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USE OF HISTORIC AERIAL PHOTOGRAPHY TO STUDY VEGETATION CHANGE IN THE NEGRITO CREEK WATERSHED, SOUTHWESTERN NEW MEXICO

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ABSTRACT—Aerial photographs from 1935 and 1991 were used in an analysis of vegetation change in the Negrito Creek watershed of southwestern New Mexico. Vegetation maps interpreted from aerial photographs were digitized and analyzed in a Geographic Information System to derive a transition matrix used to quantify past changes and project potential future changes. Vegetation-change data were compared with land-use and climate histories to provide background information for land-management activities. Photographs demonstrated a significant shift from open-structured vegetation in 1935 to high canopy-cover woodlands and forests in 1991. In 1935, less than 50% of the study area consisted of woodlands and forests with canopy cover greater than 40%; by 1991, that figure had increased to over 80%. Dramatic changes occurred on gently sloping mesas where relatively dense stands of *Juniperus deppeana* replaced former grasslands and juniper savannas, and on mountain slopes where increases in *Pinus ponderosa* resulted in the loss of former pine savannas and open montane coniferous forests. During the 56-year period, grasslands and juniper savannas decreased from a combined 15% of the study area to less than 2%. If past trends continue, by the year 2047 less than 9% of the study area will consist of open woodlands and forests; grasslands and savannas will account for less than 0.5%. Historic changes appear to have resulted from the combined effects of livestock grazing, fire suppression, and climatic fluctuations, and have several implications for management.

RESUMEN—Se usaron fotografías aéreas de 1935 a 1991 en un análisis de los cambios de vegetación en la cuenca "Negrito Creek" del suroeste de Nuevo México. Los mapas de vegetación interpretados de las fotografías aéreas fueron digitalizados y analizados en un Sistema de Información Geográfica (GIS) para derivar una matriz transisional usada para cuantificar los cambios en el pasado y para proyectar los posibles cambios en el futuro. Los datos del cambio de la vegetación fueron comparados con el uso de la tierra y el registro del clima para obtener información básica de las actividades del manejo de la tierra. Las fotografías demostraron un cambio significativo de vegetación rala en 1935 a montes y bosques con una cubierta de copas altas en 1991. En 1935, menos del 50% del área estudiada consistía de montes y bosques con cubierta de copa alta de más del 40%; para 1991, esa figura se había incrementado a más del 80%. Los dramáticos cambios ocurrían en las mesas de suaves pendientes donde relativamente densos grupos de *Juniperus deppeana* reemplazaron los antigüos pastos y las savanas de enebro, y en las pendientes de las montañas donde los aumentos de *Pinus ponderosa* provocaron la pérdida de las antigüas savanas de pino y bosques de coníferas de monte abierto. Durante el período de los 56 años, la combinación de los pastos y las savanas de enebro disminuyó del 15% del área de estudio a menos del 2%. Si las tendencias del pasado continúan, para el año 2047 menos del 9% del área de estudio consistirá de montes y bosques abiertos; los pastos y las savanas serán menos de 0.5%. Los cambios históricos parecen ser el resultado de los efectos combinados de pastoreo de ganado, supresión de fuego, y fluctuaciones climáticas, y tienen varias implicaciones para el manejo de la tierra.

Repeat photography is a technique that has been widely applied to analyses of vegetation change (Hastings and Turner, 1965; Rogers, 1982; Veblen and Lorenz, 1991). However, compared to the large number of studies that have employed ground photographs (Rogers et al., 1984; Hart and Laycock, 1996), studies based on the application of aerial photographs are relatively few (Archer et al., 1988; Allen, 1989; Bahre, 1991; Savage, 1991; Scanlan and Archer, 1991; Bahre and Shelton, 1993). This is surprising because vertical aerial photographs are well-suited to quantitative analyses, and the earliest good-quality photographs predate digital imagery (available since the early 1970s) by 30 to 40 years. In the southwestern United States, the earliest available aerial photographs are those commissioned by the United States Department of Agriculture [Natural Resources Conservation Service [formerly Soil Conservation Service] (SCS)] for much of the region during the mid-1930s drought. These photographs, obtainable from local SCS offices or from the National Archive in Washington, D.C., can be compared with modern photographs or with multi-year photo sequences for purposes of basic research on spatiotemporal patterns of vegetation dynamics and applied research related to particular land-management issues.

In this paper, aerial photographs from 1935 and 1991 were used to study vegetation change in a portion of the Negrito Creek watershed in southwestern New Mexico. Objectives of the study were to quantify patterns of historic vegetation change and to assess the relative effects of climate and land-use factors in order to provide background information for land-management activities planned for the watershed and surrounding region.

METHODS AND MATERIALS—*Study Area*—The 52,000-ha Negrito Creek watershed lies on multiple-use lands of the Gila National Forest east of the town of Reserve, in Catron Co., New Mexico (Fig. 1). This region lies at the southeastern end of the Mogollon Rim, a broadly elevated escarpment that trends southeastward from north-central Arizona to southwestern New Mexico (Hunt, 1974). The focus of this study is the 9,071-ha northwestern corner of the watershed, approximately centered at 33°40′N, 108°40′W. Elevation in the study area ranges from 1,750 m where Negrito Creek joins the Tularosa River, to 2,983 m at the top of Eagle Peak. Average annual precipitation in the town of Reserve (elevation 1,778 m, located 4 km northwest of the study area) is 39 cm; about 45% of this occurs as a result of convective thunderstorms from July through September (United States Department of Commerce, 1916–1992). Based on 77 years of record (1916–1992), about 62% of all years receive less than the average amount of precipitation (United States Department of Commerce, 1916–1992).

Major vegetation types in the study area are montane coniferous forest, coniferous woodland, and montane grassland (Dick-Peddie, 1993). Ponderosa pine (*Pinus ponderosa* Laws) dominates coniferous forests at lower elevations. With increasing elevation on the slopes of Eagle Peak, lower montane forests grade into upper montane mixed conifer stands consisting of Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco], white fir [*Abies concolor* (Gord. and Glend.) Lindl.] and southwestern white pine (*Pinus strobiformis* Engelm.). Dominant species in coniferous woodlands are alligator juniper (*Juniperus deppeana* Steud.) and Colorado piñon pine (*Pinus edulis* Engelm.). Throughout the study area, considerable intermixing of forest and woodland vegetation occurs as a consequence of aspect-related microhabitat interspersion. Thus alligator junipers occur on south-facing slopes in mixed-conifer stands at elevations over 2,680 m. Likewise, ponderosa pine occurs at varying levels of abundance in woodlands numerically dominated by junipers and piñons, although it often is restricted to drainages at lower elevations. Montane grasslands generally are inclusions within the woodland and forest types and currently constitute only a minor component of the overall landscape; more extensive montane grasslands occur elsewhere in the Negrito watershed. In woodlands and montane grasslands throughout the study area, the dominant herbaceous species is blue grama [*Bouteloua gracilis* (H.B.K.) Lag.].

