

EVALUATING JUNIPER CANOPY COVER CHANGE
FROM 1936-1997 AROUND WUPATKI
USING REPEAT AERIAL PHOTOGRAPHY

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ABSTRACT

EVALUATING JUNIPER COVER CHANGE FROM 1936-1997

IN THE WUPATKI AREA

USING REPEAT AERIAL PHOTOGRAPHY

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There is general consensus among scientists that there has been an increase in the range and density of pinyon/juniper (PJ) woodlands across the west over the last 150 years. In many locations, the pinyon and juniper trees have been recorded as moving into areas that were historically open grasslands. As trees move into open grassland areas, important ecological changes begin to occur. For example, while elk and mule deer are commonly found in wooded areas, pronghorn show a distinct preference for open grassland areas.

In Wupatki National Monument (NM), a unit of the National Park Service (NPS) located in north central Arizona, pronghorn are considered a species of concern. Recent studies in Wupatki NM, and the adjacent areas of the Coconino National Forest (NF), generally agree that there has been an increase in the range and density of regional PJ woodlands. Quantifying the change that has occurred would be useful to the National Park Service natural resource managers.

Continuous quadrats with a one hectare grid size, and a classification system that defined six levels of canopy cover, were applied to two sets of aerial photographs to quantify the change. The first set of air photos was taken in 1936 by the Soil

Conservation Survey (SCS); the second was taken in 1997 by the United States Geological Survey (USGS). This effort was designed to be a landscape-scale study, and examined 13,490 hectares. Approximately half of this area is within Wupatki NM, while the other half is within the Coconino NF.

The results of this study show that approximately 27% of the 1936 landscape (3,695 ha) was open, treeless grassland. By 1997, this area had been reduced to 9.5% of the landscape (1,290 ha). A full two-thirds of the previously treeless grasslands in 1936 had obtained some number of trees by 1997. The rest of the landscape showed various amounts of canopy cover increase. The greatest increase occurred in the closed woodland designation, which revealed an increase in area of just under 7%.

This study suggests there is marked instability at the grassland end of the ecological spectrum in the study area, while there is considerable stability at the wooded end. Information of such historical trends are useful to land managers charged with ecological preservation. Decisions on issues such as grazing and fire management may be informed by the results of this study.

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CHAPTER 1

INTRODUCTION

Descriptive reports from early explorers, western pioneers, scientific expedition members, and surveyors indicate that a number of grass rangelands and savannas across the West have become wooded within the last 150 years (Woodbury 1947; Humphrey 1958; Blackburn and Tueller 1970; Zarn 1974; West *et al.* 1975; West 1988). This phenomenon was also observed and chronicled by scientists early in the 20th century (Leopold 1924; Nichol 1937; Woodbury 1947). Recent investigations using more sophisticated dendrochronological methods, repeat photography, and other techniques continue to provide strong evidence of this change (Johnsen 1962; Arnold *et al.* 1964; Burkhardt and Tisdale 1969; West *et al.* 1975; Johnsen and Elson 1979; Tausch *et al.* 1981; Cinnamon 1988; Jenkins *et al.* 1991; Mast *et al.* 1997; Jackson and Betancourt 2000; Soulé *et al.* 2003; Romme *et al.* 2009). Studies indicate that this expansion is primarily down slope and into areas that were previously grassland or shrubland (Leopold 1924; Johnsen 1962; Burkhardt and Tisdale 1969; Blackburn and Tueller 1970; Zarn 1974; Wright *et al.* 1979; Brown 1994; Mast *et al.* 1997; Lanner and Van Devender 1998; Soulé *et al.* 2003). Upslope expansion, however, has also occurred, especially in the Great Basin (West *et al.* 1975; Tausch *et al.* 1981). Tausch *et al.* (1981) estimate that as much as half of the pinyon-juniper woodlands in the Great Basin have become established since 1860. Most scientists agree that these changes are due to a combination of factors, including fire suppression, climatic fluctuations, and the intensive grazing that accompanied European settlement of the West.

This study evaluates the changes in juniper cover over the western half of Wupatki NM and an adjacent portion of the Coconino National Forest to the south using repeat aerial photography (1936 and 1997). Continuing the evaluation of change in this area started by Hassler (2006) and Ironside (2006), this study quantifies how much change occurred, what kind of change occurred, and where this change occurred.

Any ecosystem change can present challenges to land managers, and a shift from grassland to woodland habitat is no exception. Although grasslands exist on every continent except Antarctica, temperate grasslands are only able to persist within a fairly narrow set of environmental constraints¹ (Bock *et al.* 1993; Brown 1994). Grasslands are one of the most fragmented and endangered habitats in North America (Fleischner 1994), and the potential for species extinction within these habitats is of serious concern (Fleischner 1994; Samson and Knopf 1994). With a shift from grassland to woodland habitat comes an increase in canopy cover and a decrease in understory flora density and diversity (Arnold *et al.* 1964; Blackburn and Tueller 1970; Tausch *et al.* 1981). Removal of the woody overstory can reverse this trend (Tausch and Tueller 1975).

Grassland birds are especially sensitive to the characteristics of a grassland habitat, including the structure and composition of woody plants (Coppedge *et al.* 2004). Although most are not endangered, grassland-breeding birds have shown steeper and more persistent population declines than any other group of birds in North America (Peterjohn and Sauer 1995). Patches containing as little as 10% woody vegetation cover are avoided by many grassland birds (Chapman cited in Coppedge *et al.* 2004). Working

¹ Temperate grasslands are closely associated with Koeppen's BSk climate type (Strahler and Strahler 1978). The BSk climate type is defined as a cold, midlatitude, semiarid (steppe), climate with mean annual temperatures less than 18°C (64.4°F), where mean evaporation typically exceeds precipitation.

in the grasslands in Northern Arizona, Rosenstock (1999) found that avian species richness is often highest in the developing juniper woodlands (~ 90 trees/ha) that occupy the boundary between grassland and mid-aged woodland (>128 trees/ha). Rosenstock also found the number of grassland-obligate bird species decreases rapidly as the size and density of trees increase beyond a threshold of 10 trees/ha. Grassland fragmentation by woody species often leads to a loss of endemic and obligate avian species and to an increase in open-habitat generalists² (Rosenstock 1999; Coppedge *et al.* 2001).

Other species are also affected by a shift from a grassland to woodland habitat. Lizards (Meik *et al.* 2002) and butterflies (Swengel 1998) show a general decline with loss of grassland habitat. Rodents show a marked shift from field-adapted species to wood-adapted species (Lambrechtse 1982). Mule deer and elk prefer wooded habitats over open grasslands (Short and McCulloch in Lambrechtse 1982). Pronghorn, on the other hand, show a preference for open grassland areas (Johnsen and Elson 1979; Wood 1989; Ockenfels *et al.* 1994). Although Merriam's turkey hens with poults will use the forb-rich edges of large meadows and woodland openings for feeding (Green 1990; Mollohan *et al.* 1995), they prefer juniper-pinyon (*Juniperus-Pinus*) and ponderosa pine (*Pinus ponderosa*) habitats over grasslands (Scott and Boeker 1977; Mollohan *et al.* 1995). Bats often proliferate in the grassland/woodland ecotonic edge (Rabe 1999).

One of the largest native grassland areas in the Southwest not being domestically grazed is located within Wupatki National Monument (NM), Arizona (Figure 1.1).

Wupatki NM was originally established by Presidential Proclamation (Calvin Coolidge)

² Habitat generalists are species that occur in a wide variety of habitats and can be successful under diverse and heterogeneous conditions. Specialists have more specific habitat requirements and can be more vulnerable.

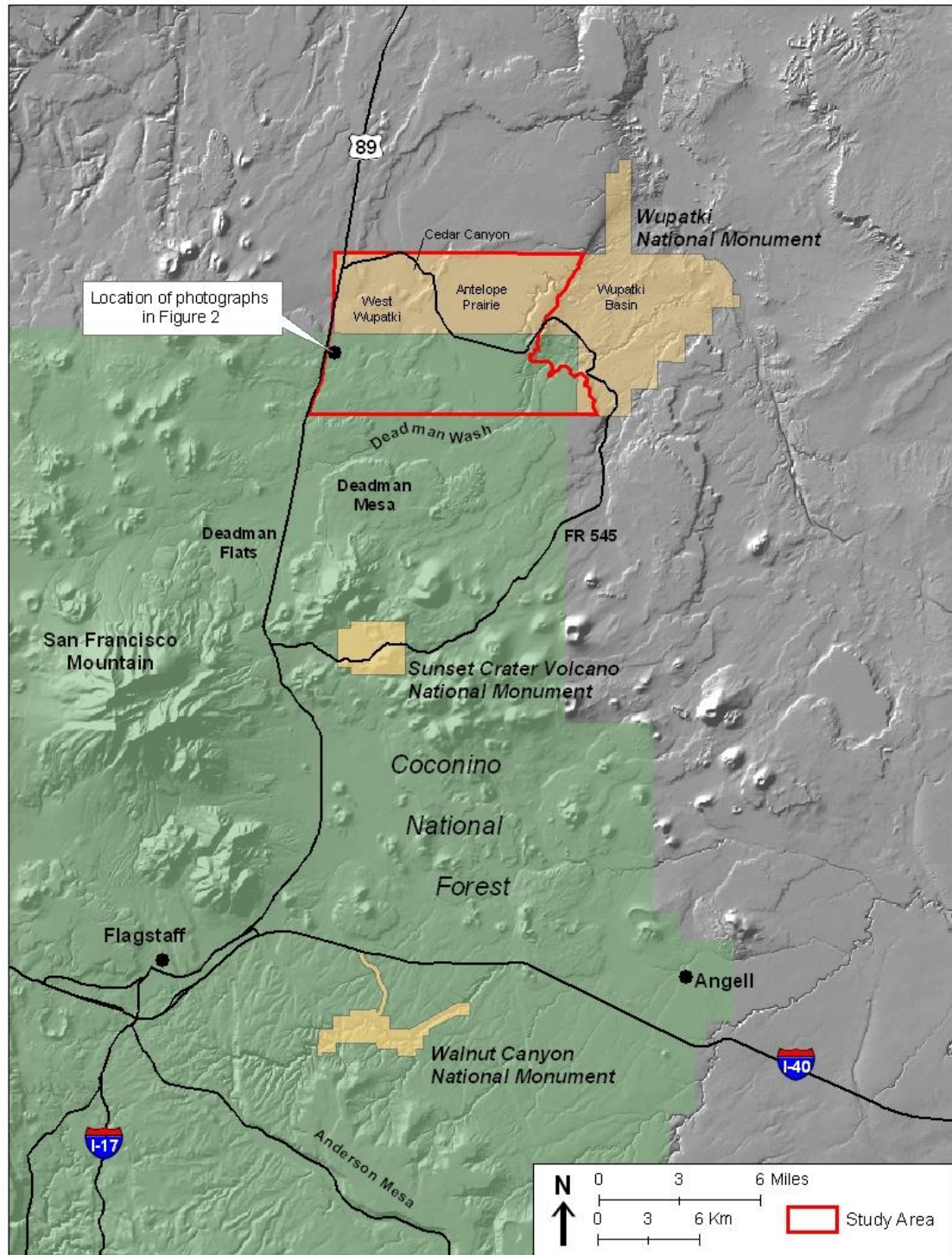


Figure 1.1. Location of features in and around the Northern Arizona study area.

