. Using this method, the 1998 Stratum 1 fell within the 1978 Garita strata, and the 1998 Stratum 24 and 1978 Dome Road stratum were matched. The boundary of the 1978 Toledo stratum and the 1998 Stratum 19 did not exactly coincide, and the 1978 Banco Bonito stratum was not exactly colinear with its complementary contemporary strata, but their boundaries were close enough (we believe) for the purposes for this analysis.

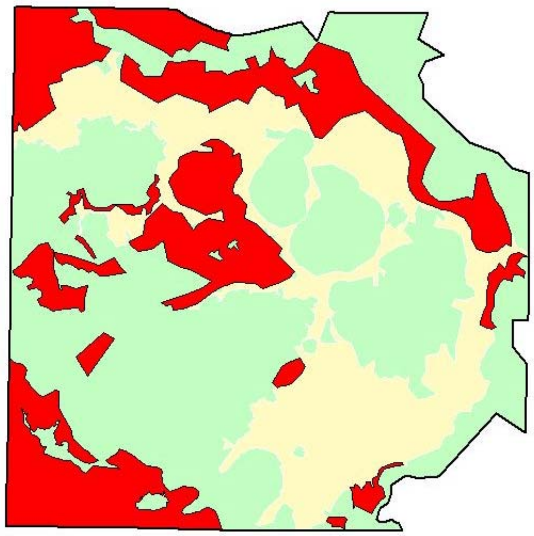
# RESULTS

Logging as a discrete ecological disturbance has affected most forest stands in the VCNP. Harvests varied in extent and intensity over both space and time within the context of technology, economics, and landscape values. While there was no evidence of harvest prior to 1935, there was extensive high grading of the timber resources during the first logging era, 1935-1962. The practice of clear-cutting removed the large trees but was initially restricted to easily accessible pine and mixed conifer forests. The construction of an extensive road network enabled more widespread logging in all vegetation zones and all areas of the VCNP during the second era, 1963-1972. After an absence of logging for a decade, less intensive, targeted harvests continued during the third era, 1980-2000.

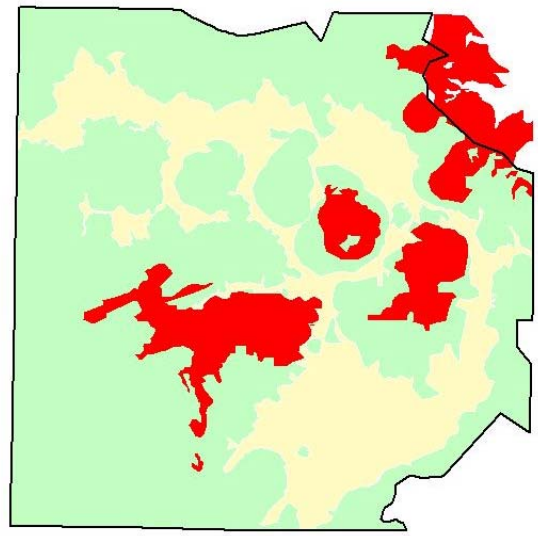
## Logging and Timber Cruise GIS Layers

Four digital spatial data sets were created and attributed with appropriate metadata based on our delineation of logging extent and timing. (These layers are held by the Valles Caldera Trust in ArcGIS™ coverage format.) Each layer displays logging activity and severity for a given period, as described earlier (Fig. 20). From 1935-1962 low elevation ponderosa pine stands bordering the grasslands endured light to heavy selective cutting, with our mapped locations for this phase of logging concurring with descriptions from Martin (2003) and the USFS (1993). From 1963-1972 clear-cutting occurred over a range of elevations, enabled by a new network of logging roads. There was no visible logging activity from 1973-1979. From 1980-1991 and 1992-2000 selective harvest (ranging from light to heavy) and patch cutting were prevalent throughout the VCNP but on a smaller scale. Absent and imprecise NMSF maps and spatial ambiguity of selective harvests on airphotos leaves the 1980-1991 coverage (and to a lesser extent the 1992-2000 coverage) relatively incomplete (Fig. 21). These layers serve as minimum harvest maps since some areas of harvest may not have been identifiable by the methods employed. The 1980-1991 period is particularly suspect, hence its separation from the 1992-2000 logging era. We used logging evidence from the timber cruise field tally sheets, vegetation plots (Muldavin and Tonne 2003), and field reconnaissance (Koski et al., in prep.) to check digitized location of logging occurrence. Although harvests in the Santa Clara Pueblo's western corner are shown, they are not included in analyses of VCNP harvest history.

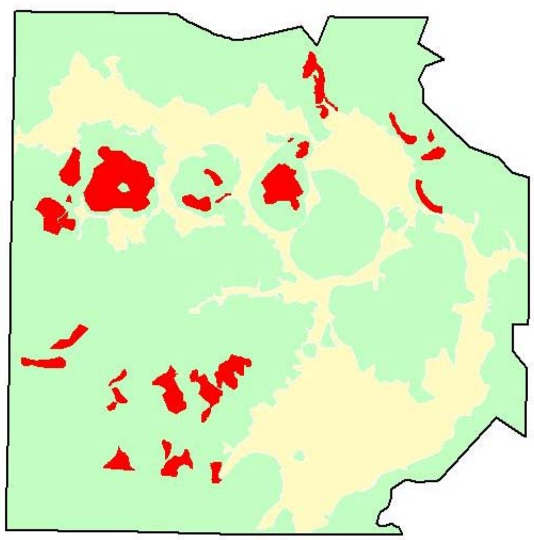
Part of this study also involved creating a digital database of the Keel timber cruise data that would be available for future resource management planning. Because we were unable to locate the survey transect start points or other survey point locations in the field (and no GPS coordinates were recorded on the cruise tally sheets), we digitized locations of the start points as mapped on USGS 1:24,000 quads. Subsequent survey locations were then estimated based on distance and direction along the transect as recorded on the survey sheets. Where possible, we "error-checked" the locations by



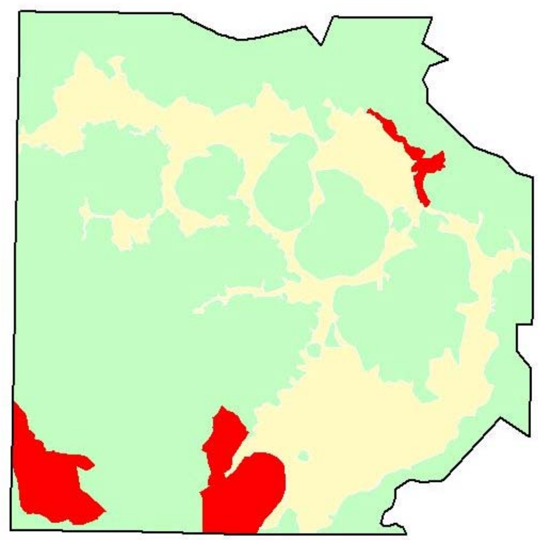
a: 1935-1962



b: 1963-1972



c: 1980-1991



d: 1992-2000

**Figure 20. Digitized harvest maps for the major commercial logging eras in the Valles Caldera (the third era, 1980-2000, is divided into two time periods). Red shading indicates minimum harvested area on a green background of forest extent. No commercial logging is believed to have taken place between 1972 and 1980.**

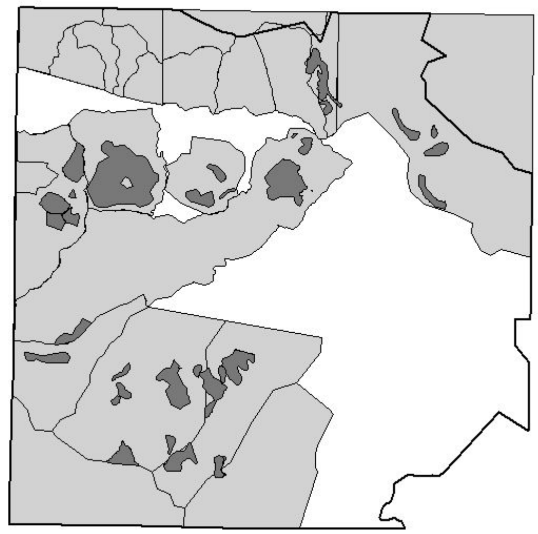
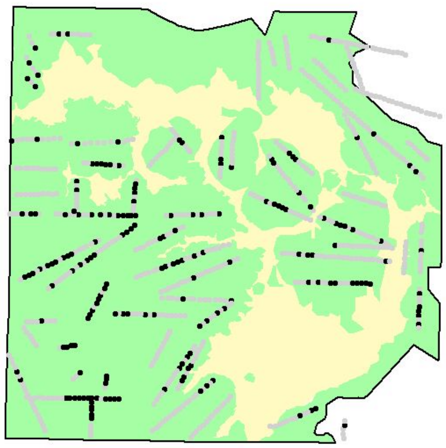


**Figure 21. Illustration of the incomplete spatial record of harvest during the 1980-1991 era. Cut blocks within which harvesting was known to have occurred are shaded light gray while known harvests within the blocks are shaded dark gray.**

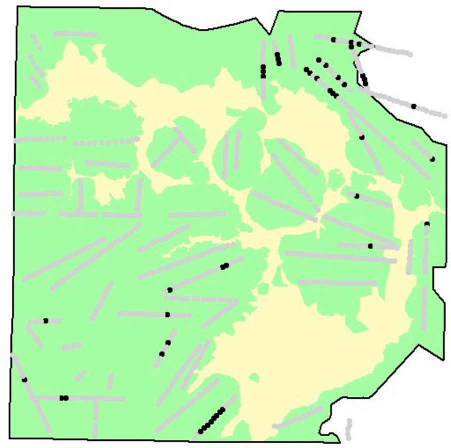
consulting the survey sheets (e.g., to insure that points fell in forested areas or to compare noted evidence of logging with logged areas on the airphotos; Fig. 18). This method is undoubtedly imprecise but: 1) it provided the best available method for approximating individual sample point locations and thus generating a spatial coverage of the Keel data, and 2) small errors in sample point locations are likely unimportant when data are aggregated to the scale of geographic stratum. The resulting dataset can be queried for information about trees at each sample point or used to analyze or visually present preserve-wide timber data within the constraints imposed by the original dataset (Fig. 22).

**Current Timber Estimates**

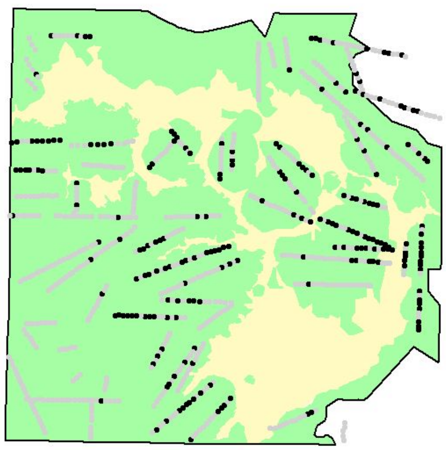
Current estimates of timber volume and density should be interpreted within the context of past logging practices. Specifically, ponderosa pine and Douglas-fir were the species of principal economic value and hence the most heavily harvested, but all major conifer species have been logged to some extent. Preference was also scaled proportional to size; typically all trees over 20 cm (8 inches) were harvested in clear-cuts while selective harvesting favored large, “overmature” trees of greater economic value. Use of small diameter timber was limited to small-scale firewood and Christmas tree collection (NMSF records, USFS 1993).