Livestock ranching has long been important in the region surrounding the study area. The San Francisco River Valley west of the study area was first settled by sheep ranchers in the 1860s and 1870s. Cooper (1960) cited early reports indicating that during the years 1875 to 1882 up to 60,000 sheep were grazed annually on what currently is the Gila National Forest. General Land Office surveyors recorded the presence of large herds of livestock and abundant feral cattle in the Negrito watershed when they first surveyed the area in 1890 and 1891 (Miller, 1994). Rixon (1905) reported that large areas of the newly established Gila River Forest Reserve were intensively grazed when he surveyed the area in 1903. Today, ranching remains an important source of employment income for residents of Catron Co.

Photo Interpretation—Major structural changes in vegetation were determined by comparing vegetation maps interpreted from aerial photographs taken in 1935 (black and white, scale 1:31,680) and 1991 (true color, scale 1:15,840). Vegetation was mapped using nine cover-class categories defined on the basis of physiognomy and tree canopy cover (Table 1). Areas were classified as grasslands if no trees were apparent in the photographs, or if scattered trees within a grassland matrix had less than 5% canopy cover. Woodlands were defined as those areas dominated by alligator juniper and/or Colorado pi-

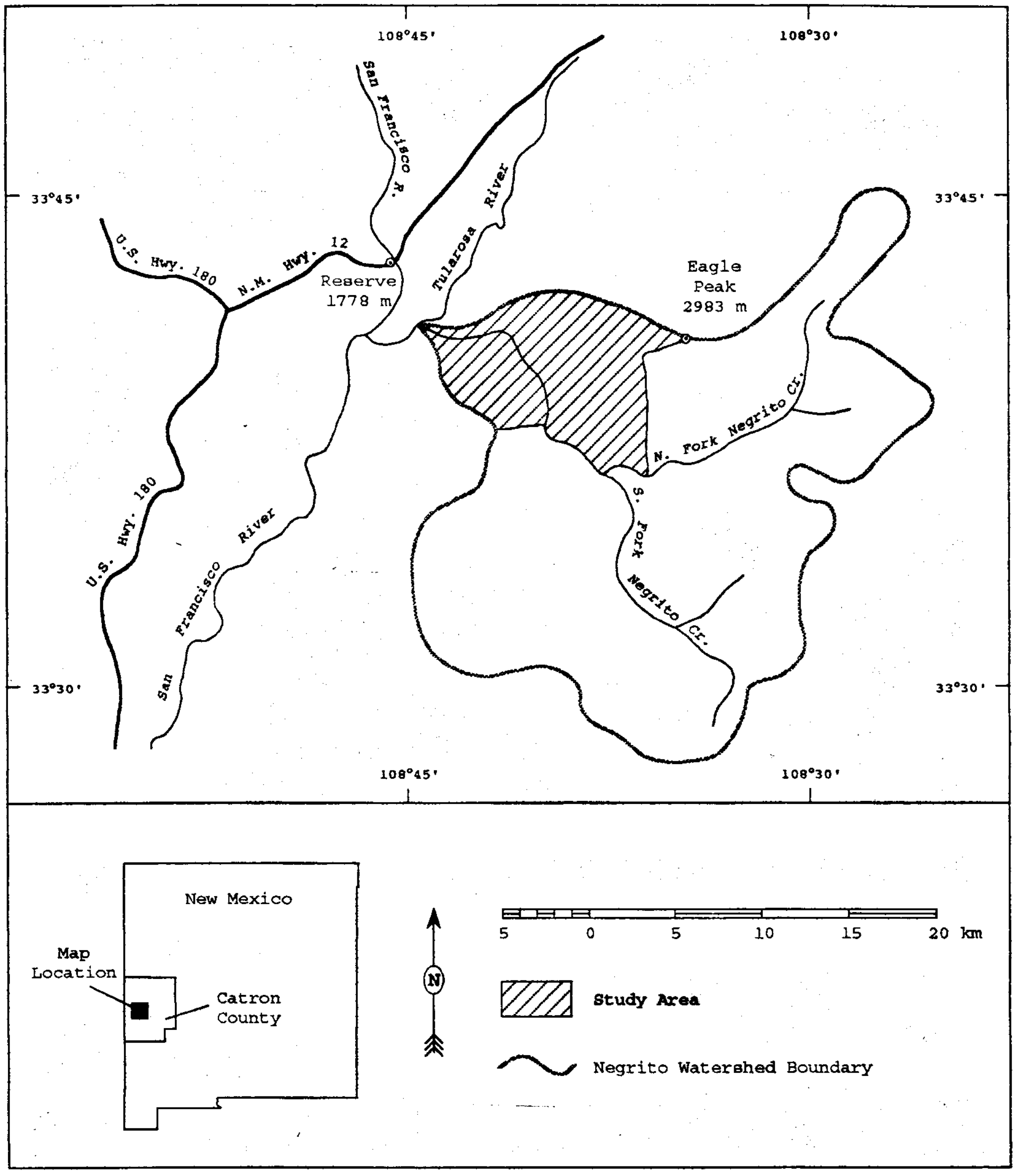

FIG. 1—Map of the Negrito Creek watershed and study area, Catron Co., southwestern New Mexico.

ñon with ponderosa pine contributing less than one-third of the total canopy cover. Forests were defined as those areas where ponderosa pine was dominant (contributing at least one-third of total canopy cover when occurring with alligator juniper and/or Colorado piñon), or where upper-montane coniferous species such as Douglas fir were dominant. For simplification, riparian areas along Negrito Creek that were dominated by narrowleaf cottonwood (*Populus angustifolia* James) also were included in the forest category. Canopy-cover classes within the woodland and forest types were estimated ocularly using a standard Forest Service key. Minimum map-unit dimensions were 2 ha (minimum size of forest stands mapped by the Forest Service) and 100 m in width.

Cover-class categories were determined with the aid of a binocular mirror stereoscope and delineated by drawing polygons on acetate sheets covering

TABLE 1—Physiognomic type, tree canopy cover (%), and code designator associated with each of the nine cover-class categories used in the interpretation and analysis of 1935 and 1991 aerial photographs, Negrito study area, southwestern New Mexico.