The study area is located about 30 miles northeast of Flagstaff, Arizona. The northern half of the study area is located within Wupatki National Monument; the southern half is located in the Coconino National Forest.

in 1924 to preserve and protect ancestral Hopi ruins (National Park Service 2002). The mission of the National Park Service (NPS) has expanded since then to include protecting plant and animal resources.

Local studies suggest that a shift from grassland to woodland habitats could have profound ecological consequences for various species at Wupatki NM. For example, Persons (2001) found that all the anurans (spadefoots and true toads) and most of the lizards found in Wupatki NM show a preference for the grasslands of West Wupatki, or the desert scrub of Wupatki Basin, over the juniper woodland of Antelope Prairie (Figure 1.1). Similarly, all snakes, except gopher snakes and rattlesnakes (both habitat generalists), are found in greater abundance in the grassland and desert scrub areas than in juniper woodland areas. Rosenstock (1999) found that, at Wupatki NM, approximately 10 juniper trees per acre was the threshold that defined the habitat suitable for grassland-obligate birds, including the horned lark, western meadowlark, and eastern meadowlark. While pronghorn are not listed as endangered, wildlife biologists are generally concerned that pronghorn habitat across Arizona has been diminishing due to an increase in housing developments, roads, and fencing. Although female pronghorn make limited use of open juniper savannas, when movement is possible, pronghorn preferentially select open grassland areas (Ockenfels *et al.* 1994; Bright and van Riper 2001).

Bright and Van Riper (2001) determined that the grasslands of the Wupatki area provide critical pronghorn habitat, and that the pronghorn population was declining. They listed over-hunting, habitat fragmentation, migration impediments (e.g., range fences), and lack of permanent water sources as possible causes for this decline. Ockenfels *et al.*

(1994) suggest that the gradual reduction of grassland habitat due to woodland expansion could be another factor causing the decline in the pronghorn population.

Repeat terrestrial photography provides visual evidence that juniper cover and density in the Wupatki area have been increasing, causing a reduction in the grassland habitat over a large area. This is illustrated in Figure 1.2, which shows the same scene in 1905 and 1985.

The few studies that have examined the change of tree cover in the Wupatki area, however, have produced varying results. Ffolliott and Gottfried (2002), for example, concluded that the pinyon and juniper on Deadman Flats (10 km/6 mi southwest of Wupatki – Figure 1.1) had simply matured, growing in height and diameter, since 1948 and had not expanded their range. Cinnamon (1988) working in western Wupatki, Jenkins *et al.* (1991) working at Walnut Canyon NM (40 km/25 mi south of Wupatki) and Landis (2003) working at Anderson Mesa (48 km/30 mi south of Wupatki), on the other hand, all concluded that tree cover had increased in both areal extent and stand density.

Although Cinnamon (1988) examined the vegetation change in Cedar Canyon (Figure 1.1) in west Wupatki, no one has performed a landscape-scale study over this area. Nor has any quantitative evaluation been performed that encompasses the full transition from mature woodland through varying degrees of young woodland and savanna, into pure grassland. This study uses repeat aerial photography (1936 and 1997) to evaluate changes in juniper cover over the western half of Wupatki NM and an adjacent portion of the Coconino National Forest to the south. Changes in extent and canopy cover will be

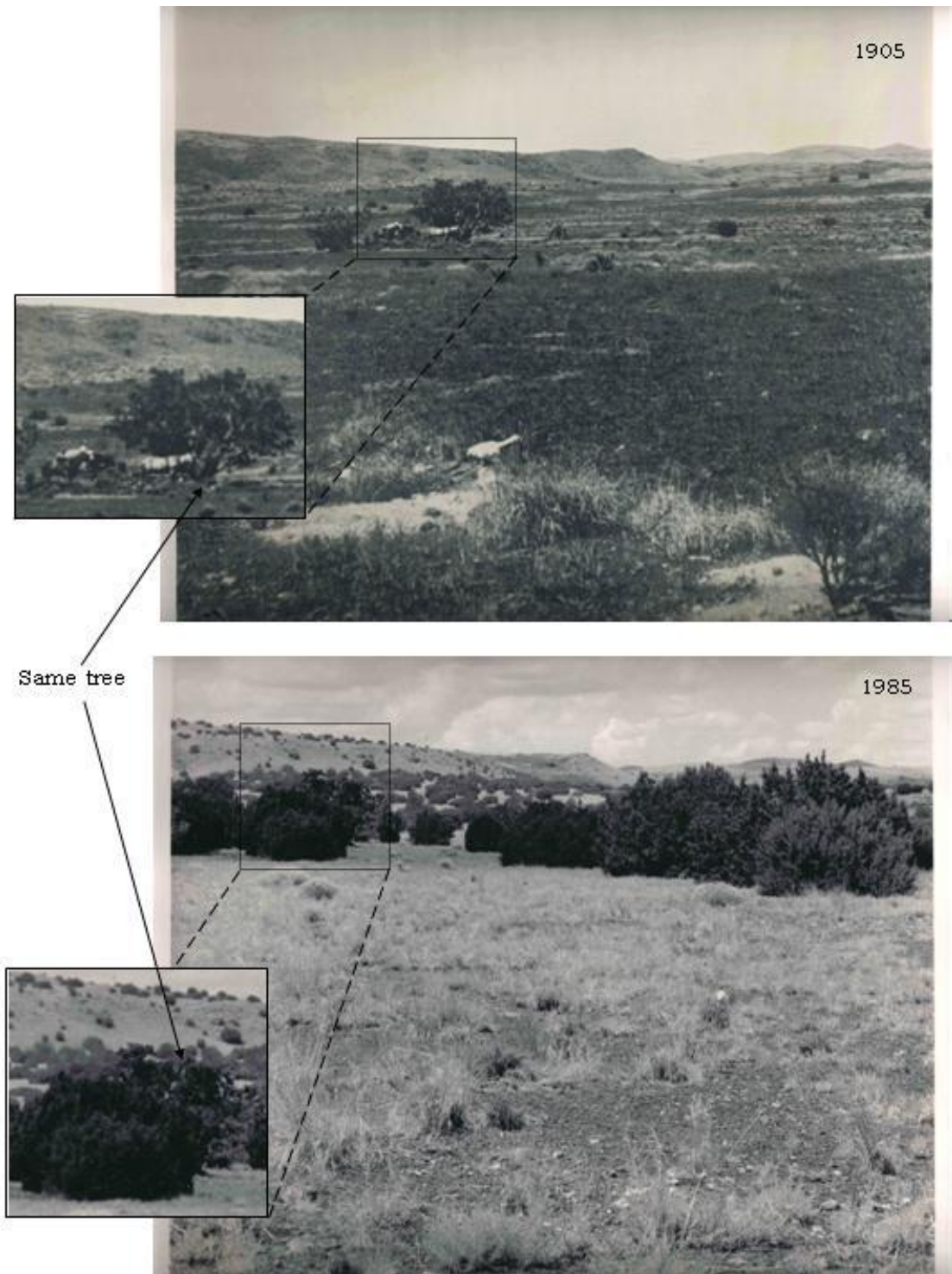


Figure 1.2. Repeat terrestrial photography of a site within the study area.

Note the same tree in both photographs. This tree was old and gnarled, even in 1905 (the date of the earlier photograph). Photos received from Michael Hanneman, USFS Range Staff, Peaks Ranger District, Coconino National Forest.

quantified and analyzed, and relationships to land use, fire history, and climate will be explored.

Chapter 2 will present the reader with a literature review background on pinyon-juniper woodlands in the Southwest. Chapter 3 will describe the location and physical condition of study area, including climate, soil and vegetation. Chapter 3 will also provide brief fire, cultural and grazing histories of the study area. Chapter 4 will define the methods used, Chapter 5 will provide the results and analysis of the findings of this study, and Chapter 6 will close with a discussion.

CHAPTER 2

LITERATURE REVIEW

Pinyon-juniper woodlands occupy vast portions of the North American West, including large areas of northern Mexico (Merkle 1952; Wright *et al.* 1979; West 1988). Providing fuel, building materials, medicine, and food, pinyon-juniper woodlands have played a critical role in human history, both historically and prehistorically (Lanner 1975). Anecdotal reports of woodland expansion throughout the West are now legendary (Springfield 1976). Both descriptive historical writings and repeat photography provide convincing evidence that considerable changes to woody plant ranges have occurred, especially in the last 150 years (Blackburn and Tueller 1970; Zarn 1974; West *et al.* 1975; Johnsen and Elson 1979; West 1988; Soulé *et al.* 2003; Shaw 2006; Romme *et al.* 2009). Most researchers agree that these changes include an increase of both woodland range and density, and most that these changes are due to some combination of climate fluctuation, fire suppression, and the intensive grazing that accompanied European settlement (Johnsen 1962; Blackburn and Tueller 1970; West *et al.* 1975; Johnsen and Elson 1979; Wright *et al.* 1979; West 1988; West 1999; Lanner and Van Devender 1998; Soulé *et al.* 2003). Although not widely accepted, some scientists believe an increase in atmospheric CO² over the last century might also be a contributing factor (Soulé *et al.* 2003).

The prehistoric human population affected woodland structure by cutting trees for fuel and building materials. This impact, though sometimes extreme, was fairly localized. The need for fuel wood of the ancestral Pueblo people (Anasazi), for example, decimated

the pinyon population around Chaco Canyon a thousand years ago (Lanner and Van Devender 1998). Prehistoric people also intentionally started fires to maintain and expand grassland areas, which promoted wildlife populations that served as food sources (Leopold 1924). The extent and impact of anthropogenic burning is not agreed upon. Leopold (1924), Sauer (1950), and Pyne (1982) contend that the indigenous people of this continent made extensive use of fire. Pyne (1982) even suggests that it was the fire use of the indigenous people that kept much of this continent in a savanna, or open forest-like, state and, that where Europeans settled, the forests tended to increase in density and range due to the reduction of fire on the landscape. Swetnam and Baisan (1994), on the other hand, argue that the historical role fire played was primarily nature driven, and that, in the Southwestern U.S., the addition of anthropogenic burning had little effect. They do acknowledge, however, that in certain times and places the actions of indigenous people had an impact, but overall they believe that humans only augmented natural conditions.

All prehistoric human influences are dwarfed by the impact of European settlement (West 1988). With the conclusion of the Mexican-America War in 1848, and the improvements in transportation and communication, the seemingly endless acres of grassland of the West began to attract ranchers in rapidly increasing numbers. The already burgeoning cattle population, estimated at 4 to 5 million head in the 17 western states in the 1870s, exploded to a peak population of 35 to 40 million head by 1884 (Jacobs 1991). With the ranchers came homesteading settlers, and with these settlers came the fear of wildfire (Grahame and Sisk 2002), and the beginning of 150 years of fire suppression (Pyne 1982).

Pinyon-Juniper Woodlands

Pinyon-juniper woodlands extend eastward from the eastern slopes of the Sierra Nevada through the mountains of the Great Basin in Nevada and Utah (Figure 2.1) (Merkle 1952; Wright et al. 1979). They cover both flanks of the Rocky Mountains in Colorado, many of the interior valleys and mesas of the Colorado Plateau, and spread south into Arizona and New Mexico. Woodlands dominated by juniper also extend well into Canada (Merkle 1952), Texas (West *et al.* 1975), and northern Mexico (Wright *et al.* 1979, West 1988).