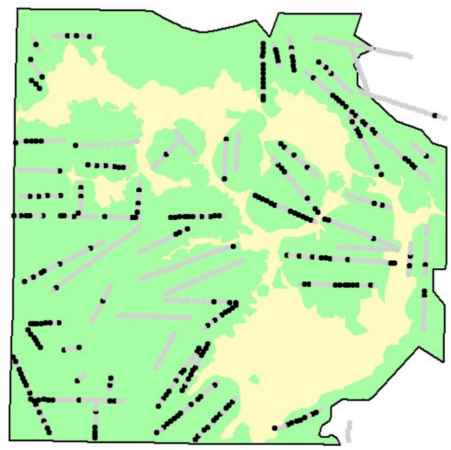
*Abies concolor* (White fir)



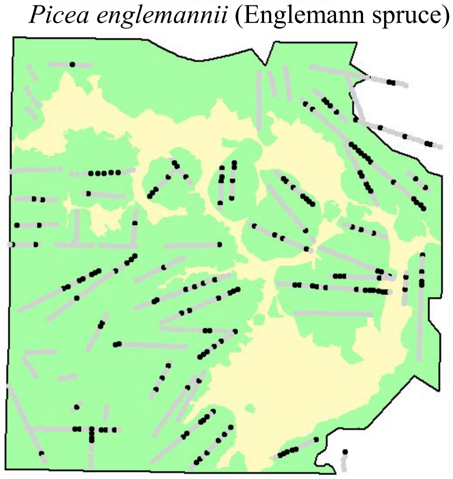
*Abies lasciocarpa* (Corkbark fir)



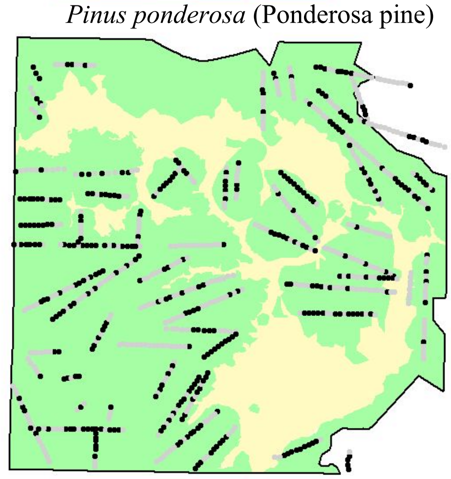
*Picea englemannii* (Englemann spruce)



*Pinus ponderosa* (Ponderosa pine)



*Populus tremuloides (*Aspen)



*Pseudotsuga menziesii* (Douglas-fir)

**Figure 22. Presence (black dots) of specific species at 1998 Keel timber cruise points (data from Keel 1998).**

Data from the Keel survey put the 1998 VCNP timber volume at 489,049,000 board-feet on 25,390 ha (62,748 ac) of timbered land (Keel 1998). (Keel reports the total volume as 486,049,000 board-feet but a summation of partial volumes stratified by either species or by stratum verifies a calculation of 489,049,000 board-feet. Calculations based upon other output tables provide slightly different results based on rounding error.) This 1998 estimate of 489 million board-feet is the most current estimate of the total timber resource on the VCNP and falls within the range of Glover's (1990) two suggested estimates of pre-1935 Baca timber volumes, 400 and 500 million board-feet. Despite the large uncertainty surrounding Glover's uncorroborated estimates, it is probable that current total timber volume is similar to pre-logging volume.

As would be expected, timber volume and density vary by species and strata because of environmental variation within VCNP and differences in disturbance history (Tables 5 and 6; Fig. 23). However, the major species recorded in the 1998 timber cruise exhibited similar patterns of merchantable timber volume (Fig. 24) and total number of merchantable stems (Fig. 25) by size class. Each species, except corkbark fir, shows a unimodal volume distribution, with a sharp decline in timber volume with increasing diameter and a scarcity of volume derived from trees greater than 122 cm (48 inches) in diameter (Fig. 24). Similarly, all abundance distributions demonstrate a negative exponential decline in number of trees with size (mathematically similar to the derivative of the volume curves), with few trees greater than 61 cm (24 inches) and very few over 76 cm (30 inches) in diameter (Fig. 25).

Because of the limited number of trees recorded at each cruise point, the cruise data are only meaningful when aggregated to the scale of the strata or preserve. With only minimal logging having occurred since 1998, the major potential sources of biomass removal have been fire, insects, and drought, and it is reasonable to assume that timber volume has remained relatively constant or increased during this period. The multiple pathways of vegetation response to past logging in the VCNP have yet to be described so the direction of change of forest stands is relatively uncertain. Even if pre-1935 and current volumes are similar, the population structure of timber is certainly different today than in pre-logging times. In many stands, a greater proportion of smaller and more numerous trees populate today's landscape (e.g., Koski et al., in prep.), and it is likely that species composition is very different today from a century ago, as is the case throughout much of the West. The recent pulse of establishment is due to a combination of post-logging regeneration and increased tree survival in the absence of fire. Logging regeneration includes shade-intolerant species (ponderosa pine, aspen, corkbark fir) established in severely logged stands and shade-tolerant species (Douglas-fir, white fir) established where less severe logging opened canopy gaps. Understory infilling of shade-tolerant species is a typical product of fire exclusion in fire-adapted conifer forests of the Southwest (Covington and Moore 1994).

**Table 5. Current (1998) timber volume (board-feet) by stratum and species (Keel 1998).**

| Stratum | Acreage | Ponderosa pine | Douglas-fir | White fir | Englemann spruce | Corkbark fir | Total |
|---|---|---|---|---|---|---|---|
| 1 | 1,663 | 1,540,495 | 970,928 | 1,623,742 | 5,046,400 | 0 | 9,181,565 |
| 2 | 4,901 | 12,766,277 | 13,897,522 | 9,758,828 | 4,546,915 | 120,418 | 41,089,960 |
| 3 | 2,447 | 3,312,768 | 5,767,889 | 2,917,524 | 2,735,336 | 0 | 14,733,516 |
| 4 | 1,349 | 3,808,507 | 11,747,391 | 0 | 2,724,164 | 0 | 18,280,062 |
| 5 | 939 | 1,443,097 | 545,255 | 507,338 | 2,717,600 | 0 | 5,213,290 |
| 6 | 647 | 2,809,686 | 2,330,487 | 2,035,898 | 391,718 | 0 | 7,567,788 |
| 7 | 1,761 | 3,038,467 | 6,400,431 | 5,231,909 | 966,027 | 0 | 15,636,832 |
| 8 | 1,421 | 380,827 | 9,672,499 | 991,320 | 3,132,245 | 0 | 14,176,891 |
| 9 | 1,137 | 332,873 | 2,675,960 | 816,976 | 2,206,537 | 0 | 6,032,347 |
| 10 | 2,489 | 9,122,282 | 1,266,139 | 4,152,653 | 2,033,699 | 0 | 16,574,773 |
| 11 | 5,053 | 11,784,386 | 12,095,255 | 8,816,882 | 554,990 | 429,739 | 33,681,252 |
| 12 | 4,527 | 432,851 | 4,198,455 | 6,091,922 | 9,656,092 | 586,692 | 20,966,012 |
| 13 | 1,427 | 3,936,247 | 6,090,868 | 1,490,922 | 844,551 | 0 | 12,362,587 |
| 14 | 2,028 | 11,079,344 | 8,067,906 | 244,921 | 6,572,949 | 2,739,055 | 28,704,174 |
| 15 | 2,421 | 11,432,374 | 11,622,603 | 2,053,782 | 2,821,314 | 233,036 | 28,153,108 |
| 16 | 4,127 | 10,808,270 | 7,152,929 | 11,575,625 | 508,155 | 2,087,929 | 32,131,906 |
| 17 | 2,066 | 3,974,321 | 2,076,295 | 4,319,862 | 0 | 0 | 103,740,477 |
| 18 | 1,974 | 11,312,451 | 2,665,077 | 0 | 336,455 | 2,238,069 | 16,552,052 |
| 19 | 2,215 | 42,254 | 3,364,200 | 53,615 | 2,204,026 | 636,127 | 6,300,222 |
| 20 | 3,318 | 8,134.02 | 6,692,121 | 1,843,328 | 2,799,789 | 2,572,063 | 22,041,324 |
| 21 | 3,274 | 4,907,443 | 6,733,436 | 3,006,982 | 4,980,660 | 0 | 19,628,250 |
| 22 | 6,527 | 6,698,608 | 8,123,651 | 4,983,119 | 14,712,992 | 438,738 | 34,957,108 |
| 23 | 1,880 | 13,409,748 | 12,271,938 | 241,161 | 0 | 0 | 25,922,846 |
| 24 | 3,157 | 10,218,105 | 30,708,478 | 3,772,010 | 4,084,999 | 0 | 48,783,592 |
| | | | | | | | |
| Sum | 62,748 | 146,725,705 | 177,137,713 | 76,529,319 | 76,577,613 | 12,081,866 | 489,052,204 |

**Table 6. Current (1998) timber volume per area (board-feet per acre) by stratum and species (Keel 1998).**

| Stratum | Ponderosa Pine | Douglas Fir | White Fir | Engelmann Spruce | Corkbark Fir | Total |
|---|---|---|---|---|---|---|
| 1 | 926 | 584 | 976 | 3,035 | 0 | 5,521 |
| 2 | 2,605 | 2,836 | 1,991 | 928 | 25 | 8,384 |
| 3 | 1,354 | 2,357 | 1,192 | 1,118 | 0 | 6,021 |
| 4 | 2,823 | 8,708 | 0 | 2,019 | 0 | 13,551 |
| 5 | 1,537 | 581 | 540 | 2,894 | 0 | 5,552 |
| 6 | 4,343 | 3,602 | 3,147 | 605 | 0 | 11,697 |
| 7 | 1,725 | 3,635 | 2,971 | 549 | 0 | 8,880 |
| 8 | 268 | 6,807 | 698 | 2,204 | 0 | 9,977 |
| 9 | 293 | 2,354 | 719 | 1,941 | 0 | 5,305 |
| 10 | 3,665 | 509 | 1,668 | 817 | 0 | 6,659 |
| 11 | 2,332 | 2,394 | 1,745 | 110 | 85 | 6,666 |
| 12 | 96 | 927 | 1,346 | 2,133 | 130 | 4,631 |
| 13 | 2,758 | 4,268 | 1,045 | 592 | 0 | 8,663 |
| 14 | 5,463 | 3,978 | 121 | 3,241 | 1,351 | 14,154 |
| 15 | 4,722 | 4,801 | 848 | 1,165 | 96 | 11,633 |
| 16 | 2,619 | 1,733 | 2,805 | 123 | 506 | 7,786 |
| 17 | 1,924 | 1,005 | 2,091 | 0 | 0 | 5,020 |
| 18 | 5,731 | 1,350 | 0 | 170 | 1,134 | 8,385 |
| 19 | 19 | 1,519 | 24 | 995 | 287 | 2,844 |
| 20 | 2,451 | 2,017 | 556 | 844 | 775 | 6,643 |
| 21 | 1,499 | 2,057 | 918 | 1,521 | 0 | 6 |
| 22 | 1,026 | 1,245 | 763 | 2,254 | 67 | 5,356 |
| 23 | 7,133 | 6,528 | 128 | 0 | 0 | 13,789 |
| 24 | 3,237 | 9,727 | 1,195 | 1,294 | 0 | 15,453 |