Physiognomic type	Tree canopy cover (%)	Code	Cover-class category
Grassland	<5	G	Montane grassland
Woodland	5–9	W1	Juniper savanna
	10–39	W2	Open piñon-juniper woodland
	40–69	W3	Moderately dense piñon-juniper woodland
	70–100	W4	Closed piñon-juniper woodland
Forest	5–9	F1	Ponderosa pine savanna
	10–39	F2	Open montane coniferous forest
	40–69	F3	Moderately dense montane coniferous forest
	70–100	F4	Closed montane coniferous forest

the photographs. Polygons were transferred from photographs to mylar overlays covering 1:24,000 topographic maps of the study area by matching stereoscopically viewed landscape features in photographs with corresponding features represented on topographic maps. Field visits were made prior to and during photo interpretation for training purposes, and additional field visits were made following photo interpretation for verification.

GIS Analyses—To facilitate analyses, vegetation maps were digitized and incorporated into a raster-based Geographic Information System (GIS) using a grid-cell size of 0.5 ha. The two vegetation maps were overlaid in the GIS, and all grid cells in the study area were cross tabulated according to their 1935 and 1991 cover-class categories. The resulting transition matrix quantified changes among cover-class categories during the 56-year photograph span. Transition probabilities derived from this matrix also were used in a Markovian vegetation-change model (Usher, 1992) to project future vegetation transitions in the study area. Inherent in this probabilistic approach is the simplifying assumption that transitions among cover-class categories during the succeeding 56-year period from 1991 to 2047 will occur in proportion to those that occurred between 1935 and 1991. A weakness of this form of model is that it does not consider spatial relationships among the model's various states (i.e., cover-class categories). Nevertheless, Markovian models can provide useful first approximations to simple questions regarding future vegetation change (Usher, 1992).

As a measure of landscape-scale change, GIS data were used to calculate indices of landscape diversity for the years 1935 and 1991. Several measures have been used by others to assess landscape pattern and diversity (Romme, 1982; O'Neill et al., 1988). The Shannon-Wiener diversity index (Pielou, 1975) was used in this study because of its relative simplicity and widespread application. When applied to landscapes, the index (H') incorporates the number of distinct cover-class categories present (i.e., richness) with the relative abundance of each category (i.e., evenness) into a single measure.

Fire, Grazing, and Climate History—Studies of historic vegetation change in the southwestern United States have emphasized the effects of three principal factors–fire, livestock grazing, and climate (Hastings and Turner, 1965; Allen, 1989; Bahre, 1991; Savage, 1991; Archer, 1994). For this study, data on fire occurrence and livestock grazing were compiled from Forest Service records. Fire data available for the years 1949 to 1992 consisted of approximate fire locations plotted on maps by year and categorized by size and likely ignition source. The cumulative amount of the study area burned during the 43-year period was estimated by multiplying the number of fires in each size-class category by the class midpoint. Fire-history studies conducted in the Southwest (Swetnam and Dieterich, 1985; Allen, 1989) typically present results in terms of a fire interval—that is, the number of years between two successive fires in a specific area (Romme, 1980). For comparative purposes, stand-level fire intervals were estimated by excluding all fires smaller than 0.1 ha and subdividing the study area into 139 65-ha (160-acre) quarter-sections comparable in size to sample stands used in fire-history studies. Forest Service grazing allotment records available for years 1929 to 1992 were used to estimate trends in cattle stocking rates (numbers of cattle per 1,000 ha of grazing land per year).

Climatic data consisted of precipitation records from the town of Reserve (United States Department of Commerce, 1916–1992) and a tree-ring chronology provided by the University of Arizona's Laboratory of Tree-Ring Research. Annual precipitation in Reserve was defined as the total amount received from the beginning of November through the end of the following October. This adjustment prevented winter precipitation (which is critical for

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TABLE 2—Number of hectares (ha) and proportion of the study area (%) within each cover-class category in 1935 and 1991, the percent change in each category between the two years, and corresponding values projected for the year 2047, Negrito Creek study area, southwestern New Mexico. Projections for the year 2047 are based on category transitions that occurred between 1935 and 1991.

	Actual					Projected		
	1935		1991			2047		
Cover-class category	Ha	Proportion of study area (%)	Ha	Proportion of study area (%)	Change (%) 1935 to 1991	Ha	Proportion of study area (%)	Change (%) 1991 to 2047
G	926.3	10.2	92.0	1.0	−90.1	22.2	0.2	−75.9
W1	433.4	4.8	66.0	0.7	−84.8	6.8	0.1	−89.7
W2	1,684.6	18.6	1,248.8	13.8	−25.9	679.3	7.5	−45.6
W3	2,539.7	28.0	3,120.5	34.4	22.9	2,763.2	30.5	−11.5
W4	209.0	2.3	606.9	6.7	190.4	930.0	10.3	53.2
F1	146.5	1.6	13.5	0.1	−90.8	1.7	0.0	−87.4
F2	1,552.6	17.1	225.5	2.5	−85.5	103.4	1.1	−54.1
F3	1,393.1	15.4	2,827.7	31.2	103.0	2,798.7	30.9	−1.0
F4	185.5	2.0	869.8	9.6	368.9	1,766.4	19.5	103.1

spring and early summer tree growth) from being split between two different calendar years (Fritts, 1965) and allowed a better comparison with the tree-ring chronology. The chronology was derived from increment cores taken in 1967 from approximately 10 arid-site Douglas fir trees on the west side of Rainy Mesa, which is located within the Negrito Creek watershed less than 4 km south of the study area. Ring-width measurements were processed by the Tree-Ring Laboratory to remove the effects of age-dependent differences in growth rate, and the data were standardized to provide a single time series of annual ring-growth indices from the year 1600 through 1967. Fritts (1965) found that ring-width variations in arid-site Douglas fir trees were best explained by fluctuating levels of precipitation during the spring and winter immediately preceding the spring-summer growing season. High spring temperatures also affected ring widths, but to a minor degree. In the Rainy Mesa chronology, index values less than 1.00 indicate years when the climate was dry and warm (below-average growing conditions), and index values greater than 1.00 represent years when the climate was wet and cool (above-average growing conditions).

RESULTS AND DISCUSSION—*Vegetation Changes*—Major structural changes in vegetation occurred in the study area between 1935 and 1991 (Table 2). Between the two photograph years, grasslands (G), juniper, and pine savannas (W1, F1), and open woodlands and forests (W2, F2) all decreased in total area. Combined, these relatively low-cover categories decreased from over 50% of the landscape in 1935 to about 18% in 1991. Over the same period, there were corresponding increases in moderately dense and closed woodlands and forests (W3, W4, F3, F4; Table 2).