Pinyon-juniper woodlands, often referred to as simply “PJ”, are comprised of some combination of 11 species of small-statured, large-seeded soft pines (the *Cembroides* subsection of *Pinus*; family Pinaceae) and nine species of juniper (*Juniperus*; family Cupressaceae), which grow in form from prostrate shrubs to small trees (West 1984). Classified in the mid-20th century as the *Pinus-Juniperus* association of the Woodland Formation by Weaver and Clements (Merkle 1952), today it is sometimes referred to as pigmy conifer woodland (West *et al.* 1975; West 1988). Pinyon and juniper exist in a variety of stand structures (Table 2.1)³, from mixed stands of the two genera to pure stands of either (Howell 1941; Woodbury 1947; West 1988; Brown 1994). Typically one juniper species and one pinyon species define the stand structure unique to each area (West 1988). When more than two species are involved, the number of juniper species is usually greater than the number of pinyon species (Springfield 1976; Brown 1994). This variation in stand structure complicates estimation of woodland size. West *et al.* (1975)

³ In Arizona’s Mogollon Rim region, West (1988) included the Arizona cypress (*Cupressus arizonica*), which is not a true juniper. Both cypress and juniper belong to the Cypress family (*Cupressaceae*).

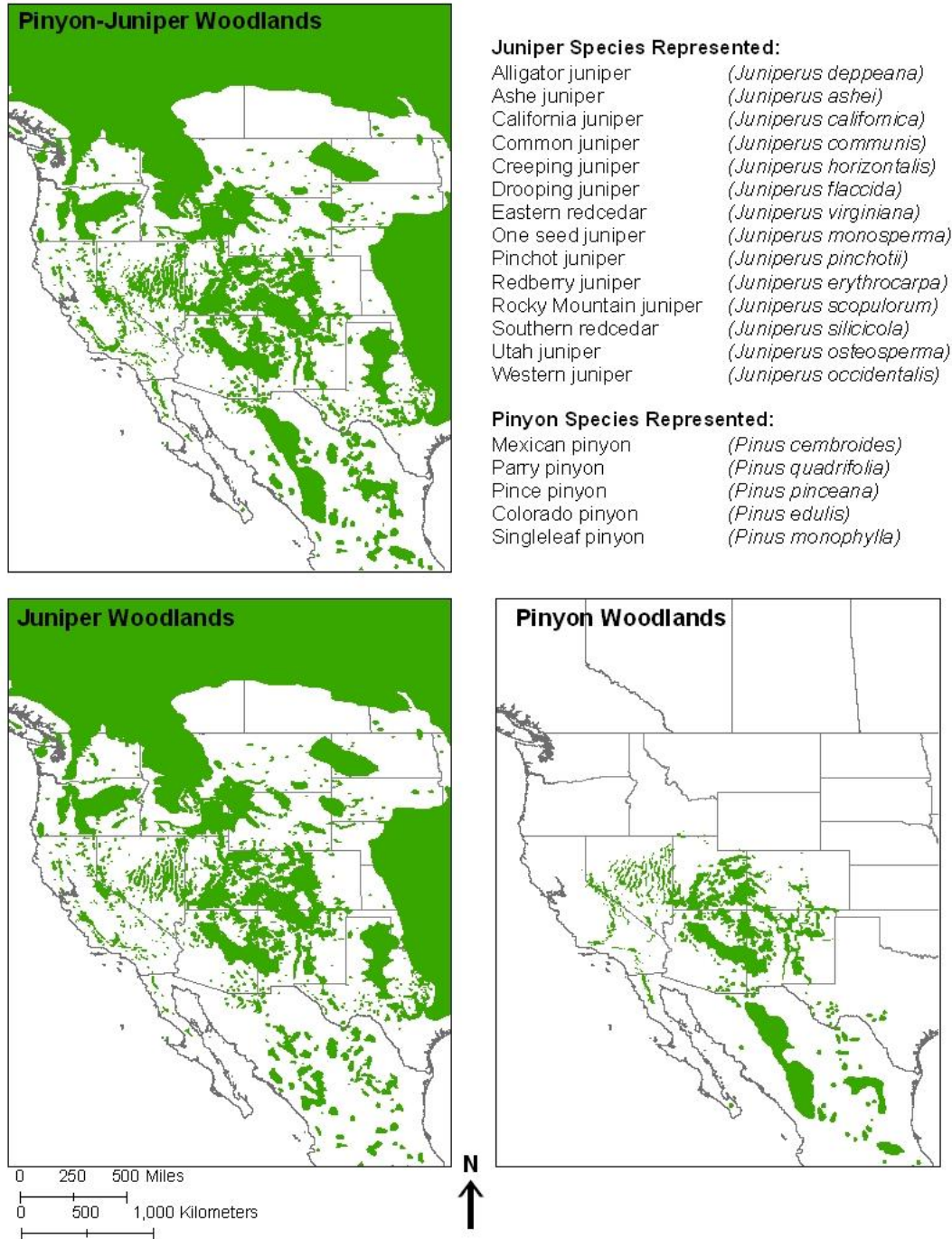


Figure 2.1. Current distribution of pinyon, juniper, and combined juniper-pinyon woodlands in the Western United States, Southwestern Canada and Northern Mexico.

Adapted from: *Digital Representations of Tree Species Range Maps from "Atlas of United States Trees"* by Elbert L. Little, Jr. <<http://esp.cr.usgs.gov/data/atlas/little>>

Table 2.1. Distribution of the principal tree species found in U.S. pinyon-juniper woodlands (adapted from West 1984).

Colorado Plateau: eastern Utah, western Colorado, northern Arizona, northwestern New Mexico	
<i>Juniperus osteosperma</i>	Utah juniper
<i>Pinus edulis</i>	Colorado pinyon
<i>Juniperus monosperma</i>	One-seed seed juniper
Mogollon Rim: central Arizona	
<i>Juniperus osteosperma</i>	Utah juniper
<i>Juniperus monosperma</i>	One-seed juniper
<i>Juniperus deppeana</i>	Alligator juniper
<i>Cupressus arizonica</i>	Arizona cypress
Great Basin: Nevada, western Utah, California east of the Sierra Nevada	
<i>Juniperus osteosperma</i>	Utah juniper
<i>Pinus monophylla</i>	Single leaf pinyon
Pacific Northwest: eastern Oregon, southwestern Idaho, northeastern California	
<i>Juniperus occidentalis</i>	Western juniper
Northern Rockies: Wyoming, northern Colorado Front Range, Montana, eastern Idaho	
<i>Juniperus osteosperma</i>	Utah juniper
<i>Juniperus scopulorum</i>	Rocky Mountain juniper
Southern Rockies: southern Colorado, northern New Mexico	
<i>Juniperus monosperma</i>	One-seed seed juniper
<i>Pinus edulis</i>	Colorado pinyon
Sonoran Border: southern Arizona	
<i>Pinus cembroides</i> var. <i>bicolor</i>	Mexican pinyon
<i>Juniperus deppeana</i>	Alligator juniper
<i>Pinus edulis</i>	Colorado pinyon
<i>Pinus monophylla</i>	Single-leaf pinyon
<i>Juniperus erythrocarpa</i>	Redberry juniper
Edwards Plateau: central Texas	
<i>Juniperus pinchotii</i>	Pinchot's juniper
<i>Juniperus ashei</i>	Ashe's juniper
<i>Pinus cembroides</i> var. <i>remota</i>	Texas pinyon
Trans-Pecos: western Texas, southeastern New Mexico	
<i>Pinus cembroides</i> var. <i>remota</i>	Texas pinyon
<i>Juniperus erythrocarpa</i>	Redberry juniper
<i>Juniperus pinchotii</i>	Pinchot's juniper
Mohave Border: southern California	
<i>Pinus monophylla</i>	Single-leaf pinyon
<i>Juniperus californica</i>	California juniper
<i>Pinus quadrifolia</i> Parl. ex Sudworth	Perry pinyon
<i>Juniperus monosperma</i>	One-seed seed juniper

estimated 42 to 76 million acres throughout the West; the smaller value is an estimate of mixed woodland areas, while the larger value includes woodlands containing juniper without pinyon. The US Forest Service determined that approximately 46.2 million acres of the Western United States were covered with pinyon-juniper woodlands (Powell *et al.* 1992). Excluding Alaska, which has no pinyon-juniper woodland, this accounts for 23.5% of all wooded acreage in the Western US. In Arizona and New Mexico, the US Forest Service estimates 16.6 million acres are covered by pinyon-juniper woodland and 4.1 million acres by juniper woodland (O'Brien 2002, O'Brien 2003). Arizona contains 3.1 million acres of juniper woodland and 7.8 million acres of pinyon-juniper woodland; well over three times the acreage as ponderosa pine saw-timber, and representing 56% of Arizona's forest land (O'Brien 2002). These numbers are thought to be contracting due to current drought conditions (Breshears *et al.* 2005).

Climate and Elevation

Throughout its range, pinyon-juniper woodlands are associated with various grassland and sagebrush vegetation types. As a mid-elevation, semi-arid vegetation type (West 1984), pinyon-juniper woodlands commonly occupy the zone directly above the grassland or desert scrub and below the ponderosa pine (Emerson 1932; Woodbury 1947; Blackburn and Tueller 1970; Wright *et al.* 1979; West 1988) or submontane scrub⁴ (Woodbury 1947). Pinyon-juniper woodlands also occupy the lowest elevations of the coniferous zone of the Rocky Mountains and Great Basin (Merkle 1952).

⁴ Submontane scrub is a vegetation type dominated by Gambel oak (*Quercus gambelii*) that occurs where conditions are not conducive to the reproduction of ponderosa pine.

Pinyon-juniper woodlands are typically found where average annual precipitation ranges from 250 to 500 mm (10 to 20 in.) (Brown 1994), although their best development occurs between 300 and 450 mm (12 and 18 in.) (West *et al.* 1975; West 1988). The amount and seasonality of the precipitation varies considerably within the range of these woodlands. This causes notable variation in stand composition and structure, as well as in the understory (West *et al.* 1975; West 1988).

The elevational range for pinyon-juniper woodlands is generally considered to be about 1,525 to 2,285 m (5,000 to 7,500 ft) (Woodbury 1947; West *et al.* 1975), although Springfield (1976) puts the lower bound closer to 1,370 m (4,500 ft). Hansen *et al.* (2004) record one-seed juniper trees scattered throughout the Wupatki Basin (within Wupatki NM), at an elevation of 4,500 feet. On the Coconino Plateau, the elevation range is restricted to 1,900 to 2,200 m (6,500 to 7,300 ft) (Merkle 1952; West *et al.* 1975). In the high deserts of California, the average elevation for this woodland type drops to 760 m (2,500 ft) (Johnsen 1962; West *et al.* 1975). The highest recorded elevation for pinyon-juniper woodlands is close to 3,000 m (nearly 10,000 ft) in the White Mountains of California where the Sierra Nevada creates an extreme rain shadow effect (St. Andre *et al.* 1965 cited in West *et al.* 1975).