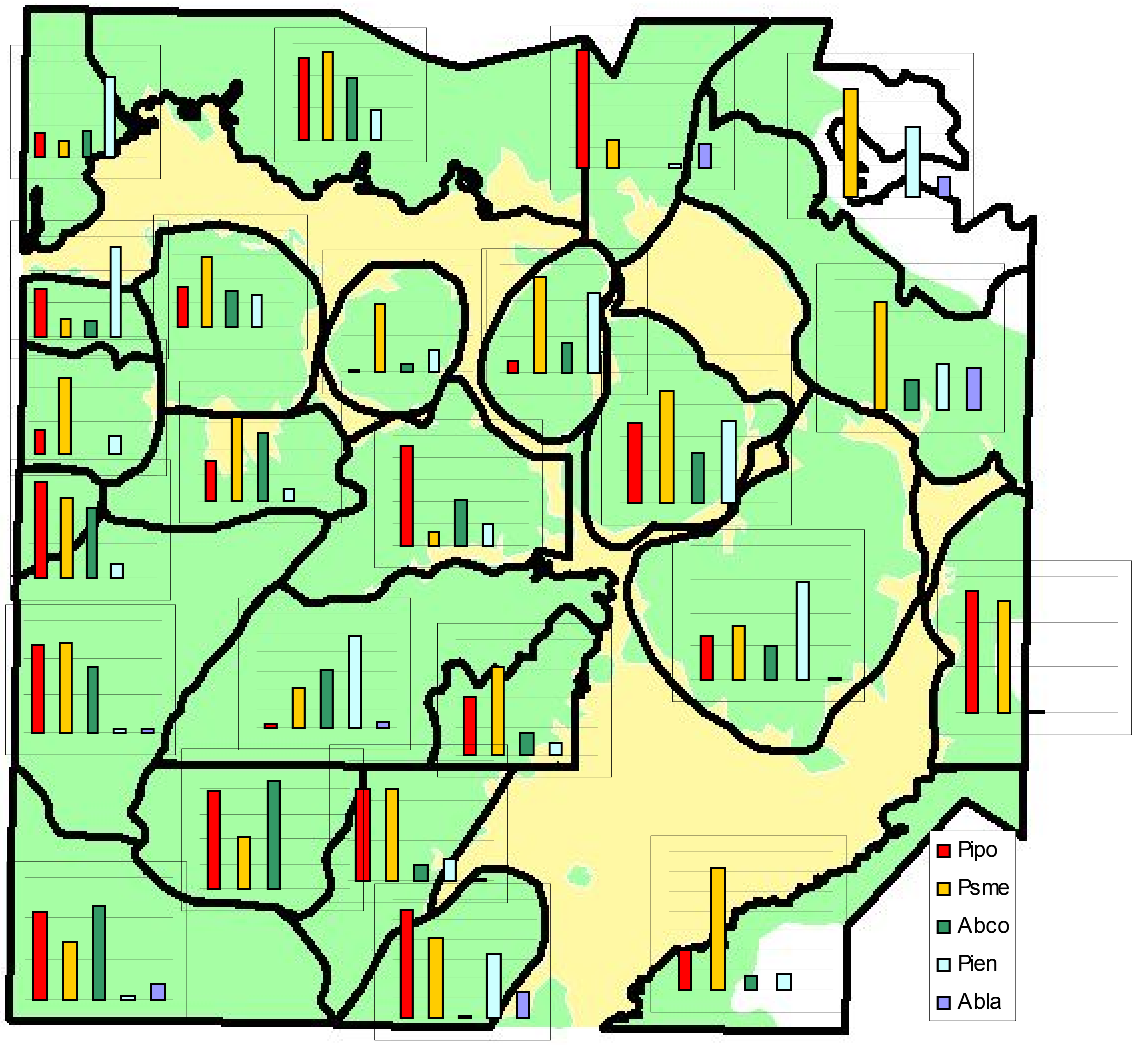



**Figure 23. Current (1998) volume of merchantable timber by stratum and species. The y-axis range varies among strata, but the raw data can be found in Table 5. Species codes: Pipo = *Pinus ponderosa* (ponderosa pine); Psme = *Pseudotsuga menziesii* (Douglas-fir); Abco = *Abies concolor* (white fir); Pien = *Picea engelmannii* (Engelmann spruce); Abla = *Abies lasiocarpa* var. *arizonica* (corkbark fir).**

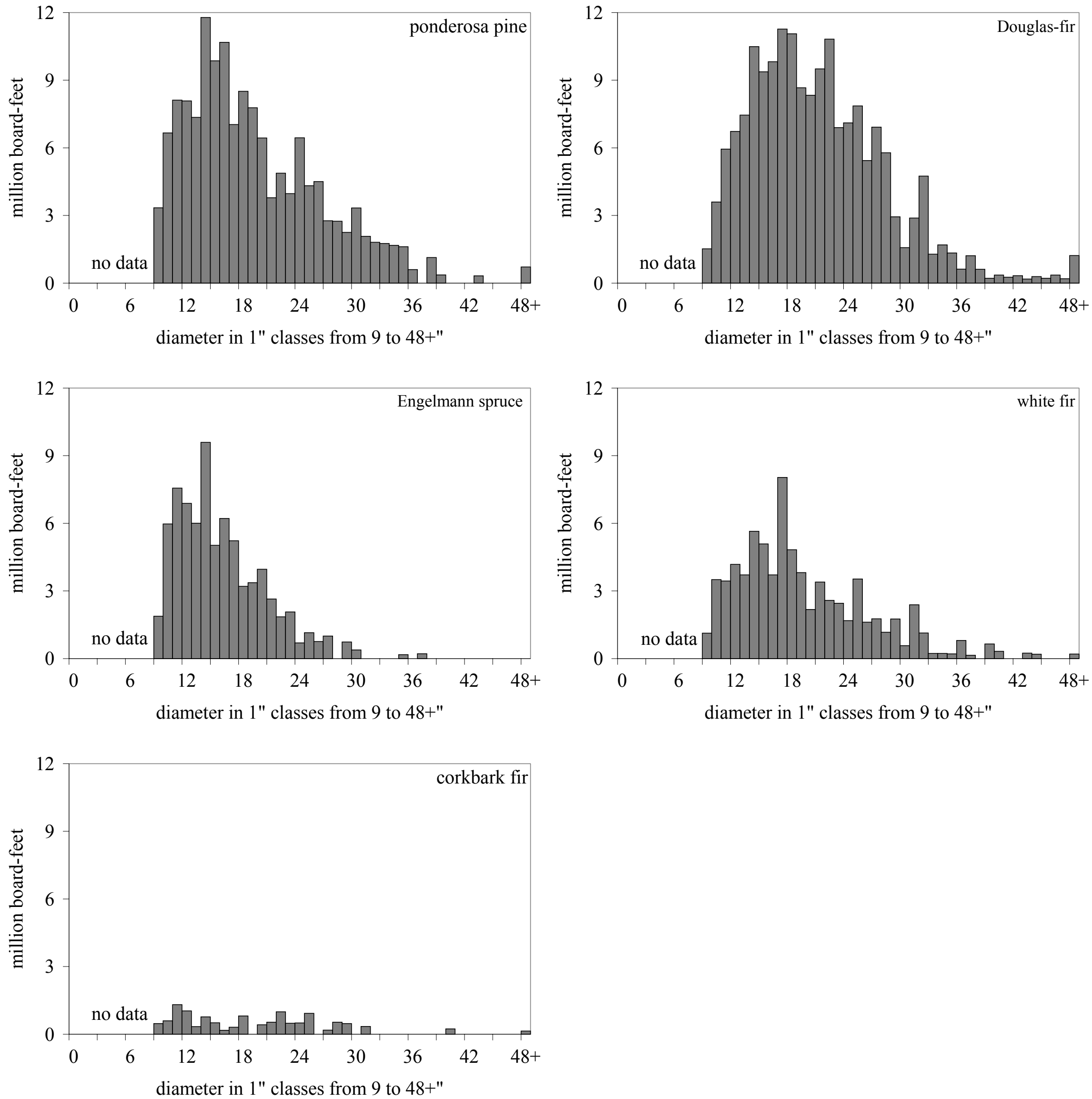



**Figure 24. Estimated current (1998) total volume of merchantable timber (millions of board-feet) by one-inch diameter classes, ranging from 9" (23 cm) to 48"+ (122+ cm) (data from Keel 1998).**