Losses of mesa-top montane grasslands (G) and juniper savannas (W1) primarily were due to replacement by juniper-dominated woodlands (Table 3). Over 69% of 1935 mesa-top grasslands (G) were converted to open (W2) or moderately dense woodlands (W3) by 1991. The substantial replacement of grasslands by moderately dense woodlands strongly suggests that small junipers already were present in some grasslands in 1935, although they were not distinguishable on aerial photographs. Of the mesa-top juniper savannas (W1) in 1935, over 80% were converted to open (W2) or moderately dense woodlands (W3) by 1991.

This is the first study to quantify the degree to which alligator junipers have increased in former montane grasslands and savannas in the Southwest, although anecdotal accounts exist (Leopold, 1924). In the Jemez Mountains of northern New Mexico, Allen (1989) found that open montane grasslands decreased by 55% between 1935 and 1981, but invasion of those higher-elevation grasslands primarily was by ponderosa pine and Douglas fir. In the Chuska Mountains of northern Arizona and New Mexico, a 30% reduction in the extent of

TABLE 3—Number (and percent) of hectares in the study area cross-tabulated according to their cover-class categories in 1935 and 1991 aerial photographs, Negrito Creek watershed, southwestern New Mexico. Percent values represent transition probabilities for shifts between corresponding cover classes.

Cover-class category in 1935	Cover-class category in year 1991									Total ha in year 1935
	G	W1	W2	W3	W4	F1	F2	F3	F4	
G	69.0	53.0	424.4	216.9	0.0	8.0	28.5	114.5	12.0	926.3
	(7.4)	(5.7)	(45.8)	(23.4)	(0.0)	(0.9)	(3.1)	(12.4)	(1.3)	(100.0)
W1	0.0	4.5	90.0	273.4	6.0	0.0	10.0	49.5	0.0	433.4
	(0.0)	(1.0)	(20.8)	(63.1)	(1.4)	(0.0)	(2.3)	(11.4)	(0.0)	(100.0)
W2	12.0	0.0	447.4	824.8	93.5	0.0	20.5	250.4	36.0	1,684.6
	(0.7)	(0.0)	(26.6)	(49.0)	(5.6)	(0.0)	(1.2)	(14.9)	(2.1)	(100.0)
W3	2.5	0.0	142.5	1,234.1	299.4	0.0	15.0	587.3	258.9	2,539.7
	(0.1)	(0.0)	(5.6)	(48.6)	(11.8)	(0.0)	(0.6)	(23.1)	(10.2)	(100.0)
W4	0.0	0.0	0.0	19.5	148.0	0.0	0.0	10.0	31.5	209.0
	(0.0)	(0.0)	(0.0)	(9.3)	(70.8)	(0.0)	(0.0)	(4.8)	(15.1)	(100.0)
F1	6.0	4.5	27.0	13.5	0.0	0.0	27.0	28.5	40.0	146.5
	(4.1)	(3.1)	(18.4)	(9.2)	(0.0)	(0.0)	(18.4)	(19.5)	(27.3)	(100.0)
F2	1.5	3.5	65.5	306.9	32.0	5.5	101.5	982.2	54.0	1,552.6
	(0.1)	(0.2)	(4.2)	(19.8)	(2.1)	(0.4)	(6.5)	(63.3)	(3.5)	(100.0)
F3	1.0	0.5	52.0	231.4	28.0	0.0	23.0	781.3	275.9	1,393.1
	(0.1)	(0.)	(3.7)	(16.6)	(2.0)	(0.0)	(1.7)	(56.1)	(19.8)	(100.0)
F4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.0	161.5	185.5
	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(0.0)	(12.9)	(87.1)	(100.0)
Total ha in year 1991	92.0	66.0	1,248.8	3,120.5	606.9	13.5	225.5	2,827.7	869.8	9,070.7

Total ha in year 1991	92.0	66.0	1,248.8	3,120.5	606.9	13.5	225.5	2,827.7	869.8	9,070.7

montane meadows between 1935 and 1979 was associated with an increase in ponderosa pine populations (Savage, 1991). Numerous studies have documented and analyzed twentieth-century increases in populations of other species of *Juniperus* throughout western North America (Johnsen, 1962; Blackburn and Tueller, 1970; Burkhardt and Tisdale, 1976; Davis and Turner, 1986).

Significant increases in tree canopy cover also occurred in previously existing forests and woodlands between 1935 and 1991. Most of the area categorized as ponderosa pine savanna (F1) in 1935 shifted to a higher canopy-cover forest category in 1991. Likewise, more than half of area categorized as open woodlands (W2) in 1935 converted to moderately dense (W3) or closed-canopy woodlands (W4) by 1991. In terms of total area, the single largest transition that occurred over the 56-year period was the change from open (F2) to moderately dense montane coniferous forests (F3). Almost 20% of the area categorized as moderately dense forests (F3) in 1935 became closed-canopy forests (F4) by 1991. Most of the increases in forest cover occurred on the upper slopes of Eagle Peak, on east-facing slopes above Negrito Creek, and in canyons throughout the study area.

Overall, the percentage of the Negrito study area covered by relatively high (≥40%) canopy-cover categories increased from less than 50 in 1935 to over 80 in 1991. This trend is consistent with other reports of increased cover or density of southwestern forests and woodlands since the late nineteenth and early twentieth centuries (e.g., Arnold, 1950; Cooper, 1960; Madany and West, 1983; Allen, 1989). For example, Savage (1991) reported an increase (14 to 63%) in the coverage of moderately dense and dense forests of her study area in the Chuska Mountains between 1935 and 1979. Vegetation descriptions in field notes of nineteenth-century government surveyors also suggest that Negrito forests and woodlands structurally were much more open in the 1890s than they are today (Miller, 1994).

Data collected in stand-structure plots indicated that piñon is increasing rapidly in current mesa-top woodlands within the Negrito study area and likely will become the eventual dominant (Miller, 1994). Piñon was more abundant and had greater reproduction than alligator juniper in mature woodlands throughout the study area (M. E. Miller, pers. obser.). These findings are consistent with Evans' (1988) observation that junipers generally invade adjacent communities first and then are replaced over time by piñons, especially on relatively mesic sites. In mature piñon-juniper woodlands on the margins of the San Augustin Plains northeast of the study area, Potter (1957) found that the density and cover of Colorado piñon were twice those of alligator juniper, and that piñon saplings were more abundant than juniper saplings by a factor of seven. Of the eight distinct *P. edulis-J. deppeana* habitat types found by Hill et al. (1992) in the Gila National Forest, piñon was strongly dominant over juniper in seven.