The structure of a pinyon-juniper woodlands typically varies with elevation (Howell 1941), and this variation appears to be related to both temperature (West *et al.* 1975) and available moisture (Woodbury 1947; Wright *et al.* 1979). Pinyon, when it is present, tends to occupy the upper elevational limits of the stands (Arnold *et al.* 1964; West *et al.* 1975). Juniper most often dominates the lower elevations, while the mid-elevations usually contain a mixture of both trees (Howell 1941; Woodbury 1947; Merkle 1952;

West *et al.* 1975; Springfield 1976; Wright *et al.* 1979; Brown 1994). Although more resistant to harsh climatic conditions than other pines (Philips 1909), pinyons are not as adapted to arid conditions as junipers. The shorter and bushier juniper (Brown 1994) is more tolerant to drought and cold than the pinyon (West 1984). As such, juniper is able to survive both further downslope into the heat and aridity (Wright *et al.* 1979; West 1988; Brown 1994) and further north into the higher, colder latitudes (Wright *et al.* 1979; Brown 1994). The maps in Figure 2.1 show how this effects the distribution of both tree types. The thin-barked pinyon is also more susceptible to fire damage than the juniper (Philips and Mulford 1912).

In the Southwest, pinyon-juniper woodlands are frequently bordered upslope by ponderosa pine and Gambel oak, and downslope by grassland, oak woodland, or desert scrub (Emerson 1932; Woodbury 1947; Springfield 1976; Wright *et al.* 1979). Where pinyon-juniper woodlands meets ponderosa forests, pinyon-juniper will often occupy the harsher south and west slopes, with ponderosa pine claiming the cooler, damper north and east slopes (Philips 1909; West *et al.* 1975). Woodbury (1947) determined that the upper limits of pinyon-juniper woodlands are defined by biotic competition, while the lower limits are controlled by a combination of biotic competition, available moisture, and periodic fires.

The density of pinyon-juniper woodlands tends to vary with elevation and the boundary is often irregular and discontinuous, especially at the lower boundary (Woodbury 1947). In many instances, the stand density increases upslope until it reaches the upper ecotonic limit. Here it often thins rapidly, sometimes giving way to other vegetation types within only 60 to 90 m (200 to 300 ft) of elevation change (Woodbury

1947; Merkle 1952). In other areas, the densest growth occurs in the center of the belt (West *et al.* 1975). At higher, moister elevations the trees appear to grow faster and taller, reaching heights of 9 m (30 ft) or more (Lanner 1975). Trees at the drier, lower elevations tend to be considerably shorter, and very old trees under 2 m (6 ft) tall can be found in exposed areas (Woodbury 1947). The thickest woodlands are often pinyon-dominated and can be so dense that almost no understory is present (Springfield 1976). In some locations, the woodland thins gradually downslope until it reaches a savanna-like structure (Woodbury 1947). These savannas are usually juniper-dominated and often contain a lush understory of grass or shrubs (Springfield 1976). It is not uncommon for fingers of lower elevational vegetation, such as sagebrush (*Artemisia tridentata*) in the Great Basin, to extend upslope into the woodlands. It is also common for the woodlands to extend a considerable distance downslope into the coarser, rockier areas of canyons, mesas, and washes, leaving the finer-soiled areas to grasses or shrubs (Woodbury 1947). Unlike the gradual shift from woodland to savanna, the downslope boundary of these woodland protrusions is often abrupt and sharply defined.

Soils

The range of pinyon-juniper woodlands does not seem to be related to, nor limited by, either soil parent material or soil texture (Emerson 1932; Woodbury 1947; Merkle 1952; Johnsen 1962; West *et al.* 1975; Wright *et al.* 1979). While historical accounts often depict the location of pinyon-juniper trees as restricted to rockier areas (Phillips and Mulford 1912), studies have shown that both species can thrive in soils derived from a variety of parent materials, including limestone, sandstone, basalt, granite, and mixed alluvium (Emerson 1932; Springfield 1976). These soil types are typically low in fertility

(Howell 1941; Springfield 1976). Soil texture and depth also do not appear to be limiting factors. Both species can be found in shallow and deep soils, and with textures ranging from clay and clay-loam to cobbly and gravelly-loams (Springfield 1976). Although typically found in areas where thin soils predominate, at elevations below 2,000 m (6,560 ft) pinyon-juniper woodlands often occupy sites with deeper soils (Brown 1994).

Understory Vegetation

The composition of understory vegetation in pinyon-juniper woodlands varies greatly by region and tends to be related more to climatic patterns than to any generalized association with pinyon or juniper trees (West *et al.* 1975). In fact, pinyon and juniper are the only species common to these woodlands (West 1988). The mix of understory species appears to be entirely influenced by adjacent vegetation types, which will often appear in abundance in the adjoining forests, grasslands, and scrub steppes (West *et al.* 1975). On the Colorado Plateau, heavy cryptogamic⁵ soils are common (West *et al.* 1975).

While the wide distribution of pinyon-juniper woodlands allow it to include a rich variety of component species overall, a single stand will usually have a fairly low species diversity (West 1984). Brown (1994) considers pinyon-juniper woodlands to be one of the most structurally simplistic communities in the Southwest. In 1952, Merkle found only 22 understory species within 40 test plots of pinyon-juniper woodland on the south rim of the Grand Canyon. This led him describe the understory as being “quite sparse” (p 379). In a species diversity study of 30 plots in Utah and New Mexico, Harner and

⁵ A cryptogamic soil is composed of an association of algae, lichen, mosses, and fungi. Called crypto (Gk. for *hidden*) gamic (*marriage*), these organisms stabilize the soil, hold moisture, trap and fix nutrients, and provide protection for seed germination.

Harper (1976) found an average of just under 50 species per hectare (the overall species range was 24 to 87). West (1984) used the Harner and Harper results to compute an average population of one or two tree species, two or three shrubs, three to five perennial grasses, 10 perennial forbs, 20 annual grasses, and about six species of microphytes per hectare.

These low numbers contrast with the numbers found in vegetation types that typically abut pinyon-juniper woodlands, especially on their upslope sides. Griffis *et al.* (2001) found 195 species (156 native, 39 exotic) of understory plants in 16 stands of ponderosa pine forest along the Mogollon Rim, and Laughlin *et al.* (2004) found 118 species across 27 plots in ponderosa pine forests along the north rim of the Grand Canyon. Interestingly, in a more local study, Fisher and Fulé (2004) found only an average of 32.6 species across 26 plots of ponderosa pine forest along the south-facing slopes of San Francisco Mountain. In studies of typical downslope vegetation types, Hochstrasser *et al.* (2002) found 67 species in 30-40 plots of short grass steppe in north-central Colorado, 50 species in Chihuahuan Desert grassland in southern New Mexico, and 52 species in a transition site between the two grassland types in central New Mexico.

Unlike the tree species, the understory vegetation in a pinyon-juniper woodlands can be influenced by soil structure (Thatcher and Hart 1973). Understory vegetation also appears to be affected by stand characteristics, such as percent canopy cover (Arnold *et al.* 1964; Ueckert *et al.* 2001), fire history (Arnold *et al.* 1964; Thatcher and Hart 1973), browsing history (Fuhlendorf *et al.* 1996), and grazing history (Arnold *et al.* 1964; Brotherson *et al.* 1983). On an individual tree-scale, influences on understory vegetation include tree size (Springfield 1976; Fuhlendorf *et al.* 1996), canopy closure (Schott and

Pieper 1984), canopy height (Schott and Pieper 1984; Armentrout and Pieper 1987), and distance from tree stem (Schott and Pieper 1984; Armentrout and Pieper 1987; Fuhlendorf *et al.* 1996). Each of these factors influence the depth of duff (Schott and Pieper 1984), shading (Schott and Pieper 1984), root competition (Johnsen 1962), interception of precipitation (which appears to be greater with juniper than pinyon) (Johnsen 1962), and allelopathic effects (again, greater with juniper than pinyon) (Arnold *et al.* 1964; Johnsen 1962; Armentrout and Pieper 1987).

The understory vegetation in pinyon-juniper woodlands is typically sparse and tends to occupy the open spaces between trees, rather than under the tree crowns. In a pinyon-juniper woodland in Arizona, Arnold *et al.* (1964) found a 40-65% decrease in herb and forb production (measured in pounds per acre) with a 10-30% increase in canopy coverage, and an 82% reduction when canopy cover was 50%. Under redberry juniper in Texas, however, Ueckert *et al.* (2001) found herbage production declines slowly as canopy cover reaches about 14%, but increases rapidly after canopy cover reaches 20%.

Changes in Woodland Cover

While there is broad agreement that Euro-American activities have impacted pinyon-juniper woodlands (Woodbury 1947; Johnsen 1962; Ellis and Schuster 1968; Young and Evans 1981; Lanner and Van Devender 1998; Miller *et al.* 1999; Romme *et al.* 2003), there continues to be debate over just how these activities have altered pre-settlement stand structure, geographic range, and fire regime.

Descriptions and Theories

While research has been done on the dynamics of pinyon-juniper woodlands (Lanner and Van Devender 1998; Romme *et al.* 2003), especially old-growth woodlands (Miller *et al.* 1999), there is still no conclusively established cause for woodland expansion (Lanner and Van Devender 1998). Most scientists agree that some combination of the following factors are responsible:

1. the curtailment of tree population control by fire due to fire suppression and the removal of fine fuels by grazing (Leopold 1924; Sauer 1950; Johnsen 1962; Arnold *et al.* 1964; Ellis and Schuster 1968; Blackburn and Tueller 1970; Burkhardt and Tisdale 1979; Young and Evans 1981; Hutchinson *et al.* 2000) ,
2. a marked reduction of grass and its competitive effects due to overgrazing (Leopold 1924; Woodbury 1947; Johnsen 1962; Blackburn and Tueller 1970), and
3. climate fluctuations favorable to tree establishment (Johnsen 1962; Arnold *et al.* 1964; West 1984; Soulé *et al.* 2003).

As early as 1924, Aldo Leopold postulated that lower fire frequency and reduced grass competition were increasing tree populations. He correlated both of these to the introduction of Euro-American grazing practices. Leopold (1924) noted the perception that “the brush has ‘taken the country’ ” (p. 1) was already widespread in the Southwest by that time. Working in south and central Arizona, Leopold used fire scars, tree-ring counts, and cattle-branding records to support his claim that considerable range degradation had occurred since Euro-American settlement. He claimed that this

degradation reduced tree population control by fire and grass competition to the point that the trees were able to reach what he considered their natural ecological domination.

Although Leopold considered the pre-settlement condition of thick grass and fewer trees a “transitional type” (p. 2), he also considered it critical to the preservation of watershed integrity. This transitional condition had historically been maintained by lightning and indigenous anthropogenic fire; fires which, even by 1924, could no longer be sustained over grasslands that he described as having been “grazed to death” (p. 2).

In 1962 Johnsen studied one-seed juniper in northern Arizona, including some sites located on Deadman Flats in the Coconino National Forest (Figure 1.1). In this study, he determined that the primary change in juniper involved both an increase in tree density in formerly open juniper stands and the movement of trees into grassy openings within juniper woodlands. He also observed that the trees were migrating into lower slopes and across valleys previously dominated by grass. Since grassland fires frequently do not kill established juniper trees, Johnsen did not think fire exclusion was sufficient to explain these changes. He thought that a population increase of this scale would also require climatic periods favorable to tree establishment. Looking into the effects of wet and dry periods on both juniper and grasses, Johnsen found that grasses were able to out-compete young juniper trees under drought conditions. Under more mesic conditions, however, the juniper effectively out-competed the grasses.