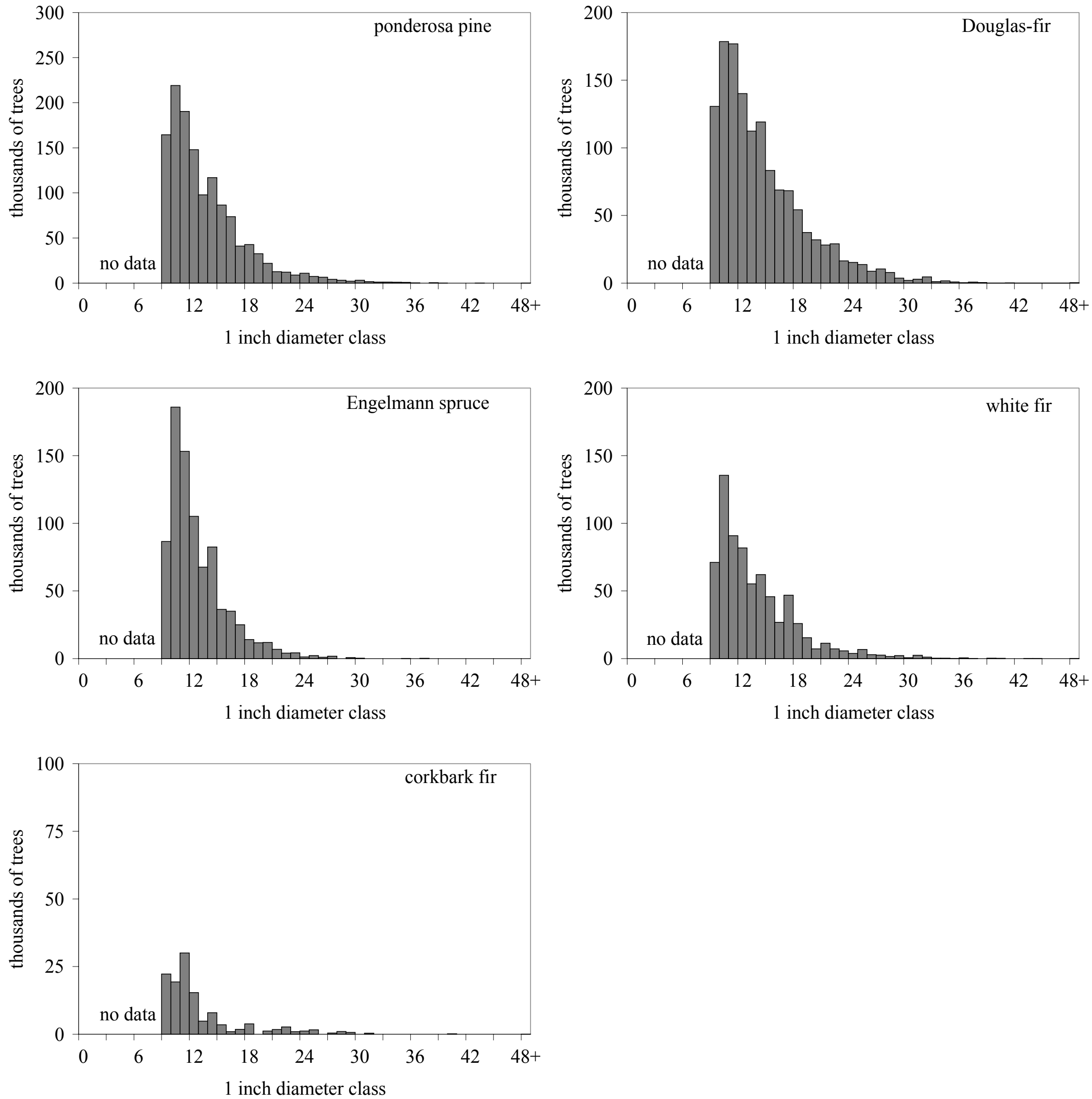



**Figure 25. Estimated current (1998) total number of merchantable stems (in 1000's) by one-inch diameter classes, ranging from 9" (23 cm) to 48"+ (122+ cm) (data from Keel 1998).**

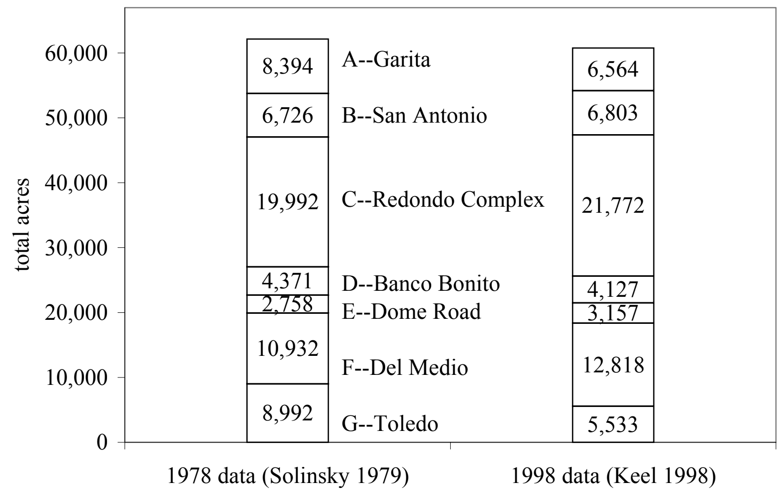



**Figure 26. Area comparison between the 1978 and 1998 redefined strata (62,165 and 60,774 acres, respectively; data from Solinsky 1979 and Keel 1998).**

**Timber Comparison, 1978-1998**

Seven new strata were produced for the purpose of comparing 1978 and 1998 timber volumes on the Baca (Fig. 19). A comparison of the total area (acres) encompassed by each strata between the 1978 and 1998 redefined strata showed that areas of the new strata are relatively colinear, with the greatest discrepancy being for the Garita and Toledo strata (Fig. 26). Differences in the former are due to arbitrary boundary delineation while differences for latter are the result of a change in the property boundary.

With a few minor exceptions, both absolute timber volume (board-feet) and volume per area (board-feet per acre) increased for every species in each of the seven strata (Figs. 27-28). The relative magnitude of change was not consistent among species or strata, however. Solinsky stated that Garita, Del Medio, and Toledo (heavily clear-cut) were adequately stocked with young regeneration in 1978. This regeneration soon reached sawtimber size and was counted by Keel in 1998 so these strata had between two and six-fold increases in volume. Garita, Redondo Complex, and Del Medio (strata A, C, and F) increased the most in total volume of ponderosa pine while all strata except Redondo Complex at least doubled their stocking of Douglas-fir. White fir increased from absent or nearly so to having a significant presence in Garita (stratum A) and Banco Bonito (stratum D), two of the lowest elevation strata. The latter, a low elevation, generally southerly-sloping plateau, is particularly interesting because it was populated with ponderosa pine forests in 1935. After intensive logging in the first logging era and additional logging in the most recent era, ponderosa pine has failed to increase in volume

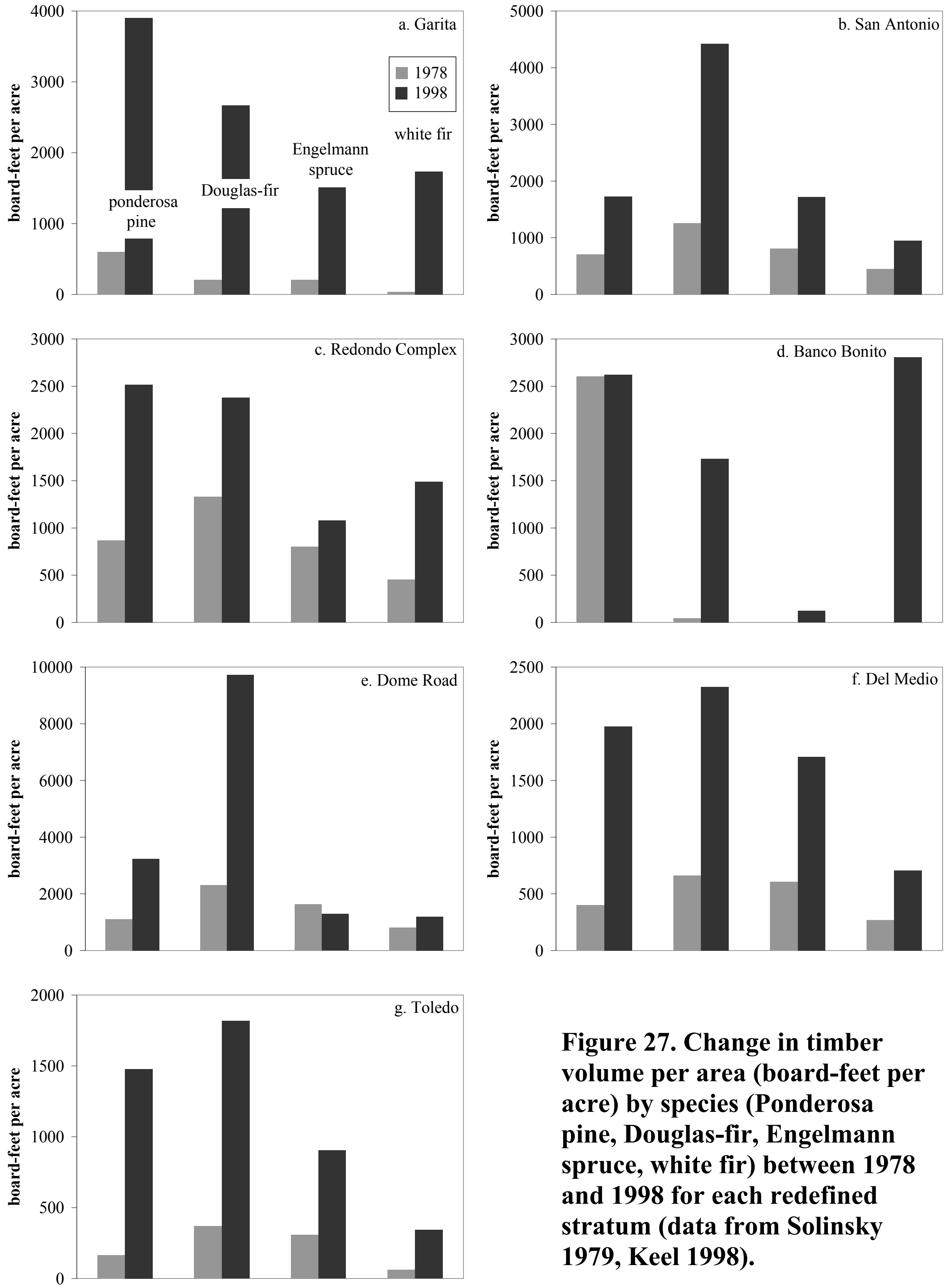



**Figure 27. Change in timber volume per area (board-feet per acre) by species (Ponderosa pine, Douglas-fir, Engelmann spruce, white fir) between 1978 and 1998 for each redefined stratum (data from Solinsky 1979, Keel 1998).**