In addition to the conversion of grasslands to woodlands, other transitions among major physiognomic types occurred during the 56-year period (Table 3). Some grasslands and woodlands were reclassified as forest types in 1991 photographs; many of these transitions occurred in canyons and may represent the localized migration of ponderosa pine upslope from canyon bottoms. Conversions of high canopy-cover woodlands to high canopy-cover forests also occurred, primarily on north-facing slopes and upper canyon reaches where ponderosa pine increased in abundance relative to woodland tree species. Several hundred hectares of land classified as forests in 1935 photographs were reclassified as woodlands in 1991 photographs. Some of these changes occurred at the interface of canyon bottoms and slopes and may represent localized mortality in ponderosa pine.

Stability (resistance to change) of cover-class categories increased with increasing canopy cover (Table 3). Less than 10% of the area categorized as grassland (G), juniper savanna (W1), ponderosa pine savanna (F1), or open forest (F2) in 1935 photographs was classified as that same category in 1991 photographs. In contrast, greater than 50% of the area classified as moderately dense forest (F3), closed-canopy woodland (W4), or closed-canopy forest (F4) in 1935 was classified as that same category in 1991. This result is a consequence of the general pattern of increasing canopy cover with time. Compared with the other low canopy-cover categories, the open-woodland class (W2) remained relatively stable between 1935

TABLE 4—Number, size class (ha), and cause of fires reported during years 1949 to 1958 and 1960 to 1992, Negrito Creek study area, southwestern New Mexico. No data were available for 1959. (United States Department of Agriculture Forest Service, Reserve Ranger District.)

Cause	1949–1958	1960–1992				
	<16 ha	<0.1 ha	0.1–3.9 ha	4–39 ha	40–119 ha	Total
Lightning	18	62	12	2	2	96
Smoking	0	1	1	0	0	2
Miscellaneous	0	1	0	0	0	1
Total	18	64	13	2	2	99

and 1991. Most stable woodlands were located on steep, south-facing escarpments above Negrito Creek in the northwestern portion of the study area.

As a consequence of the vegetation changes that occurred, the diversity of the Negrito landscape declined during the 56-year photograph span. The Shannon-Wiener diversity index calculated for the Negrito landscape decreased from $H' = 0.812$ in 1935 to $H' = 0.692$ in 1991. Because the number of cover-class categories on the landscape was the same in the two years (i.e., richness was constant), the lower diversity index in 1991 was due solely to an increase in the dominance of the higher canopy-cover classes (a decrease in evenness). This result contrasts with that of Allen (1989) who found that landscape diversity in his study area in the Jemez Mountains increased between 1935 and 1981. The difference can be explained by the fact that the Jemez area contained urban and agricultural lands that increased between 1935 and 1981 at the expense of forests and woodlands. The conversion of forest and woodlands (dominant cover types) to urban and agricultural lands (relatively minor cover types) resulted in a more even distribution of lands among cover types.

Based on vegetation changes that occurred between 1935 and 1991, the vegetation-change model projects several changes for the succeeding 56-year period between 1991 and 2047 (Table 2). All cover-class categories are expected to decrease in abundance except closed woodlands (W4) and closed forests (F4). Moderately dense woodlands (W3) and moderately dense forests (F3) will continue to be the most abundant cover types, but both types are projected to decrease because losses to higher canopy-cover classes should exceed gains from lower canopy-cover classes. Both by percentage and number of hectares, the greatest change projected is the increase in the amount of closed forests (F4). By the year 2047, the model predicts that over 90% of the study area will be covered by woodlands or forests with greater than 40% canopy cover; grasslands (G), juniper savannas (W1), pine savannas (F1), and open forests (F2) will become almost nonexistent. Associated with continued increasing dominance of high canopy-cover classes, landscape diversity (H') is expected to decrease slightly from 0.692 to 0.671 between 1991 and 2047.

Fire History—Fire is an important ecological component of southwestern forests, woodlands, and grasslands (Brown, 1982; Dick-Peddie, 1993). Nevertheless, ecologically significant fire was nearly absent from the study area from 1949 to 1992 (Table 4). Although ignitions were abundant, most fires covered less than 0.1 ha and presumably had very little ecological impact on the landscape. Approximately 381.5 ha burned during the 43-year span, representing only 4.2% of the study area and an annual percent burn of 0.1. At this rate, the fire cycle, or the amount of time required to burn over an amount of land equal in size to the entire study area (Johnson and Gutsell, 1994), was approximately 1,024 years. Excluding fires smaller than 0.1 ha, over 87% (122 of 139) of the quarter-sections in the study area experienced no fire during the period from 1960 to 1992 and thus had fire intervals exceeding 33 years. The other 17 quarter-sections experienced only one fire during the 33-year period. These data generally are similar to those for the nearby Gila Wilderness where fire intervals were 4 to 8 years prior to 1900 and

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It is probable that fires have been much less common in the Negrito study area since the late nineteenth century than they were prior to that time. Post-settlement reductions in fire frequency are well-documented for areas such as the Gila Wilderness (Swetnam and Dieterich, 1985), the White Mountains of Arizona (Dieterich, 1983), and the Jemez Mountains (Allen, 1989) that have vegetation types and land-use histories similar to those of the Negrito study area. Increased canopy cover within forest and woodland types, increased relative abundance of ponderosa pine within mesic woodlands, and invasion of mesa-top grasslands by alligator junipers all can be explained in part by a reduction in the frequency of tree-thinning surface fires. A thorough fire-history study would be required to test this hypothesis in full, but it is supported by the following observations. Fire scars (in many cases, multiple scars) were apparent on the majority of old alligator junipers located throughout the study area (M. E. Miller, pers. obser.). In former grasslands and savannas, burned juniper stumps extending just a few centimeters above the ground were common (M. E. Miller, pers. obser.). Former savannas consisted entirely of scattered alligator junipers, which generally are considered to be more fire tolerant than piñons when mature (Leopold, 1924). Former grasslands occurred on relatively flat mesas where surface fires would have spread most easily, burned most completely, and thus been most effective in limiting the establishment of woody plants (Arnold et al., 1964; Vogl, 1974).