In the late 1990s, Ffolliott and Gottfried (2002) reevaluated the data collected from a 0.81 ha (2 ac) pinyon-juniper plot also situated on Deadman Flats (Figure 1.1). The plot had been established in 1938 when each tree had been numbered and tagged, and species, height, and crown diameter had been recorded. Data from the same plot were recollected

in 1948, 1958, and 1991. Reviewing these data, Ffolliott and Gottfried concluded that the tree density had remained essentially stable. While there were slightly more trees (an increase of 1.1 pinyon and 0.1 juniper trees per acre per 50 years), Ffolliott and Gottfried determined that, contrary to Johnsen's observations, the trees had primarily grown in size, rather than expanded their range. The stand was clearly young when the plot was established (average height was 1.3 ft for pinyon and 2.3 ft for juniper) and no mature, senescent or dead trees were recorded. The absence of mature/dead trees is something many researchers have used as an indication of short-term arboreal occupation (Burkhardt and Tisdale 1969; Young and Evans 1981; West *et al.* 1984). Other researchers consider tree size as important. Merkle, for example, in a 1952 survey of pinyon-juniper woodlands near the Grand Canyon, reported uniform and almost complete coverage by both species (92.5% juniper, 100% pinyon). He specifically pointed out, however, that the "greater abundance of *Pinus* is due to a great many small specimens less than one foot tall" (p. 382). Ffolliott and Gottfried seemed to ignore both the lack of mature/dead trees and the apparent youth of the stand in 1938, and concluded that the "common perception that pinyon-juniper woodlands are occupying more land might be related more to the observed increase in crown diameter and total height of existing trees than to an increase in tree numbers" (Ffolliott and Gottfried 2002, p. 7).

The findings of West *et al.* (1975) and Romme *et al.* (2009), on the other hand, agreed with Johnsen. They determined that pinyon-juniper woodlands had moved, both up and downslope, into what was previously grassland or scrub-steppe throughout the West. West (1988) also found that pre-existing woodlands, once more open and savanna-like, had increased in density, replacing and pushing out herbaceous and shrub

understories that had formerly been more abundant. Citing data obtained from fire scars, historical documents, dendrochronological data, and relic areas⁶, West (1984) considered fire to have been an important control in the past. This concept is further supported by the fact that the oldest trees (up to 1,000 years old) are usually confined to steep, rocky slopes, dissected topography, or drier terrains where fire would be naturally restricted (Burkhardt and Tisdale 1969; Young and Evans 1981; West *et al.* 1984; West 1988; West 1999; Soulé *et al.* 2003, Romme *et al.* 2009). Early in the last century, Emerson (1932) and Cottle (1931, cited in Emerson 1932) used the restriction of pinyon-juniper woodlands to such rocky areas as evidence that the true dominants of the range were xeric grasses. Emerson argued that in northern New Mexico the woodland trees grew primarily in areas which, topographically or edaphically, excluded grasses.

West (1999) agrees that reduction of fire frequency has influenced pinyon-juniper woodland expansion. Some scientists (Baker and Shinneman 2004; Romme *et al.* 2009), however, caution against considering all pinyon-juniper woodlands as having the same fire history. They propose three distinctly different fire regimes for woodlands found in different edaphic, topographic and climatic conditions, and acknowledge that there are likely more.

Like Johnsen, West also considers the effects of climate. Pointing out the notably warmer and wetter period in many areas between 1850 and 1940 - conditions that probably favored both tree seed production and competition over grasses and other understory plants (Johnsen 1962) - West suggests that this period of tree expansion was

⁶ Relic areas are places where the vegetation is old and is determined to not have been altered by modern anthropogenic activities.

probably exacerbated by the impacts of grazing and other Euro-American practices, not caused by it. More currently, Breshears *et al* (2005) have determined that current drought conditions are causing region-wide dieback of pinyon-juniper woodlands in some areas across the West.

Other studies also point out the variable impact climate can have on pinyon-juniper woodlands. While West *et al.* (1975) note that the weather from 1850 -1940 was more mesic, Phillips (1909) writes that the Southwest experienced a severe drought from 1889 to 1904 that killed thousands of trees, primarily pinyons. In Arizona, Arnold *et al.* (1964) determined that many pinyon-juniper stands had become established in 1905 and 1919, years that had >150% normal precipitation.

Although woodland increase has been recorded in areas free of grazing, both historically and presently (Ellis and Schuster 1968), in most areas the increase closely corresponds to the introduction of livestock (Cottle 1931, cited in Emerson 1932; Arnold *et al.* 1964; Blackburn and Tueller 1970; Burkhardt and Tisdale 1969). West (1984) suggests that both the reduction of vegetative competition due to grazing and the increased dispersal of seeds in livestock feces have contributed to the acceleration of this process. Johnsen (1962) and West (1984) also consider an increase of seed dispersal by livestock to be important, although other authors discount this. For example, Emerson (1932) and Lanner and Van Devender (1998) have shown that rodents and birds are extremely efficient seed dispersers, and their presence predate the introduction of domestic livestock.

The result, in the absence of fire as a control, has been what West (1984) calls “the full climatic climax expression” (p. 1301) of pinyon-juniper woodlands, the same concept

postulated by Leopold (1924). Leopold considered the “virgin condition previous to settlement” (p. 7) to be a “temporary type” (p. 7), artificially held back from its natural climatic expression by fire, which acted as the inhibiting disturbance (Leopold 1924; Sauer 1950; Johnsen 1962; Arnold *et al.* 1964; Ellis and Schuster 1968; Blackburn and Tueller 1970; Young and Evans 1981; Hutchinson *et al.* 2000, West 1999). As many researchers consider pinyon-juniper woodlands to represent a successional climax (Leopold 1924; West *et al.* 1975; West 1984), the eventual dominance of the trees in any area capable of supporting them is to be expected as long as climatic conditions remain favorable for tree regeneration, and no disturbance enters the system to prohibit the progression.

Lanner and Van Devender (1998) consider the migration of junipers to lower elevations to be “uncontested” (p. 179). They do not, however, believe that there is enough evidence to suggest that pinyons are doing the same. In his description of biotic communities, Brown (1994) would seem to agree. Lanner and Van Devender, in fact, specifically warn against the lumping together of two species as biologically different as pinyon and juniper into a single category. Although they often co-dominate a woodland, Lanner and Van Devender claim that the conclusions reached about juniper (Johnsen 1962) are often inappropriately applied to pinyon. Additionally, pinyon has been more heavily used by Euro-Americans for fuel wood, fencing, lumber, and charcoal production than juniper. Because these activities decimated pinyon populations, especially in the Great Basin, Lanner and Van Devender suggest that pinyons are not necessarily advancing into new areas, but are simply reestablishing their historical territory.

Although many physical characteristics do not seem to present limiting factors, recent studies point to the influence certain site conditions have on both stand structure and the attendant fire regime (Miller *et al.* 1999, Romme *et al.* 2003). Romme *et al.* (2003) devised a hypothetical set of three pinyon-juniper woodland “types”, each influenced by soil, climate and topography, and each having distinct historical fire regime. The three types are (1) *pinyon-juniper grass savanna*, (2) *pinyon-juniper shrub woodland* and (3) *pinyon-juniper forest*.

1. The *pinyon-juniper grass savanna* occurs where soils are fine textured, topography is gentle, and enough summer precipitation falls to produce a well-developed grassland. Historically, frequent low-severity grass fires maintained a very open stand structure by killing or thinning young trees. More recently, this type has been severely impacted by grazing and fire exclusion, resulting in a notable increase in the tree population and an altered fire regime from frequent low-severity fires to infrequent stand-replacing fires. This type is found in Arizona, New Mexico, and northern Mexico.
2. The *pinyon-juniper shrub woodland* occurs primarily in areas of the northern and central Great Basin that receive mostly winter precipitation and have deep soils that support an abundant shrub layer. As shrubs support more intense fires than grass, these areas likely tended toward stand replacing fires even prior to Euro-American settlement. Fire-free intervals of a few years to a few decades would allow tree establishment, but these intervals would be followed by high-severity fire that would kill most of the trees, perpetually keeping these areas at a lower successional stage of shrub dominance. Grazing and fire exclusion have allowed

these woodlands to mature to tree dominance, resulting in heavy, continuous fuel loads that are more likely to result in even larger and more severe fires.

3. The *pinyon-juniper forest* only occurs where the soils and topography combine to protect the stands from frequent fire. It is found in scattered locations throughout the Colorado Plateau, Great Basin, central Oregon, southern California mountains, and central Arizona. This type is typically situated on soils too shallow or coarse-textured to support a continuous cover of grass or shrubs, or in areas where topography provides a natural barrier to fire, such as cliffs and bare slopes. This type may escape fire for centuries, so that when fire does occur it is typically severe and stand-replacing. These areas have not been affected by Euro-American activities and have not yet shifted from their natural fire regimes.

The observations of Aldo Leopold (1924) could be interpreted to support the two pinyon-juniper types that one might expect to find in Arizona - the *pinyon-juniper grass savanna* and the *pinyon-juniper forest*, each with its attendant fire regimes. In southern Arizona Leopold describes “universal fire scars on all the ... trees old enough to bear them” and “old juniper stumps, often leveled to the ground, evidently by fire” (Leopold 1924, p.1). While he does not include a geographic or topographic context for these observations, the first is suggestive of surface fire, while the second describes a stand replacing fire.

Although areas in the Tusayan National Forest⁷ described by Phillips and Mulford in a 1912 Forestry Circular had already been grazed for at over 40 years, their descriptions also suggest the historical presence of both *pinyon-juniper grass savanna* and *pinyon-*

juniper forest types. They describe an expanse of Utah juniper stands that stretched from the “desert” (an archaic term for treeless grasslands) in the west to the pure stands of ponderosa pine on San Francisco Mountain. This expanse included a grass savanna-like vegetation structure, which Phillips and Mulford describe as “widely scattered individuals [of juniper] encroaching on the desert” (p. 6) as well as island stands of juniper within the grasslands. These island stands were usually found on rocky volcanic ridges, and sometimes included pinyon (Phillips 1909). They also describe large, pure juniper stands usually located on *malpais* (basaltic lava) or adobe (heavy clay) sites. Neither of these types of sites could support much grass or shrubs growth, and both were fairly protected from fire by the lack of fine fuels. Phillips and Mulford reported in 1912 that most fires were surface fires, with occasional crown fires. Interestingly, they also reported that Utah juniper was less damaged by these fires than was ponderosa pine.

Fire

The relationship between fire and tree establishment can be difficult to define. This is especially true where historical fire regimes appear to have been altered by the removal of fine fuels through grazing and decades of active fire suppression (Huffman *et al.* 2008, Huffman *et al.* 2009). Additionally, as noted by Wright *et al.* (1979), the historical role of fire cannot be separated from the effects of vegetative competition and climate (Leopold 1924; Johnsen 1962; Burkhardt and Tisdale 1979).