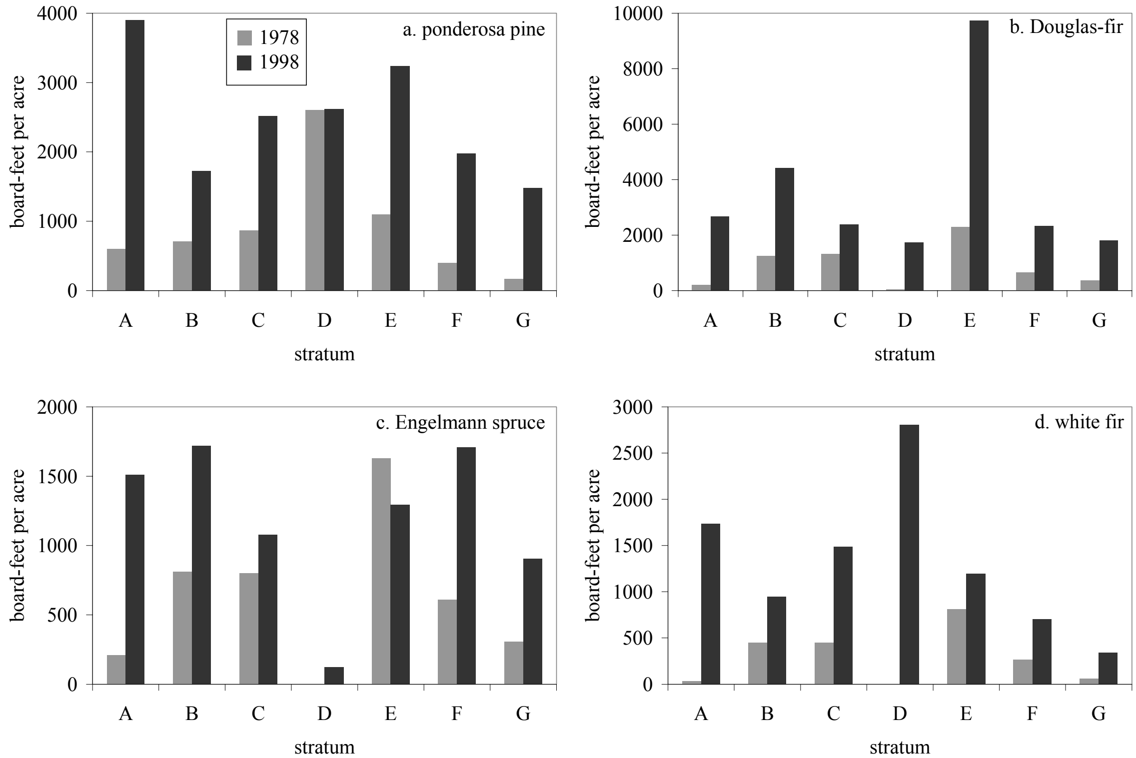



**Figure 28. Change in timber volume per area (board-feet per acre) between 1978 (left-hand bars) and 1998 (right-hand bars) for each redefined stratum (data from Solinsky 1979, Keel 1998). Strata abbreviations: a) Garita, b) San Antonio, c) Redondo Complex, d) Banco Bonito, e) Dome Road, f) Del Medio, and g) Toledo.**

while shade-tolerant white fir (and, to a lesser extent, other conifers such as Douglas-fir) has greatly increased in importance. This represents a significant change in terms of both ecological habitat and potential timber yields in any future harvests.

Some proportion of the sizable increases in volume detected from 1978 to 1998 may be an artifact of different data collection strategies, but it is logical to assume that the stocking levels of most stands have increased in the last two decades of less extensive selective logging. Favorable warm and wet growing conditions between 1976 and 1990 (Swetnam and Betancourt 1998) could also have contributed to a pulse of young growth reaching the minimum diameter threshold by 1998. We perceive area-normalized statistics and changes in relative species proportions to be less biased than simple comparisons of volume. Even if our stratum aggregation methodology is imprecise, all timber estimations should be generally comparable in assessing volume per area. It should be noted, however, that variable plot cruising (used in 1998 by Keel) is less reliable in assessing stem density than other sampling methods (Lindsey et al. 1958).

**Unlogged Stands**

Based in part on the road network, Muldavin and Tonne (2003) located and described stands they believed had not been logged. These stands, largely considered to be “non-commercial” areas by Solinsky (1979), were:

- stands where logging was not mechanically or economically viable (e.g., difficult slopes)
- immature, non-commercially viable stands
- stands composed of species with low economic value
- areas where aesthetics prevented harvesting

While we were unable to definitively map all areas of selection cutting, the logging history database provides at least a spatial representation of the minimum area logged (Fig. 29). This map generally agrees with Muldavin and Tonne (2003) and with the Keel timber cruise field notations (Fig. 30), but some unlogged areas on the map may in fact have been harvested and should be field checked (e.g., Cerro Seco, Muldavin and Tonne’s Zone 16; Cerro San Luis, Zone 15; Fig. 30). There may also be some areas (e.g., Muldavin and Tonne’s Zone 6, Willow/South Mountain) where the digitizing precision could not accurately identify internal stands of virgin forest within a selectively logged forest. Some cruise plots with harvest evidence lie within areas identified as potentially unharvested (e.g., zones 8a and 11) by the coarse-scale maps of this research and Muldavin and Tonne, but it is unclear from the Keel data how intensive or extensive any cutting in these areas might have been. Likewise, there are small patches of trees and individual trees within the minimum estimated harvest polygons that remain from original virgin forest.

Uncertainty about the accuracy and precision of the data sources used to digitize the logged areas raises the need for field-based evaluation of potentially virgin areas under consideration for conservation protection.

**Road Network**

Perhaps just as significant as the changes in forest cover due to the logging that has fragmented the VCNP landscape are the effects of the dense network of roads that accompanied logging activities, including their role in dissecting forest patches and the creation of associated edge effects. The landscape fragmentation and resultant negative ecological effects caused by road construction may exceed that of actual harvests in some locations (Tinker et al. 1998), and measures such as road density and the amount of forest

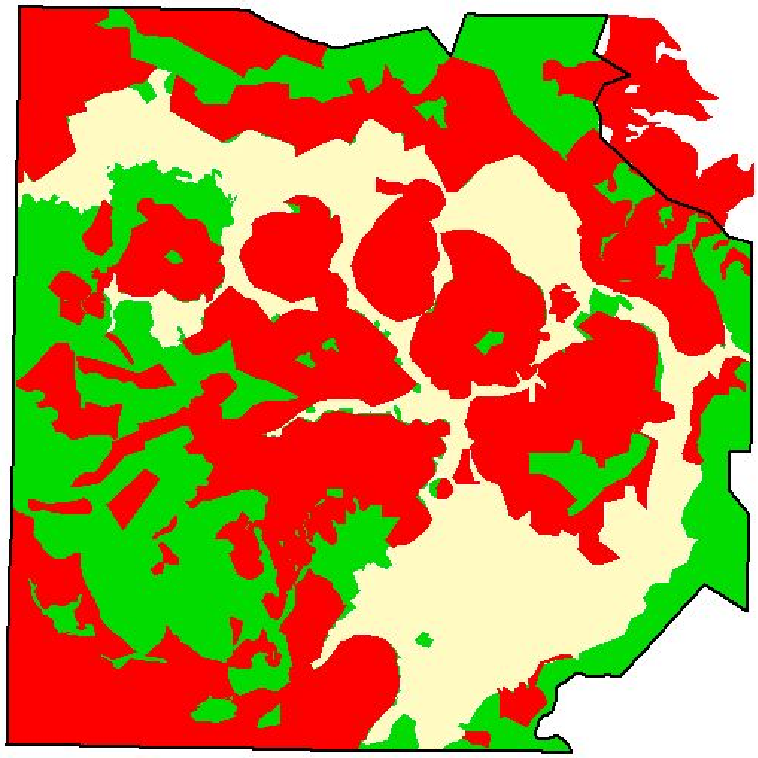


**Figure 29. Minimum estimated harvested area (red areas) based on digitized polygons of only verified harvested areas. Green shading denotes potentially virgin forest.**

within various distances to the nearest roads have been utilized in other studies as indicators of fragmentation and road effects (e.g., McGurk and Fong 1995; Reed et al. 1996; McGarigal et al. 2001; Saunders et al. 2002; Riitters and Wickham 2003). Severity of individual road effects does not necessarily vary directly with logging intensity in that a kilometer of road built to support a selective harvest would presumably have the same effects as a kilometer of road built to support a clear-cut. However, characteristics of the roads themselves such as width, cover, accessibility, and usage may have implications for a range of species and ecosystem functions.

The potential negative effects of roads are numerous and are documented in greater length elsewhere (e.g., Forman 2003), but most fall into one of three classes. First, roads represent areas of lost forest habitat, and when they serve as barriers to the movement of animal species (either directly, through road-related mortality, or indirectly, through road-aversive behavior), they fragment forested habitat and subdivide species populations. Depending on the size of the remaining subpopulations, the amount of

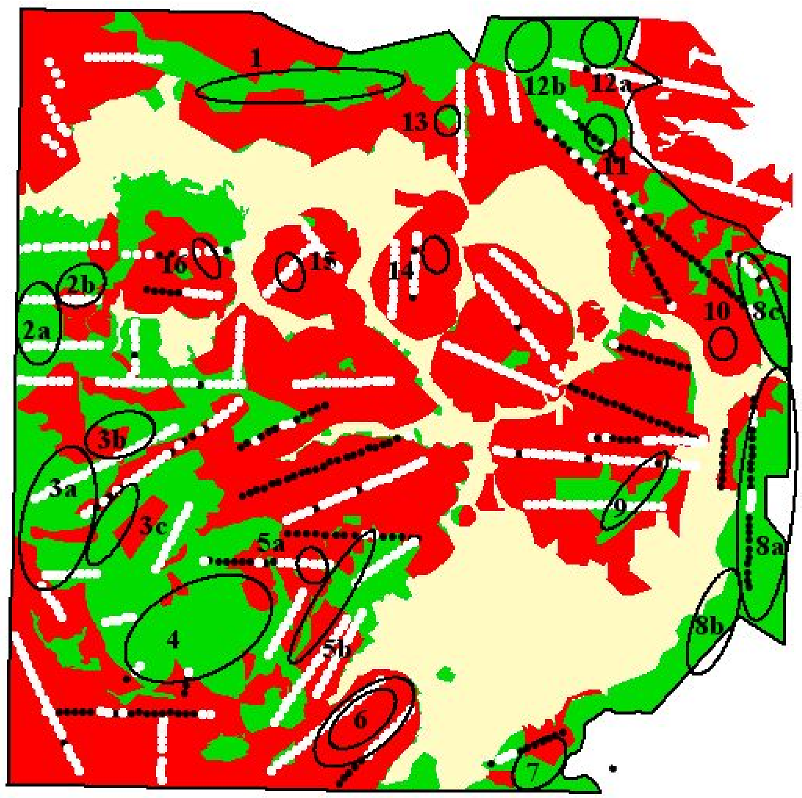



**Figure 30. Comparison between potentially unlogged areas of various studies. Forested areas in red have been explicitly identified in this research as harvested and those shaded green are potentially unharvested forest (see Figure 20). Numbered ellipses are areas identified as potentially unharvested by Muldavin and Tonne (2003). Black plots are timber cruise plots designated as having evidence of prior harvest (e.g., stumps) (Keel 1998).**

available habitat, and the willingness of individuals to cross roads, such effects may range from insignificant to highly problematic. The underlying theory and interpretations of remnant patch research suggest that as forests are fragmented, populations decline in size, leading to higher extinction rates, although such effects may not be immediately manifested (Tilman et al. 1994). Smaller populations may suffer from genetic drift, changes in gene frequency due to random variation in fecundity, and extinction due to lesser resilience to random events. The loss of genetic variability can lead to inbreeding depression, reducing the ability of populations to increase, expand, or recover from disturbance (Ricklefs and Miller 2000). Such effects are not only related to road-caused fragmentation, however, but rather include the cumulative effects of forest habitat loss and isolation coupled with the development of forest edge effects (Kupfer et al., in press).