A life-history characteristic of alligator juniper has implications for the role of fire in maintaining mesa-top grasslands and savannas. Alligator juniper is rare among gymnosperms in its ability to sprout from the roots, base, or stem following disturbance (Johnson et al., 1962; Jameson and Johnsen, 1964). Sprouting is most common in trees less than 15 cm in diameter, and the tendency to sprout declines with increasing size (Jameson and Johnsen, 1964). This suggests that pre-settlement fires on the Negrito mesas must have been relatively frequent in order to have prevented woodland development. Fire alone may not have been able to completely prevent the establishment of alligator juniper in grasslands and savannas, but frequent surface fires probably could have suppressed small trees through repeated burning. Thus over time, there may have been a gradual accumulation of small junipers in the grasslands and savannas. If some event(s) then interrupted the regime of frequent surface fires, the stand of small junipers would have been released as a single cohort to grow and eventually dominate the former grassland or savanna. Given the slow growth rate of *Juniperus* (Tueller and Clark, 1975), trees released in the late-nineteenth century may have been present in 1935 though not yet visible in aerial photographs.

A combination of factors probably was responsible for the postulated decrease in fire occurrence within the Negrito study area. Vigorous fire-suppression efforts by the Forest Service certainly minimized the spread of fires during the latter half of this century (S. Bustamante, pers. comm.). However, some studies conducted in the Southwest have found that abrupt decreases in fire frequencies preceded the initiation of effective fire suppression and coincided temporally with the introduction of large herds of domestic livestock (Swetnam and Dieterich, 1985; Savage and Swetnam, 1990; Savage, 1991) and the displacement of Native Americans (Swetnam and Dieterich, 1985). Livestock grazing can reduce the spread of surface fire by removing herbaceous fuels, and many Native American groups were reported to have used fire extensively (Stewart, 1956; Dobyns, 1981). Until the late 1880s, the Negrito area was a hunting and gathering ground for Zunis and Chiricahua Apaches (B. Ellis, pers. comm.). Of the western tribes, Apaches were second only to the Sioux in their widespread use of fire for a variety of purposes including making smoke signals, inducing rain, clearing trails, attracting, flushing, and driving game, and as a weapon against their enemies (Pyne, 1982).

Grazing History—Because herbivory and trampling by domestic livestock can greatly influence vegetation structure and composition (Crawley, 1983; Vavra et al., 1994), grazing history is an important element to consider in any assessment of factors contributing to vegetation change (Bahre, 1991). Forest Service records indicate that large herds of cattle first were introduced to the Negrito region between 1870 and 1880 and that the study area,

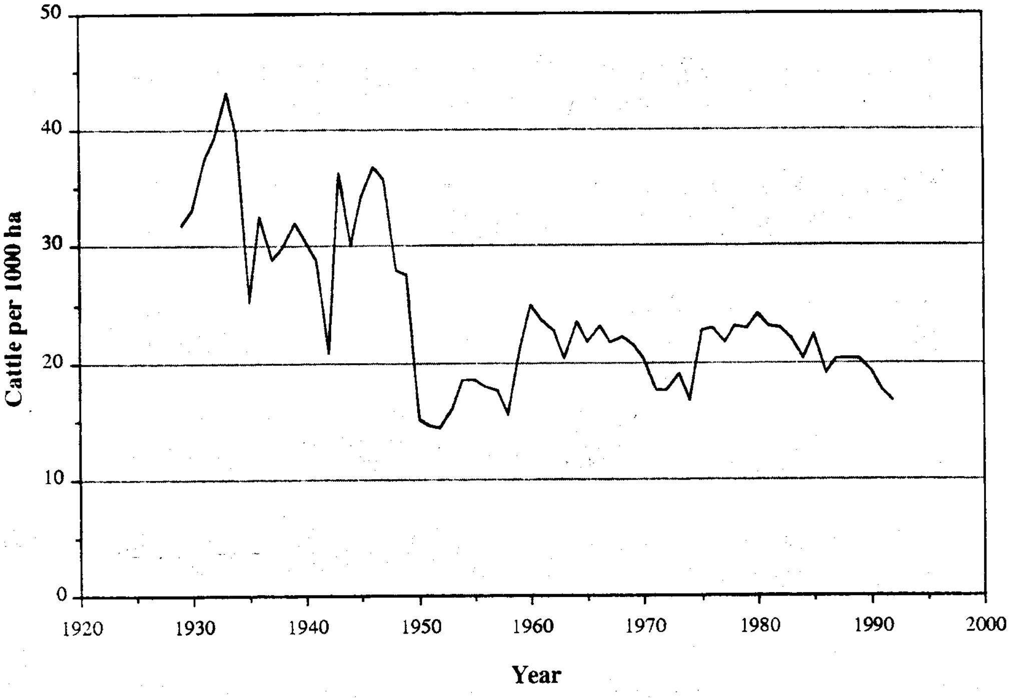
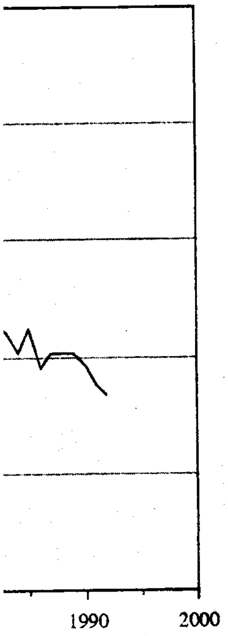


FIG. 2—Stocking rates (numbers of cattle per 1,000 ha) for years 1929 to 1992, Negrito Creek study area, southwestern New Mexico. (United States Department of Agriculture Forest Service, Reserve Ranger District.)

like much of the Southwest, was subjected to very heavy grazing in the late nineteenth century. Although numerical data for the study area are lacking, Wooton (1908) estimated that the average stocking rate in the region west of the Mogollon Mountains south of the Negrito area was 41 to 62 cattle per 1,000 ha during the period 1880-1906, with the highest rates having occurred during peak years of 1889 and 1890. Forest Service records also indicate that large numbers of sheep were grazed with cattle in portions of the Negrito study area during the late nineteenth century. Documented stocking rates in the study area from 1929 to 1949 were lower than those that probably occurred during the late nineteenth century, but also were considerably higher than recent rates (Fig. 2). The mid-1930s decline in stocking rates may have been a consequence of drought. The sharp reduction in rates after 1949 coincided with widespread stock reductions that occurred throughout the West following changes in Forest Service range-management practices in the late 1940s (Rowley, 1985) and also may have been related to drought conditions in the 1950s. Livestock could have contributed to vegetation changes in the study area by removing herbaceous materials required to fuel tree-thinning surface fires (Burkhardt and Tisdale, 1976; Tausch et al., 1981) or by altering competitive relationships between unpalatable woody and palatable herbaceous vegetation (Cottam and Stewart, 1940; Madany and West, 1983).