In any case, fires that reoccur every 10 to 30 years (Leopold 1924) can effectively prohibit long term juniper establishment. Arnold *et al.* (1964) examined two previously

⁷ The Tusayan National Forest is now the South Unit of the Kaibab National Forest and portions of the northern Prescott National Forest.

wooded areas near Cosnino, Arizona (19 km/12 mi east of Flagstaff) that had burned. One area had burned once in the early 1920s, the other had burned twice - first around 1885 and again in the 1920s. The once burned area still had some surviving juniper trees but was otherwise dominated by rabbit-brush (*Chrysothamnus nauseosus*) and blue grama (*Bouteloua gracilis*). The twice burned area had no surviving junipers and was dominated by blue grama.

The following recent studies support the hypothesis that fire historically played a role in prohibiting pinyon-juniper establishment throughout the West:

- Looking at western juniper on a hill in northern California, Young and Evans (1981) found single age stands established between 1850-1930, roughly corresponding to Euro-American settlement in the 1860s. As researchers have found in other areas (Burkhardt and Tisdale 1969; West 1984), these relatively young stands lacked stumps, snags or senescent trees that would indicate long-term juniper occupation of the site. Only on the topographically fire-resistant northern slopes did they find stands of mixed aged trees, complete with snags and senescent trees, many of which had been established prior to 1600.
- Ellis and Schuster (1968) studied the age distribution of redberry juniper on a butte in northwest Texas. They found the oldest trees on the north-facing mid-slopes, which are the most fire protected zones in an area where fires tend to be driven by prevailing southwesterly winds. On the top of the butte and on upper southfacing slopes, which contained a scattering of older trees, they determined that a spike of juniper establishment had occurred in the mid-1800s. This is about

the same time cattle grazing increased in the area, and the beginning of the great trail drives which occurred from 1866 to 1895.

- Miller *et al.* (1999) found that in many areas of the Great Basin, pre-settlement old-growth trees are found only on rocky slopes and ridges that provided natural protection from fire.
- In central Oregon, Soulé *et al.* (2003) found an increase in western juniper on all eight sites they studied, with the disturbed sites and the younger stands showing the greatest increase. They, too, found the oldest trees on rocky, upslope outcrops that were naturally protected from fire. Even considering wet years conducive to seedling establishment and increases in atmospheric CO₂, which they claim may make junipers even more drought tolerant, they concluded that it was likely the lack of fire that allowed so many trees to reach maturity.

Climate, weather, fine fuel load, woodland structure, and topography all influence how fire interacts with a pinyon-juniper woodlands (Romme *et al.* 2009, Huffman *et al.* 2009). Although both pinyon and juniper trees can be readily damaged by fire (Philips and Mulford 1912; Arnold *et al.* 1964), fire does not readily spread through mature pinyon-juniper woodlands. Even when sufficient fine fuels are available, fire will tend to die down unless sufficient drought and windy conditions are also present (Jameson 1962; Arnold *et al.* 1964).

Jameson (1962) observed two prescribed burns conducted in the Coconino National Forest in 1956 with the intent to kill scattered, mature juniper trees to improve forage for cattle. Jameson found that, even with sufficient fine fuels available, if the wind velocity was too low or the winds were out of the north, the fire tended to “hug” the ground and

did very little damage to the trees. He observed that the understory was lighter on the north side of the trees and apparently diminished the intensity of the fire. When winds were from the southwest, however, they pushed the fire toward the trees on the side that had heavier understory herbage and this higher fuel load carried the flames to the base of the trees. Trees that had sufficient tumbleweed build up at the base tended to torch, and tree mortality was notably higher. The marked decline in understory herbage that occurs with increased tree canopy (Woodbury 1947; Arnold *et al.* 1964; West 1984) make dense woodlands even harder to burn than those with an open structure. Lightning strike ignitions into a dense woodland that is not sufficiently dried, or under calm weather conditions, routinely cause fires that are confined to one or a few trees (Floyd *et al.* 2004). Often drought conditions need to exist for many years before the woodland is dry enough to support a crown fire (Floyd *et al.* 2004).

Topography has an effect on fire behavior as well, and, as noted above, it is common to find the oldest trees situated on rocky, often north-facing, slopes (Ellis and Schuster 1968; Young and Evans 1981, Miller *et al.* 1999). While increased moisture may aid initial tree establishment, trees in rocky areas likely survive to maturity because they were topographically protected from fires driven by prevailing southwesterly winds. I observed an example of this fire protection in Wupatki NM after the 2002 Antelope Fire. Driven by southwesterly winds, the Antelope Fire burned across one of the many lava topped mesas that stretch from the San Francisco Volcanic Field into the study area. The south and west sides of the mesa have gentle, grass-covered slopes, while the cliff-like north and east sides are the rugged lateral ends of the lava flow. These sides are blocky and heavily cindered, and primarily support scattered juniper trees from the base to mid-

slope. The fire clearly raced up the south and west sides of the mesa and then across the top. Looking over the north and east edges of the mesa, it was evident where the tops of the mature juniper trees had been scorched by the wind-driven flames, but the topography and lack of fine fuels had prohibited the fire from dropping off the mesa. While almost all of the small juniper trees on the mesa had been killed, the larger trees on the north and east slopes were generally damage-free.

Aerial Photography

Historical Aerial Photography

The first photographs known to be taken from an aerial platform date back to 1859, when Gaspard Felix Tournachon took oblique photographs of Paris from a hot air balloon (Avery and Berlin 1992). Wilber Wright and a Pathé news cameraman took the first airplane photographs of Centrotelli, Italy, in 1909. As with many technologies, warfare provided both the motivation and resources that gave aerial photography its first big boost. General George McClellan used balloon-based aerial photographs during the U.S. Civil War to track Confederate troop positions in Virginia. It was World War I, however, that really brought the aircraft and camera together, and inspired important improvements in both cameras and films. Major scientific use of aerial photographs (airphotos), however, did not emerge until after World War II.

Although widespread vertical airphoto coverage within the United States was not available until the 1930s (Rango *et al.* 2002), domestic use actually began in the late teens. The Coast and Geodetic Survey (C&GS) of the U.S. Department of Commerce was interested in using aerial photographs for coastal mapping projects (Smith 1981).

Working with the Army and Navy Air Services, the C&GS performed its first test flights over Atlantic City and Cape May in New Jersey in June, 1919. Three cameras were used: (1) the Army L-type camera, (2) the experimental K-1 camera and (3) the Bagley 3-lens camera. The L-type camera recorded images on glass plates and held 25 plates in its magazines⁸. One magazine was attached to the top of the camera and held the plates before exposure. After exposure, the plates were slid into another magazine attached to the rear of the camera. The K-1 camera was designed to use roll film. The Bagley 3-lens camera, also called a trimetrogon camera (Lattman and Ray 1965), was designed to take one vertical airphoto, and two adjoining oblique airphotos. This allowed for a larger ground coverage than an exposure from a single lens camera (Figure 2.2). During print processing, the oblique photographs were reprojected onto the plane of the center photograph with a transforming printer (Smith 1981).

It was the responsibility of the pilot to keep a level, straight flight course while maintaining a constant speed and altitude (Smith 1981). The camera operator was responsible for timing the exposures at intervals of 10 to 15 seconds, depending upon aircraft speed and altitude. The results of these tests were not particularly impressive (Smith 1981). Because the C&GS was interested in compiling accurate maps, the geometrical distortion of the airphotos, mostly due to tilt, restricted their use to updating existing maps with current interpretive details. Other problems that limited the usefulness of these early aerial photographs included haze, sun glare, and cloud interference. It was also discovered that using pilots and cameramen who were genuinely interested in

⁸ A magazine is a special compartment attached to the camera designed to hold the glass plates.

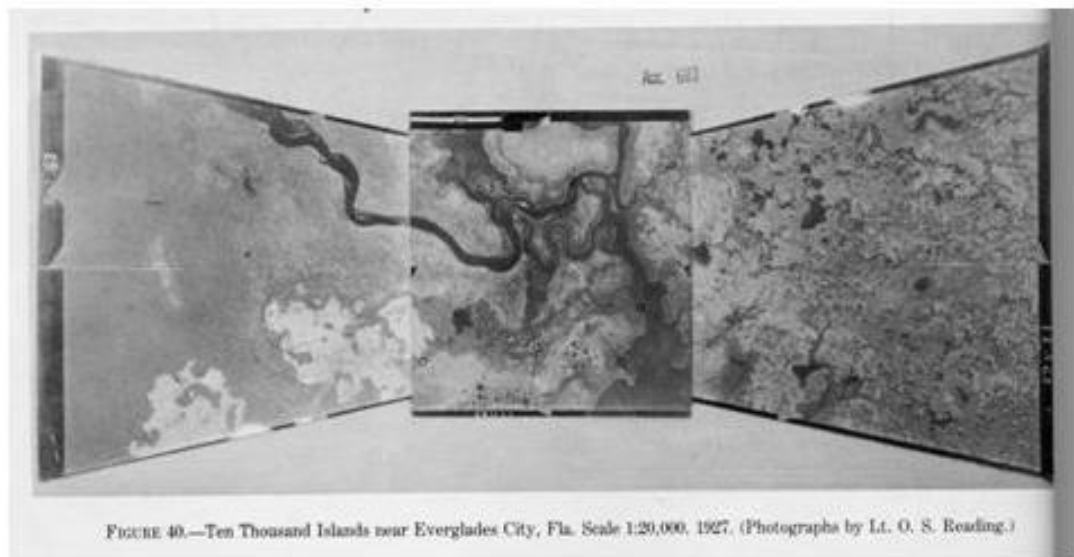
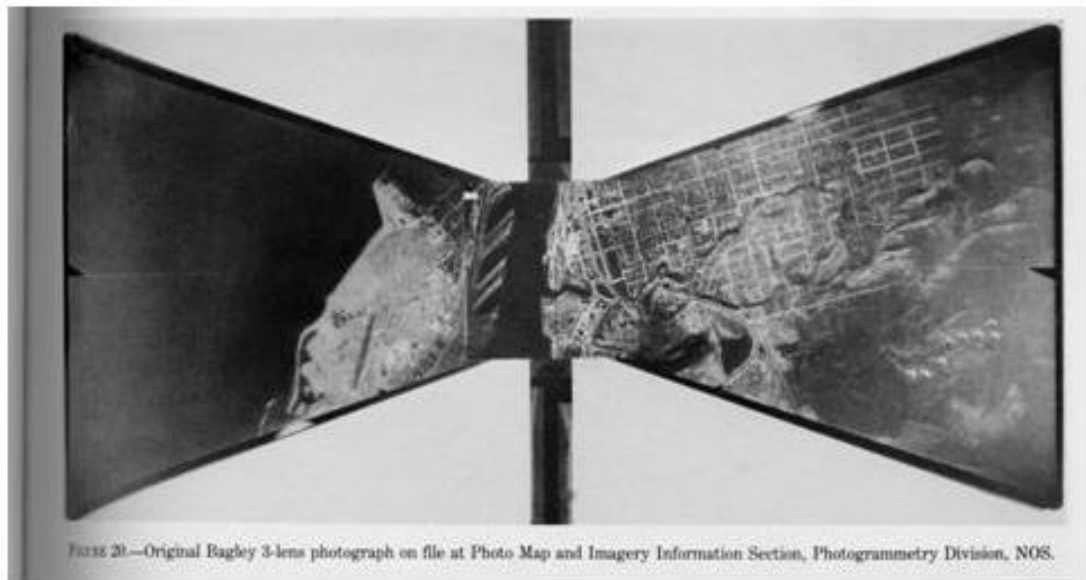


Figure 2.2. Aerial photographs taken with a Bagley trimetrogon camera.