Second, roads may serve as sources of negative impacts. Among other things, logging roads may serve as sources of sediment that affect basin hydrology (Kreutzweiser and Capell 2001), facilitate the invasion of non-native species (Clements et al. 2001), and increase the rate of human incursions (e.g., hunting access and poaching rates; Kerley et al. 2002). Roads are consequently recognized as threats to certain sensitive wildlife species and natural ecosystems (e.g., Noss and Cooperrider 1994), although again, specific effects will be highly case specific.

Finally, roads may adversely affect aesthetic or recreational benefits of an area and may serve as an impetus for stimulating future development. In the case of VCNP, many of the same roads that contributed to public outrage and a lawsuit in the 1960s while supporting intensive timber extraction (Martin 2003) are still ubiquitously visible (Fig. 6).

Although not all of these concerns about roads are relevant to the situation at VCNP, roads are pervasive within the preserve. According to the existing road network database for VCNP, more than 2600 km of roads exist within the preserve boundaries, with more than two-thirds (1,788 km; 69%) of the road network located in forested (as opposed to grassland) areas (Fig. 31a). A simple buffer analysis using a range of buffer widths (100, 200 and 300 m) helps to confirm how much of the preserve is within relatively close proximity to a road of some type. When only "primary" roads are considered (Fig. 31b), the amount of forested area falling within the buffer distances ranged from 9-25% (Fig. 32). In general, these are roads that are reasonably accessible and in some cases see a relatively high amount of traffic (including NM State Highway 4 and most of the maintained gravel and dirt roads within the preserve). When all other roads are examined (Fig. 31c), the amount of forested area < 300m from the nearest road increased dramatically, with 61% of forest area falling within 100m of a road and nearly 85% within 300m (Fig. 32). However, the status of many of these roads (e.g., their roles as sediment generators or as barriers to wildlife movement) is questionable, as many are currently unused and impassable to all but foot traffic. Taken collectively, these results suggest that an accounting of road conditions and effects is warranted.

It is also possible to superimpose the current system of roads (e.g., with a 100m buffer) on the map of potential old-growth forest areas to identify potential core roadless areas (Fig. 31d).

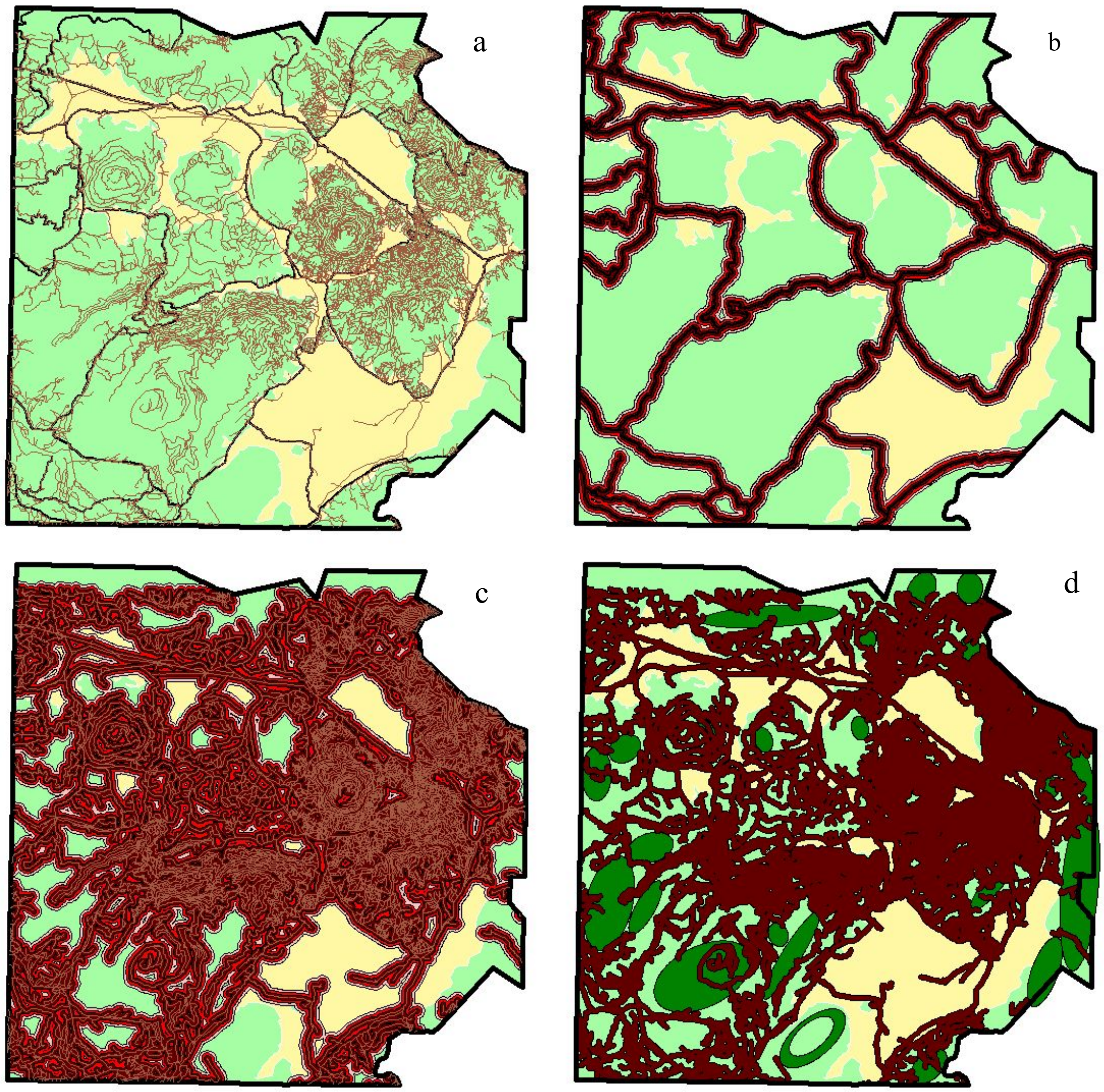



**Figure 31. Road networks within the Valles Caldera National Preserve, including areas falling within 100, 200 and 300m buffers around existing roads. (a) existing road network superimposed on areas of forest (green) and grassland (tan), with primary roads represented by thicker brown lines; (b) buffers around primary road system; (c) buffers around all other roads within the preserve; (d) forested area within 100m of any road superimposed on potential areas of virgin forest as defined by Muldavin and Tonne (2003).**

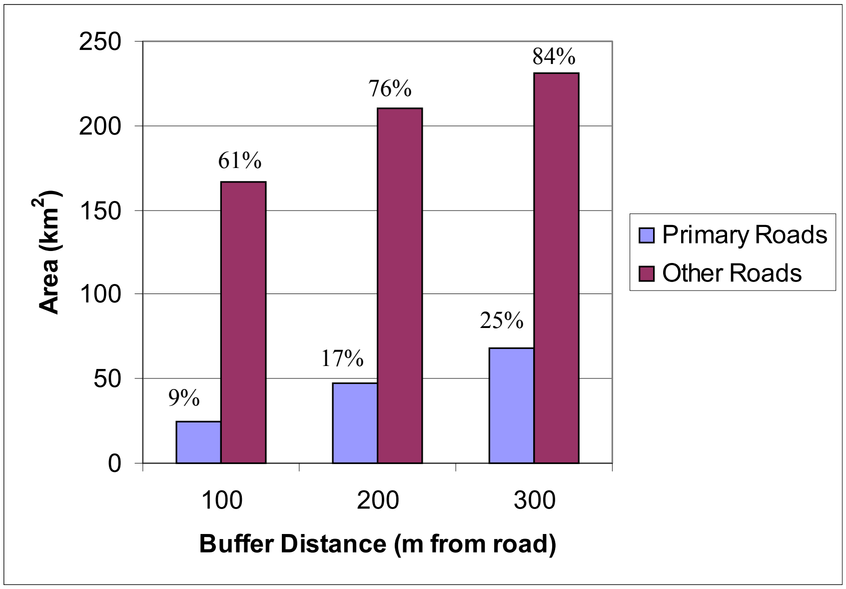



**Figure 32. Amount of forest area falling within 100, 200 and 300m buffers around existing roads. Percentages represent the % of total forest area within Valles Caldera National Preserve, based on a total forested area of ca. 2750 km$^2$.**

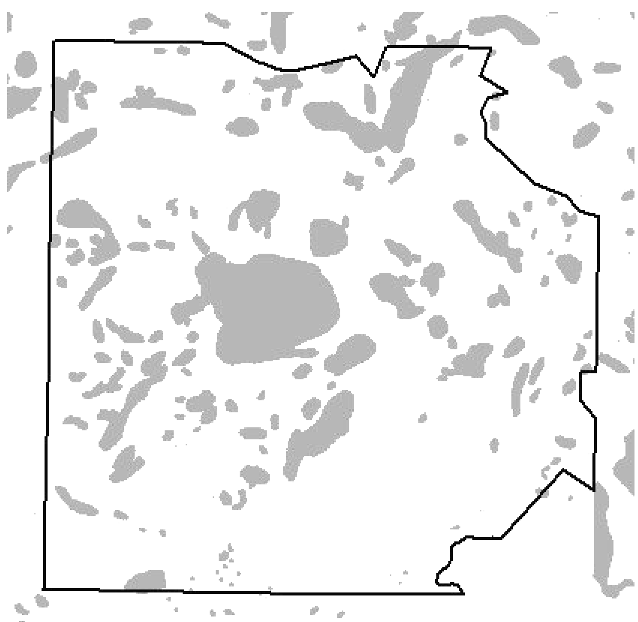


**Figure 33. Locations of some insect infestations identified in New Mexico State Forestry records, 1980-2000.**

**Other Disturbances**

Although the effects of pests and pathogens on VCNP forests have not been intensively studied, it is certain that these disturbance agents have historically played a role in ecosystem functioning and continue to do so today. NMSF records document the locations of some insect and mistletoe infestations, particularly when selective or patch cutting was being used to preclude the spread of these pests (Fig. 33).

Records from over half of the 1980-2000 timber sales mention blowdown (windthrown trees) in some capacity (NMSF records). This qualitative evidence suggests that tree mortality by windthrow is accentuated after logging, particularly along ridges and at the edge of clear-cuts (Alexander 1987). NMSF records indicate that even light selective logging in the caldera has increased windthrow potential in the past. Some sale records between 1980 and 2000 included windthrow harvest as part of the harvest plan.

# IMPLICATIONS FOR FOREST MANAGEMENT

## Stand Inventory

The integration of data from a range of sources allowed us to develop some preliminary spatial data on stand history and timber volumes at a relatively coarse-scale for this report. However, because accurate estimation of tree volume is an indispensable step in timber management planning, a finer scale stand-level assessment of forest resources is necessary to support forest management. As preparation for a timber sale, thinning project, damage appraisal, or restoration action, knowledge of stand characteristics is critical. Size (e.g., diameter, as a proxy for volume or age) and species are the fundamental variables of interest to both foresters and ecologists. Current estimates derived from the timber cruise are inadequate to address forest management objectives and inadequate to support forest monitoring and concurrent forest research.