The relative importance of grazing to vegetation changes in the Negrito study area can be clarified by considering whether grazing was necessary and/or sufficient for the changes to have occurred. With respect to the successional replacement of grasslands and savannas by juniper-dominated woodlands, grazing probably was sufficient but not necessary. Because the Negrito grasslands and savannas appear to have been fire-maintained, any factor that reduced the frequency of surface fires enough for small, fire-stunted junipers to attain a fire-



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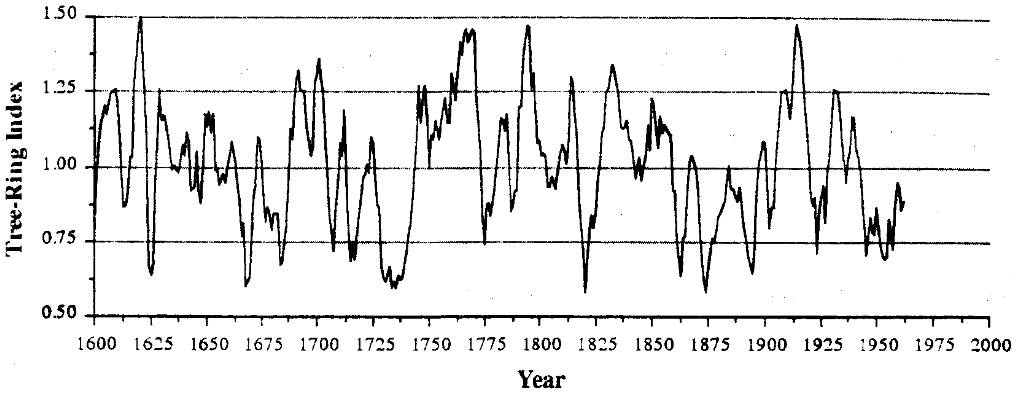


FIG. 3—Tree-ring indices (5-year running averages) based on core samples taken from Douglas-fir trees on Rainy Mesa, Negrito Creek watershed, southwestern New Mexico. An index value of 1.00 represents the long-term average annual tree-ring increment and reflects "normal" growing conditions. (University of Arizona, Laboratory of Tree-Ring Research, Tucson).

tolerant size could have enabled the physiognomic transition. It is likely that the displacement of Native Americans in the late nineteenth century and fire suppression by the Forest Service since the early twentieth century both were equally sufficient. By reducing the competitive vigor of grasses, grazing simply may have facilitated a vegetation transition that would have occurred anyway. However, if junipers were excluded primarily by root competition rather than by fire, small junipers probably would not have accumulated in the grasslands over time, and a combination of favorable climatic conditions and reduced fire frequencies would have been required for juniper establishment.

In lower montane forests and upper montane mixed-conifer stands, higher precipitation levels might have been able to maintain dense herbaceous ground cover capable of limiting tree establishment even in the absence of frequent surface fires (Rummel, 1951; Madany and West, 1983). Again, grazing might have been necessary to reduce the competitive advantage of herbaceous plants, but alone it would have been insufficient to enable an increase in tree recruitment. This is supported by Savage's (1991) work in the Chuska Mountains where a pulse of ponderosa pine establishment followed the introduction of livestock by several decades and coincided instead with a period of favorable climatic conditions.

Climate History—As suggested in the previous section, it is likely that climatic factors contributed to vegetation changes documented in the study area. Data from the Rainy Mesa tree-ring chronology (Fig. 3) show that conditions were mostly unfavorable for tree growth during the late nineteenth century (1859 through 1896). Drought conditions in the late nineteenth century thus coincided with the period of peak grazing. The tree-ring chronology is an index of winter-spring precipitation, but July precipitation also was below average during the period 1883–1906 throughout Arizona and western New Mexico (Sellers, 1960). Drought and grazing in combination probably resulted in greater decreases in cover and vigor of grasses than would have occurred with either factor alone.

In the early part of the present century (from 1905 through 1920), climatic conditions again were favorable for tree growth (Fig. 3). Although the conditions required to produce a wide tree ring are not necessarily the same as those required for successful recruitment, moist conditions probably led to a pulse of tree establishment in the study area. The climate sequence evident in the Rainy Mesa chronology corresponds well with historical records and findings of other studies indicating regional drought in the late nineteenth century followed by an extremely moist period in the early twentieth century (Schulman, 1956; Sellers, 1960; Fritts 1965, 1976; Bahre, 1991; Savage, 1991). A link between this climatic sequence

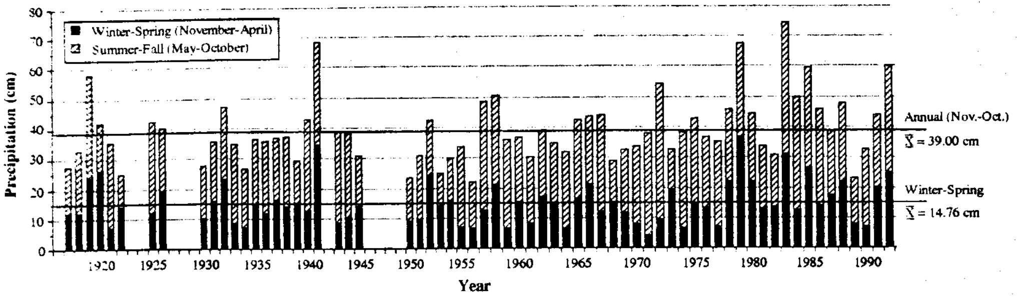


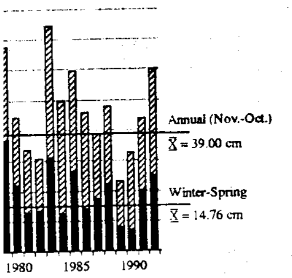
FIG. 4—Annual (November through October) and seasonal precipitation in Reserve, New Mexico, during the years 1917 to 1992. Stacked bars separate annual totals into winter-spring and summer-fall components. Missing bars indicate incomplete data. (United States Department of Commerce.)

and increased tree recruitment is supported by the fact that several forested locations throughout the Southwest experienced a large, synchronous pulse of ponderosa pine establishment in about 1919 (Arnold, 1950; Cooper, 1960; Madany and West, 1983; Savage, 1991).