The top airphoto set was taken in 1920, while the bottom set was taken in 1927 with a later version of the same camera.

Copied from Smith 1981.

mapping was essential, as boredom on the part of either party degraded the quality of the photo coverage.

Regardless of the dubious initial results, interest in aerial photography for mapping purposes remained high (Smith 1981). As both flying and establishing ground control were expensive, the desire to cover more area with fewer photographs spurred research into multi-lens cameras. By 1930, a 5-lens camera that could cover a 5-mile ground swath from a flight altitude of 5,000 feet (providing a photo scale of 1:10,000) was in use (Figure 2.3). Each lens of this camera had its own roll of film. As with the airphotos acquired with from the 3-lens Bagley camera, the oblique photographs were reprojected with a transforming printer (Smith 1981). The five photographs were then assembled and mounted to provide a single, 32-inch wide composite vertical airphoto. Due to the cross-shape of this final composite, it was necessary to rotate the camera 45° between exposures to ensure complete ground coverage. Although these cameras could provide a large area coverage and the reduction in production costs was attractive. Because four of the five views were oblique, they produced photos that could have very large radial angle errors (Smith 1981).

By the mid-1930s, improvements in film structure helped reduce distortions caused by film shrinkage, and the introduction of the vacuum paten insured that the film was perfectly flat for each exposure (Smith 1981). By 1936, a 9-lens camera considered suitable for large-scale aerial photography had been developed. All nine lenses would simultaneously expose separate images on a single roll of 23 inch wide film (Figure 2.4). The center lens produced a true vertical image, while the other 8 lenses were directed 38°



Figure 2.3. Aerial photographs taken with a 5-lens camera.
*The top airphoto set shows the five separate photographs.
 The lower airphoto set shows the transformed, assembled composite.
 Copied from Smith 1981.*

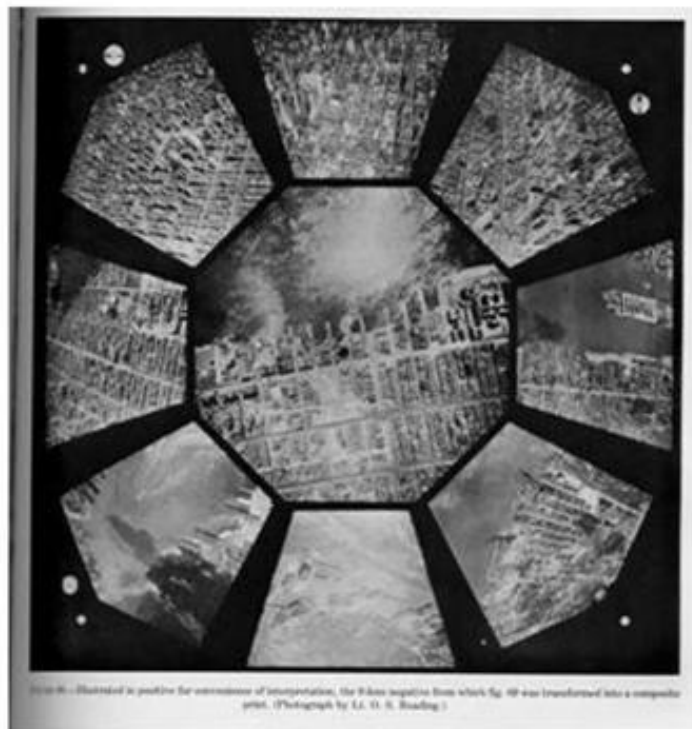


Figure 2.4. Aerial photographs taken with a 9-lens camera.
The top airphoto set shows the nine separate photographs. The lower image shows the transformed, assembled composite. Copied from Smith 1981.

away from the axis of the center lens by means of stainless steel mirrors. During processing, a specially designed transforming printer was used to produce a single, composite vertical airphoto.

First, the central image was projected directly onto the processing paper. Then the eight oblique photographs were each reprojected into the plane of the center image in the appropriate location on the same sheet of paper. From a flight height of 13,750 feet, the resulting ground coverage was an 11-mile ground swath at a scale of 1:20,000, for what amounted to an effective 130° field of view. Nine-lens cameras were used until 1961, when the cost of custom-made film and the complexity of the printing process made them uneconomical.

Modern Aerial Photography

Modern aerial photographs are taken with high-precision mapping (cartographic) cameras designed to produce high quality vertical aerial photographs with minimal geometric distortions (Avery and Berlin 1992). The United States Geological Survey (USGS) provides aerial photographic coverage for most of the United States, typically in the 1:12,000-scale digital orthophoto quarter quadrangle (DOQQ) format (USGS 2001). DOQQs are high quality, digitized aerial photographs that have been orthorectified to the traditional USGS 3¾ minute quarter quadrangle index and have a 1-meter ground and pixel resolution. Most DOQQs are panchromatic (grayscale) although color-infrared (CIR) DOQQs are available for some areas.

The photographs used to make DOQQs are centered on the standard USGS quarter-quadrangle (7½ minute series, 1:24,000 scale). They are acquired from a flying height of at 20,000 feet above mean terrain (AMT) and must meet the National Aerial Photography

Program (NAPP) accuracy standard (USGS 2001). The Digital Elevation Model (DEM) used for orthorectification must have the same ground coverage and a root-mean-square (RMS) error in elevation of no greater than 7 meters (USGS 2001).

Repeat Aerial Photography

Aerial photographs can be uniquely useful for monitoring environmental changes at the landscape-scale (Lattman and Ray 1965; Rango *et al.* 2002). A number of researchers have used repeat aerial photography to monitor changes in woodland cover. For example, Mast *et al.* (1997) used this technique to quantify the expansion of ponderosa pine into grassland along the Colorado Front Range. Miller *et al.* (1999) used it to monitor changes in cover of ponderosa pine and alligator juniper in southwestern New Mexico. Jackson and Betancourt (2000) used it to record Utah juniper woodland expansion in Wyoming. Soulé *et al.* (2003) used it to track changes in western juniper cover in central Oregon.

Modern vertical aerial photographs may also be planimetric, which allows fairly accurate measurements to be made from them (Hutchinson *et al.* 2000). When digitized, aerial photographs can provide a powerful, objective tool for quantifying environmental change on a landscape-scale, while providing a data set that can be reexamined by others to validate findings. Furthermore, the large ground coverages aerial photographs depict can provide the opportunity for randomized sampling on a landscape-scale (Lattman and Ray 1965; Rango *et al.* 2002).

Repeat Terrestrial Photography

Terrestrial, or ground, photographs are available from as early as the mid-1800s (Leggat 1995). Although these images have tremendous historical value, their usefulness

for scientific inquiry is considered by some to be limited (Rogers *et al.* 1984, Hutchinson *et al.* 2000). Terrestrial photographs are typically oblique and capture only small portions of a landscape. Their availability varies widely, and control over what scenes were recorded is often lacking, as is control over the parameters that were used during picture taking and film processing (Rogers *et al.* 1984). As most historical terrestrial photographs were taken for personal reasons by homesteaders, miners, and tourists, they are often biased in their perspective. Even those taken by scientists are usually not random samples of a controlled experiment, but may have been taken to record extreme or unique situations. Hutchinson *et al.* (2000) warn against considering historical terrestrial photographs as representative of a region.

Nevertheless, when a fairly large number of terrestrial photographs are available for a particular area, or when historical terrestrial photographs can be coupled with historical aerial photographs to provide a larger context, they can provide valuable, auxiliary visual data.

Contiguous Quadrats

To document temporal changes in a landscape, or to compare differences between landscapes, it is necessary to quantify landscape patterns (Krebs 1999; Turner *et al.* 2001). The aerial photographs used in this study represent landscape-scale vegetation “maps” of pinyon and juniper trees at two points in time. Contiguous cells, or quadrats, are one way of characterizing various types of maps, including vegetation maps (Burt and Barber 1996, Dale 1999, Krebs 1999). When laid out in either one-dimensional transects or two-dimensional grids (Dale 1999), contiguous quadrats are helpful in identifying and

documenting changes for almost any subject that has a spatial structure (Fortin *et al.* 2002). The World Health Organization, for example, suggests using contiguous quadrats to monitor litter on small beaches (Williams *et al.* 2000).

Contiguous quadrats can be particularly helpful in the spatial analysis of plants within a fixed frame of reference (Dale 1999), or when examining patterns along a gradient (Dale 1999, Fortin *et al.* 2002). Researchers working in Helsinki used contiguous quadrats to document drought damage to urban forests (Holopainen *et al.* 2006). In the Helsinki study, a grid of approximately 15,000 0.25 ha (0.62 acre) cells was placed over aerial photographs of the urban parks. The grid values were then manually filled in using nine classes of visually assessed tree damage. In Sweden, Byers (1992) placed variously sized contiguous quadrat grids over the point data of trees infested by bark beetles to produce cell contour maps of point densities in a manner similar to the isonome maps devised by Ashby and Pidgeon in the 1940s.

As in all sampling techniques, there is some risk involved in using contiguous quadrats, especially in regards to scale and its influence on recorded distribution. Unless the study area is large enough in relation to the size of the organisms being examined, spatial autocorrelation, which tends to cause adjacent cells to be more common to each other than distance cells, could lead to faulty conclusions on density and clumping (Dale 1999). As with any sampling technique, care must be taken in selecting both the study area size and sample unit size to limit any confounding influence that either can have on the test results (Dale 1999; Krebs 1999; Turner *et al.* 2001).

Although contiguous quadrats are not independent random samples of a population in the way random, individually placed quadrats are, they nevertheless provide certain

benefits. When determination of pattern is the desired result, for example, contiguous quadrats are better at capturing pattern characteristics than are individually placed quadrats (Dale 1999; Krebs 1999). Regardless of the technique used to space individual quadrats (randomly placed or uniformly spaced), there is the unavoidable interaction between the scale of the pattern and the scale of the spaces between quadrats. Additionally, compared to randomly placed individual quadrats, contiguous quadrats represent a high intensity of sampling. Unfortunately, this means that data collection can be time consuming and expensive.

Contiguous quadrats can be used in a variety of ways when analyzing landscape-scale vegetation change. A continuous grid of densities can be used to provide colored contour (isoline) maps which aid in the visualization of patterns, as well as cell-count (frequency) histograms for statistical comparison (Byers 1992). Both cell-to-cell and histogram comparisons can be performed on fixed grids of contiguous quadrats (Byers 1992), which can be useful in temporal change studies.

CHAPTER 3

STUDY AREA

The study area is situated in north-central Arizona, approximately 48 km (30 mi) northeast of Flagstaff (Figure 3.1). It lies within the San Francisco Volcanic Field and on the southern portion of the Colorado Plateau. This is a landscape-scale study that examines 13,584 ha (33,567 acres) of land, with approximately half falling within of Wupatki National Monument (NM) and half within the adjacent Coconino National Forest (NF) to the south.