A forthcoming vegetation map of VCNP (E. H. Muldavin, unpublished data), vegetation plots established through this research (analyzed in Koski et al., in review), and other forest research (P. Barney and S. Yool, unpublished data) will contribute to stand-level understanding of VCNP forests. With these data sets it will be possible to construct a mosaic of management units. These units of relatively homogeneous forest structure and harvest history (on the order of hundreds of acres in size) would form the basis of future forest management in the VCNP. Existing forest data—perhaps vegetation characteristics, logging history and effects, stand age, fuel types, economic value, and aesthetic concern—would be parsed by unit. Units could then be grouped by treatment prescription and prioritized according to treatment urgency.

## Thinning

Timber harvest has potential as a tool for promoting the multiple values of VCNP forests. One of the most urgent current management needs is for small diameter tree thinning. Thinning can be used to maintain stand health, reduce the probability of severe wildfires (Pollet and Omi 2002), improve timber quality for later harvest, improve the aesthetics of a stand, and improve habitat (Smith et al. 1997, Nyland 2002). Action should be implemented as stand-specific treatment prescriptions mindful of local forest structure and history. For example, periodic thinning around the Headquarters area may be preferable to other methods of stand structure maintenance. A combination of thinning and prescribed burning or other treatments may be preferred in other locations.

Financial profit from timber utilization is a major economic incentive for logging operations and could support the Congressional mandate of financial self-sufficiency (Valles Caldera Trust 2003). Economic benefit, however, should not supersede but rather complement concern for ecological sustainability. Scott (1998) compared various treatment methods in ponderosa pine forests in Montana (including "revenue production treatment") and found the "restoration treatment" alternative to be the best balance of ecological, social, and economic gains. Economic value per tree increases with diameter but large diameter tree thinning may be neither ecologically nor economically sustainable if carried to the extreme. Removal of many large, pre-settlement trees may actually increase fire risk (Agee 1997). Even if thinning is restricted to small diameter trees, increased fire severity may occur in the short-term, due largely to fine fuels generated by thinning procedures (Weatherspoon 1996). An effective approach would likely integrate multiple methods of restoration where possible, such as using prescribed burning or other fuel treatments after a thinning operation, to achieve management objectives (Weatherspoon 1996).

A US Forest Service's Community Forest Restoration Act (CFRA) project in the VCNP is one example of how targeted, stand-specific harvests can support management objectives. In 2001 the Pueblo of Jemez initiated a three year project under the US Forest Service's Community Forest Restoration Act (CFRA) to thin targeted stands totaling 113 ha including administrative facilities and public access routes "where movement of a catastrophic wildfire could be reasonably curtailed" (Pueblo of Jemez 2001). Targeting locations of high value or high spread potential maximized the efficiency of the work. Selective preservation of individual old, seed, wildlife, and survey trees help improve rather than degrade ecological resilience and integrity. Additional benefits include local employment opportunities and the use of salvaged timber for marketable wood products, increasing its attractiveness as an ecologically, economically, and socially sustainable endeavor (Pueblo of Jemez 2001).

Fuel reduction treatments directly address severe fire hazard by physically removing small diameter fuels that augment fire intensity and provide horizontal and vertical fuel continuity. Logging does not mirror the disturbance effects of frequent, low-severity wildfire. The proper harvesting system can, however, reduce the risk of ignition and spread of catastrophic wildfires as well as restore some of the structural characteristics of a pre-suppression forest.

Past small diameter wood production on the Baca was limited to firewood and Christmas trees (NMSF records, USFS 1993). Expansion into larger markets of small diameter products, such as those encouraged under the CFRA program, could help create an economically self-sufficient mechanism for conducting thinning operations. Using slash from thinning operations to prevent erosion along old logging roads is one example of how these operations could increase ecological sustainability. Aesthetics can be maintained through thinning by creating more visually desirable stands (Scott 1998), as is planned for History Grove, the old-growth ponderosa pine stand in Valle Grande near the Baca Ranch/VCNP headquarters.

**Old-Growth Stands and Preservation Areas**

Despite widespread harvest of the largest and oldest trees throughout the Jemez Mountains, the VCNP is home to some of the largest remaining old-growth stands in the mountain range (Allen 1989, Muldavin and Tonne 2003). One of the forest management goals of the Comprehensive Management Framework is protection and restoration of old-growth stands. The map of minimum harvest (Fig. 29) coarsely identifies areas where old-growth is most likely to occur. This map, coupled with the Muldavin and Tonne (2003) map, show a substantial level of landscape-scale agreement (Fig. 30), but they also demonstrate a lack of the fine, stand-scale knowledge necessary for effective timber management. Even if airphotos and NMSF records had been clear and complete enough to show all logging activity, not all uncut stands could be considered old-growth—this designation must be applied with reference to an individual stand's age and disturbance history.

Data limitations notwithstanding, there are still stands of outstanding ecological and social value that outweigh the economic benefit of large-tree harvest and warrant preservation. History Grove, near VCNP Headquarters in Valle Grande, is an excellent example of old-growth ponderosa pine forest and should be maintained as such. The Redondo Peak area, recognized for its spiritual, ecological, and aesthetic values (Valles Caldera Trust 2003), was also identified by Muldavin and Tonne (2003) as an area warranting preservation. It has escaped intensive harvest through its relative inaccessibility and low timber volume.

Even when old-growth stands have escaped logging, most have experienced alteration as a result of disturbance regime changes and currently require active management to maintain their structure and health. Restoration and maintenance of the structural patterns and ecological processes of old-growth forests might even involve small diameter thinning as a management prescription. The sharp negative exponential size distributions of trees displayed in the timber cruise distribution plots illustrate the high proportion of small (i.e., young) trees in all VCNP forests, not just unharvested stands (Figs. 24-25). In old-growth ponderosa pine forests under a natural disturbance regime, we would expect one or more orders of magnitude fewer trees and a shallower size distribution with a longer right-skewed tail, indicating the presence of a large proportion of large trees (Covington and Moore 1994). Stand treatments may be applied to restore forest structure to a more desirable state. Any management plan will require consideration not only of the current status of a particular stand, but its spatial context. Neighboring stands that have been harvested may affect uncut stands and the spatial nature of the GIS database allows managers to consider that when planning restoration actions.

**Road Network**

Logging roads are a secondary but significant legacy of timber harvests. Allen (1989) reports the total road length in the Jemez Mountains increased from 719 km in 1935 to 8,433 km in 1981. Many of the early roads constructed in the easily-accessible valles suffer from inadequate surface drainage, and New Mexico State Forestry records indicate that the methods used to encourage plant regeneration on logging roads often failed in the short term (e.g., in the Redondo Border area). Much of the extensive road network constructed in the 1960s to support intensive logging suffers from excessive drainage, creating erosion and surface water quality issues (Valles Caldera Trust 2003). Roads directly affect the landscape patterns, stand structure, and ecological functioning of forests and influence the regimes of disturbance processes. Logging roads may actually cause more and longer-lasting forest fragmentation than the actual clear-cut the roads supported (Tinker et al. 1998).

The existing roads also have potential benefits, in particular their value as access routes. Roads intended to support past timber harvests could continue to do so in the future. Roads have already proven their utility for access to grazing livestock, research sites, and recreational opportunities (Valles Caldera Trust 2003), and they can aid in fire management and control.. Most of the VCNP's roads, however, are not necessary to support these needs. Strategic roads that can support heavy traffic with minimal maintenance would be beneficial to the VCNP while most of the dense, spiraling dome roads could be retired. A forthcoming Valles Caldera Road Management Plan should address road maintenance, repair, and removal issues as well as the ecological restoration and damage mitigation of roads that have served their purpose.

**Other Disturbances**

Changes in composition and structure such as those described in the 1978-1998 comparison have implications not only for future harvests but for ecological disturbance regimes. Fuel loads and fuel continuity are enhanced by the growth of many short, small diameter trees, enabling more severe wildfire. Spruce budworm, bark beetle, and other pest outbreaks may increase in extent and/or severity where host species are abundant and competition-stressed. Swetnam and Lynch (1993), for example, report an increase in spruce budworm synchrony resulting from land use changes. Other factors such as the current southwestern drought accentuate the potential for disturbance regime shifts.

Qualitative evidence suggests windthrow potential increases after logging due to increased wind shear. Post-harvest windthrow is not uncommon in high elevation forests (i.e., spruce and fir) of the southern Rocky Mountains (Alexander 1987). Although it is economically advantageous to harvest windthrown trees, harvest plans should be carefully constructed so as to minimize windthrow potential since the leave trees (uncut mature trees left intact to provide seed sources for subsequent generations) hold long-term ecological and aesthetic value. Complete removal of the forest canopy does not encourage sustainability of forest productivity, economically or ecologically.

**Forest Fragmentation and Forest Management**

The ecological consequences of forest loss and fragmentation should be a major concern in the development and implementation of future logging plans within the preserve (Kupfer et al. 2004). While natural processes can cause habitat loss and the fragmentation of landscapes and habitats, human landscape modification is by far the most significant factor in many, if not most, forest ecosystems (Saunders et al. 1987; Groombridge 1992). The degree of deforestation and fragmentation varies widely as a function of the intensity of human activities and landscape history, and fragmentation by different activities (e.g., urban development vs. timber harvesting) or even between different forms of the same disturbance (e.g., dispersed vs. aggregated structural retention logging) may have very different ecological effects. Further, because organisms perceive and respond to the environment in different ways and at different spatial and temporal scales, the effects of fragmentation are impossible to generalize across all species; a gravel logging road that may be uncrossable for a small rodent may pose no restrictions to the movement of an avian species, for example.

Over the last decade, there has been a progressive shift away from the view of forest remnants as discrete habitat islands surrounded by areas of unsuitable land use toward one that recognizes the wide range of changes in habitat quality that take place in all components of the fragmented landscape (e.g., Malanson et al., in review). Cleared areas, for example, may be neither uniformly unsuitable nor serve as a fully-absorbing barrier to the dispersal of certain forest taxa while the remaining forest areas typically represent a gradient of conditions and habitat suitability. This realization underscores the importance of studying and understanding how human activities alter the flows of energy, matter and species across modified landscapes and thus affects a range of key community and ecosystem processes (e.g., succession, sediment fluxes, nutrient cycling, carbon sequestration). Further, it is clear that an understanding of the effects of fragmentation on biodiversity and ecosystem processes requires consideration of the ways in which fragmentation alters spatial configuration and habitat suitability in both non-affected forest areas and the surrounding modified matrix as well as the ways in which species respond to these changes (Lindenmayer and Franklin 2002).