Records from the town of Reserve detail fluctuating levels of seasonal and annual precipitation between 1917 and 1992 (Fig. 4). On average, winter-spring precipitation was lower and relatively more variable (coefficient of variation = 0.48) than summer-fall precipitation (coefficient of variation = 0.30). Extended periods (4 or more consecutive years) of below-average annual precipitation occurred during the 1930s, 1950s, and the late 1960s. Reserve experienced the 1930s drought primarily through reduced levels of summer-fall precipitation, and most years during that period had normal or near-normal levels of winter-spring precipitation. This probably explains why the moderate 1930s drought is not apparent in the Rainy Mesa chronology (Fig. 3). The widespread regional drought of the 1950s, considered by many to have been the most severe in several centuries (Schulman, 1956; Sellers, 1960; Allen, 1989; Betancourt et al., 1993), is reflected both in the Reserve (Fig. 4) and Rainy Mesa data (Fig. 3). Nevertheless, Reserve received near-normal levels of winter-spring precipitation during some years of the 1950s drought.

Droughts during the 1930s and 1950s would have affected mesa-top junipers and grasses differentially. By the 1930s, most junipers occurring in the grasslands should have been established long enough to have developed deep root systems enabling them to tolerate drought better than shallow-rooted grasses. This certainly would have been true by the time of the more-severe 1950s drought. In addition, alligator juniper possesses the C_3 photosynthetic pathway and is dependent mostly on winter-spring precipitation (Tueller and Clark, 1975). Blue grama, the dominant grass species on the Negrito mesas, is a C_4 species and is more dependent on summer precipitation. Because both droughts appear to have been most severe during summer in this area, it is likely that C_4 grasses suffered relatively more than junipers.

Neilson (1986, 1987*a*, 1987*b*) noted that recent physiognomic changes in desert grasslands and piñon-juniper woodlands were initiated during a period of increased warmth and rainfall (1850 to 1940) that marked the end of the global cool period known as the "little ice age" (1550 to 1850). Temperature and/or precipitation patterns associated with this climatic shift may have led to changes in vegetation composition and structure by altering establishment patterns of C_3 shrubs and trees relative to C_4 grasses. According to this argument, coincident land-use factors such as livestock grazing and fire suppression simply may have hastened the occurrence of vegetation changes driven primarily by climate. As discussed already, increased tree establishment in the study area probably was associated with the sharp increase in tree-growth conditions from 1905 to 1920 (Fig. 3). In contrast, an extended period of above-average conditions from 1740 to 1770 apparently did not have similar effects. This suggests that both land use and climate



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contributed to historic changes evident in the watershed.

Management Implications—Data regarding historic vegetation changes and the likely impacts of human activities provide important information for land managers. Supplied with such information, should managers select the presumed pre-settlement vegetation condition as an objective model for the desired future condition of the watershed (Reid, 1996; Salwasser et al., 1996)? Before anwering this question, it is relevant to consider vegetation change and human activities in a broader context.

Significant vegetation changes occurred in the Negrito watershed during this century, but the magnitude of those changes was small compared with late-Quaternary vegetation shifts documented by paleoecologists (Van Devender and Spaulding, 1979; Betancourt et al., 1990). The historic increase of *J. deppeana* in the Negrito study area did not represent a range expansion, but rather the filling in of fire-maintained grasslands and savannas that were inclusions within existing woodlands and forests. These historic changes probably fell within the range of changes that occurred prior to the historic period. Paleoecological studies of western juniper (*J. occidentalis*) in Oregon, for instance, suggest that the rate and magnitude of that species' historic increase in the northern Great Basin were met or exceeded three times during the preceding 4,000 years in response to long-term climatic fluctuations (Mehringer and Wigand, 1990; Miller and Wigand, 1994).

Historic human activities such as livestock grazing and wildfire suppression played important roles in the vegetation changes documented in this study, but it is becoming increasingly clear that pre-European environments often were far from pristine. For example, the collection of fuelwood by prehistoric inhabitants of Chaco Canyon may have been responsible for the disappearance of piñon-juniper woodlands from that area after 800 years ago (Betancourt and Van Devender, 1981; Samuels and Betancourt, 1982). Evidence also suggests that hunting by late prehistoric peoples in the Southwest was partially responsible for the scarcity of large mammals such as bison (*Bison bison*) and elk (*Cervus elaphus*) when Europeans first entered the region in the sixteenth century (Truett, 1996).

Given the dynamic nature of vegetation and the likelihood that human activities influenced vegetation patterns even before the time of European settlement, there would seem to be no a priori rationale for selecting the pre-European condition as the objective basis for management. Instead, management should be based on identifiable targets such as the maintenance of landscape-scale biological diversity and productivity (Noss, 1996; Reid, 1996; Salwasser et al., 1996). It is likely that historic changes in the Negrito watershed have had associated effects that are contrary to these and other potential management objectives. For example, understory plant cover and productivity have been found to decrease with increasing overstory canopy cover in piñon-juniper woodlands (Arnold et al., 1964; Blackburn and Tueller, 1970; West, 1984) and ponderosa pine forests (Arnold, 1950; Cooper, 1960). Declines in plant species richness, evenness, and diversity have been associated with the development of mature piñon-juniper woodlands (Tress and Klopatek, 1987). Habitat diversity for wildlife typically decreases with increasing landscape homogeneity (Frischknecht, 1975), and the continued development of high-cover woodlands and forests will increase the likelihood of stand-replacing crown fires. Negative effects of woodland development on other ecosystem properties such as water yield, runoff, and erosion often have provided additional rationale for woodland "control" projects, but data demonstrating the significance or existence of these effects usually are lacking (Belsky, 1996; but see Wilcox et al., 1996).

By restoring the ecological role of disturbance to the Negrito watershed, progress can be made toward attaining management targets concerning biological diversity and productivity (Sousa, 1984; Pickett and White, 1985; Petraitis et al., 1989). Human activities such as fuelwood cutting, selective logging, small-scale clearcutting (Franklin and Forman, 1987), prescribed burning (Severson and Rinne, 1990), and carefully managed grazing (Severson and Urness, 1994) potentially can be used by managers to complement natural wildfire and climatic episodes as patchy disturbances, and thus to enhance the diversity and productivity of the landscape mosaic. Such management actions inevitably will involve tradeoffs. For example, if surface fire is to be restored as an important ecological process on the Negrito landscape, then overstory canopies must be sufficiently open to allow growth of shrubs and herbaceous plants, and grazing must be managed to allow accumulation of surface fuels. Tradeoffs must be recognized and the success of management actions evaluated by collecting the relevant before-and-after data.

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