Natural patchiness and spatial heterogeneity are common in forested landscapes due to natural disturbances, including gap phase dynamics (Watt 1947), fires (Arno 1980), and blowdowns (Veblen et al. 2001). Many species have even developed adaptations to the common disturbances in their ecosystems (e.g., Barton 1999). Evaluations of current fragmentation levels and effects (as well as any potential changes related to future forest harvests) thus need to address not only the question of how fragmented landscapes are, but also how different landscape structures are from some temporal frame of reference (e.g., pre-European settlement conditions). The relationship between natural heterogeneity and fragmentation has usually been addressed within the context of whether human disturbances such as logging can be designed to replicate or mirror the natural disturbance regime, often with a goal of reducing the total impact of the treatment. However, human disturbance regimes will never be exact replicates of natural disturbances; logging, for instance, differs from most natural disturbances in its frequency and regularity, the species it favors, its effects on ecosystem function, the complexity of the remaining forest structure, and the spatial distribution of structural attributes (e.g., Mladenoff et al. 1993; McCarthy and Burgman 1995). Further, as traditionally practiced, existing silvicultural systems do not incorporate the landscape-level complexity that is characteristic of natural disturbance regimes (Franklin et al. 1997). Rather than trying to emulate natural disturbance regimes, the objective, argue Lindenmayer and Franklin (2002), should be to use information on natural disturbances to aid in the development of silvicultural systems that encourage the maintenance of biodiversity in the affected landscapes, including not only uncut remnants but also the modified matrix.

Hunter (1993) has suggested three properties of natural disturbance regimes that can guide management plans: frequency, spatial pattern, and levels of biotic legacies. Buskirk et al. (2000) also suggest that aspects of human fragmentation can be evaluated with respect to natural heterogeneity on the basis of: 1) novelty, which relates to how often a similar perturbation has been experienced over the evolutionary history of a forest community, and 2) distinctness, meaning how different a perturbed site is from the structure and function of the unaffected area around it. The importance of spatial heterogeneity within remnants and the matrix has significant implications on the design and implementation of new silvicultural systems. Different systems (e.g., clear cutting, shelterwood cutting, selection cutting) create very different forest patterns across the landscape and may be expected to have different ecological consequences. Even a cursory examination of logged areas within VCNP shows the influence of different logging regimes on forest recovery, although a detailed examination of logging effects (e.g., a contrast of different harvesting systems on soil properties and subsequent forest succession) has not been conducted. Systems that reduce the impact of some fragmentation effects may increase the effects of another (e.g., selection cutting may result in less area effect but increase edge effects through the creation of a larger transportation network).

Of particular recent interest has been the use of structural retention harvesting strategies, which involve retaining structures from the original stand at the time of harvest (Franklin et al. 1997). Structural retention may make substantial contributions to biodiversity conservation by: 1) maintaining biota on a harvested site by conserving essential habitat (e.g., snags or logs), 2) adding structural heterogeneity to the stand and allowing organisms to return more quickly, 3) modifying post-harvest conditions (e.g., microclimate), making it more suitable for certain species, 4) facilitating movement of species through the harvested areas, and 5) buffering protected zones such as riparian areas within the matrix (Lindenmayer and Franklin 2002). Retention can thus be used to increase the habitat quality of the logged area, facilitate movement across the landscape, and limit the number of hard edges in a landscape (potentially reducing the importance of the edge effect). The extent to which these functions are enhanced, however, depends on what structures are retained, how much is retained, and in what spatial pattern the retentions are left. Perhaps one of the best models for such research is the Demonstration of Ecosystem Management Options (DEMO) Study, an ongoing large-scale experiment on structural retention harvests in Pacific Northwestern forests (http://www.cfr.washington.edu/Research.demo/index.htm).

With respect to forest fragmentation, an extensive literature has been developed over the last thirty years from which we can draw to create guiding principles for developing comprehensive forest management plans at VCNP that recognize the effects of fragmentation on forest biodiversity and ecological processes. We use the objectives and principles for developing comprehensive plans for forest biodiversity conservation that are presented by Lindenmayer and Franklin (2002) as our basis for three principles more specifically associated with forest fragmentation.

*Principle 1: Promote connectivity using a variety of approaches.* By altering the degree of structural and functional connectivity in a landscape, deforestation and fragmentation influence population dynamics and persistence in landscapes in a range of ways. The effects of such changes are interactive and non-linear such that the degree of functional connectivity in a landscape is a function of not only inter-patch distance or other measures of isolation but also the degree of forest loss. Because connectivity is the ease with which species move across a landscape, it can be improved in a range of ways, including not only the creation or reservation of habitat corridors to maintain structural connectivity but also the implementation of stepping stones and other features that help to facilitate the movement of species across the landscape (e.g., Collingham and Huntley 2000). In many landscapes, managing the matrix to increase its suitability as habitat and increase its permeability to movement may be one of the best options for increasing connectivity because connectivity is fundamentally controlled by the degree to which the matrix is hostile or habitable (Wiens 1997, Kupfer et al., in press). A matrix-based approach may especially benefit poorly dispersing but more competitive species that are at a disadvantage in fragmented landscapes (e.g., Malanson 2002). These concepts are directly relevant to the development and implementation of silvicultural systems that can be used to help maintain connectivity in logged areas while still meeting pre-defined harvest goals.

*Principle 2: Maintain stand structural complexity and landscape heterogeneity.* Two of the primary effects of logging are reductions in the structural complexity of stands and alterations of the landscape's natural heterogeneity. Structural complexity pertains to: 1) the variety of stand structural attributes that are present in natural forests in an area (e.g., the stand age and size class structure, presence of standing snags and downed woody debris, variation in canopy gap structure, vertical heterogeneity associated with different canopy layers), and 2) how these features are arranged across a landscape (i.e., spatial heterogeneity). Maintaining such structures can be valuable in four ways (Lindenmayer and Franklin 2002): 1) it may allow organisms to persist in logged areas from which they would otherwise be eliminated; 2) it may allow logged and regenerated stands to more quickly return to suitable habitat; 3) it may enhance the dispersal of animal species through the logged matrix and also enhance plant dispersal by serving as seed sources; and 4) it may be essential to providing within-stand habitat heterogeneity that is needed for some species. Perhaps even more so than with connectivity, research on how alternative harvesting regimes can be used to maintain vertical (structural) and horizontal (spatial) heterogeneity within the logged matrix are needed. Further, because structural and spatial heterogeneity inherently vary among forest types and ecoregions, ecologists can help to inform forest management plans by documenting conditions in a range of forest types that have a range of disturbance histories (e.g., to help understand the effects of biotic legacies).

*Principle 3. Embrace risk spreading and recognize the importance of different conservation strategies at different spatial scales.* Lindenmayer and Franklin (2002) note several advantages to adopting management techniques associated with the principles above, especially when management plans are implemented at multiple scales. First, identifying how changes in forest extent or connectivity associated with fragmentation affect even a single species can be a monumental task (see the literature on the northern spotted owl, as an example) so the adoption of multiple strategies at multiple scales increases the likeliness that suitable habitat, connectivity, heterogeneity, and stand complexity will be provided in at least some parts of the landscape. Second, if one strategy is found to be ineffective (e.g., the establishment of wildlife corridors), others such as structural retention will be in place that might help to protect important elements of the landscape or help to perform the functions intended by the unsuccessful strategy. Using a multi-faceted approach thus reduces the over-reliance on any single strategy that may be found to be of limited value.

As Lindenmayer and Franklin (2002) admit, this risk-spreading approach (which focuses on ensuring a range of conditions at all spatial scales) contrasts fundamentally with the norm of strict production forestry, which tries to limit heterogeneity at both the stand and landscape level, posing potential hurdles to the acceptance and implementation of such an approach. Investment in some strategies may also preclude the implementation of other alternatives – for example, money spent (or revenues forgone) to protect habitat corridors may be money that can’t be spent on protecting other features. Research that continues to clarify the importance of fragmentation at various levels of deforestation can help to inform managers when strategies to maintain connectivity may be especially important. Further, research on the importance of habitat quality (e.g., of the matrix or corridors) may help to show the value of sometimes improving the quality of existing habitat over setting aside other areas.

Recent attempts to address the effects of fragmentation in forest management plans and incorporate some of these principles have been made. Cissell et al. (1999), for example, present the development of management plans in western Oregon based on natural disturbance regimes in the area. Their approach involved: 1) stratifying the area based on the dominant fire regimes, 2) identifying special reserve areas, and 3) developing silvicultural prescriptions for each of the non-reserve areas based on the historic patterns of disturbance. Projects in the Chequamegon National Forest in Wisconsin provide another example (Parker 1997). Three alternative management plans were proposed and analyzed that: 1) emphasized the creation of large units of habitat for plant and animal species, 2) emphasized human recreation and creating large habitat units for nongame wildlife species, and 3) emphasized harvesting timber in small (<15 ha) clear cuts.

## CONCLUSIONS

The landscape legacies of logging have significant implications for current and future sustainable management of VCNP forests. The VCNP is today a mixture of high value stands and degraded but recovering stands. High value forest stands include some selectively harvested and unharvested stands that have maintained high ecological, economic, and aesthetic value. Heavily logged and clear-cut stands may still be in the early stages of vegetative response, but their timber volume and ecological value are increasing. This research addresses the need to understand these legacies by documenting the occurrence of logging on in the VCNP. This analysis supports several management recommendations.

Small diameter thinning targeted at vulnerable locations can be a beneficial treatment for reducing stand density. Such treatment reduces fuel connectivity thereby vulnerability to stand-replacing fire. Once stands are thinned, reintroduction of low severity fire is a viable management option. Thinning dense understories of shade-tolerant trees may also reduce vulnerability to insect outbreaks. Small diameter thinning should not greatly increase windthrow potential.

Old growth stands are beginning to succumb to the cumulative effects of human action (e.g., fire exclusion which increases competitive stress) and natural events (e.g., insect and drought-induced stress). Additional management in the form of small diameter thinning can mitigate some of these effects and restore resilience and integrity to old growth stands. Ecologically-based silviculture has potential as an applied ecological tool to support the multiple ecological, economic, and social values of the VCNP's mission. However, the effects of logging on the natural systems of the VCNP are, to a large degree, yet to be determined.

Additional knowledge of stand-level forest structure and history is required to assist decision-making. Currently available data sets are too coarse to inform decisions about local treatment options. A new forest inventory would assess stand structure and history and be comparable to other ecological and silvicultural VCNP data sets. Stand-specific treatment prescriptions should be developed based upon this stand inventory database. Subsequent management action should be accompanied by ongoing monitoring and research.

This research synthesizes information about the logging history of the Valles Caldera National Preserve into a single narrative. We describe data sets relevant to the history of logging and its potential ecological effects are described and present the current estimate of the VCNP timber resource. Integration and analysis of these data sets identifies patterns and potential ecological impacts. This work and future research on logging and its effects will provides an important historical context for management decisions in the VCNP.

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