The study area is delimited by the Wupatki NM boundary to the north, the Wupatki NM boundary and Arizona State Highway 89 to the west, Doney Cliffs and Woodhouse Mesa to the east, and the southern edge of Township 26 North to the south. The rolling grasslands and juniper savannas and woodlands that stretch west of the Doney Cliffs to the Wupatki NM boundary comprise the Wupatki portion of the study area. The Coconino portion, located in the Coconino NF directly to the south, is more uniformly and heavily wooded.

Topography and Geology

The topography in the vicinity of the study area slopes downward from San Francisco Mountain (3,850 m/12,633 ft) (Bezy 2003) in the southwest to the Little Colorado River (1,305 m/4,280 ft) in the northeast (SCS 1971). Within the study area, the elevation also varies from a maximum at the southwest corner (1,850 m/ 6,000 ft) to a minimum at the northeast corner (1,550 m/ 5,080 ft) for a local relief change of 300 m (920 ft).

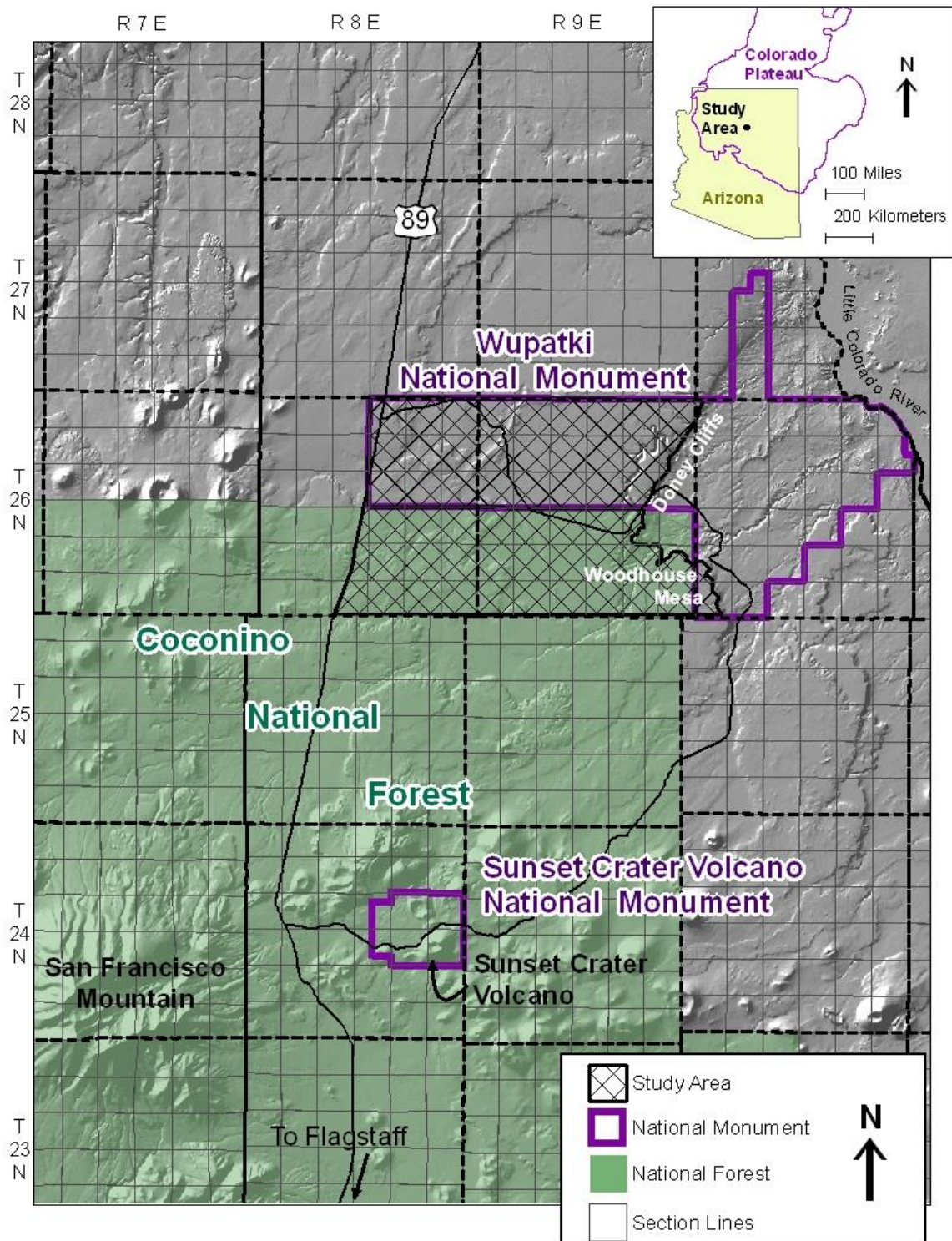


Figure 3.1. Map showing study area location.

The northern half of the study area is within Wupatki National Monument, while the southern half is in the Coconino National Forest.

Cinder cones dot the landscape and dark lava flows cover much of the study area. The most prominent sedimentary rocks are the buff colored Kaibab Formation (primarily limestone) of Permian age and the red Moenkopi Formation (primarily sandstone) of Mesozoic age (Hanson 2006). Although the Moenkopi Formation caps the entire Wupatki Basin (Figure 3.2), only isolated remnants of this younger strata exist within the study area, typically as scattered mudflat deposits. Elsewhere, the Moenkopi Formation is overlain by protective lava flows.

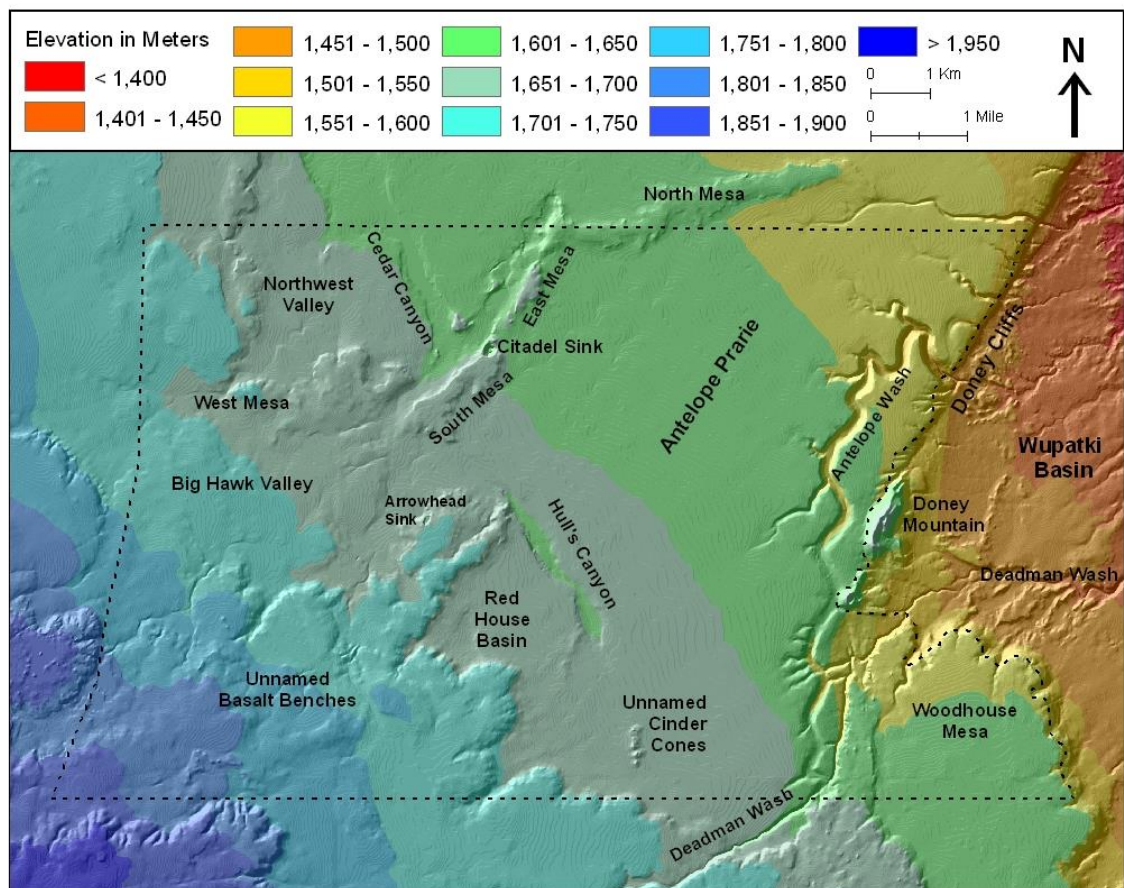


Figure 3.2. Elevations and major topographic features in the study area.

This figures shows the descending basalt benches and basalt topped mesas in the study area. The boundary of the study area is shown by dashed lines.

Activity in the San Francisco Volcanic Field began roughly 6 million years ago when magma pushed through preexisting fault lines and onto the surface as lava flows (Bezy 2003; Hanson 2006). Increased activity between 3 million and 1,000 years ago created additional volcanic features, including the San Francisco Mountain (a stratovolcano), several lava domes, and hundreds of cinder cones. A recent study by Hanson (2006) in the Wupatki region suggests that there were eight or nine individual eruptions that created the series of basalt benches and basalt-capped mesas that give the local topography its stair-stepped appearance. Many of these lava flows overlap, often covering the originating eruptive vent. This makes dating and correlating the flows difficult. Many source vents have been covered by younger volcanic flows and erosion has separated some flows, making flow direction determination and flow correlations difficult. Nevertheless, results from the Hanson study suggest the study area contains flows that might be as old as 2.7 million years in the Citadel area to as young as 100,000 years at Arrowhead Sink (Figure 3.2).

Approximately 900 years ago, Sunset Crater (Figure 3.1) was formed by a series of sporadic eruptions that also blanketed about 2,072 km² (800 mi²) of the surrounding landscape in ashfall deposits (Amos 1986, Hooten 2001, Ort 2002). Water erosion and strong prevailing southwest winds have since reduced the size of the area covered with these deposits to about 315 km² (122 mi²). Within the study area, wind action has formed aeolian cinder deposits of various depths (Soil Conservation Survey 1971). The thickest deposits are found on the slopes below the basalt plateaus (Hansen *et al.* 2004), within incised drainage channels, and below other topographic high points, especially on their leeward (northeast facing) slopes (personal observation).

The surface of the sedimentary strata is fractured in many locales. Cedar and Hull's canyons are small graben structures (Figure 3.2), and open, narrow fissures, known locally as earth cracks, are found in several locations (Anderson 1990). These cracks typically run parallel to the grabens, and the deepest earth crack discovered to date is nearly 153 meters (500 ft) deep (Cave Research Foundation 1976, in Anderson 1990). The Cave Research Foundation estimates the grabens to be approximately 30,000 years old, while camel bones found in one earth crack indicates that it has been open for at least 20,000 years (Anderson 1990). When the vertical displacement along a fault is small, the fissure remains open as an earth crack. When the displacement is large, the subsequent collapse of large blocks along the fault produces large depressions, such as Citadel Sink (Figure 3.2). Although these depressions resemble karst sinkholes they are believed to be formed by tectonic forces, and not by solution (Colton 1950; Cave Research Foundation 1976 in Anderson 1990). Where the fracturing is largely subterranean but opens to a small surface hole, the features are known as blowholes or breathing wells. Many of these blowhole systems have enough air volume to "breathe" diurnally in the same manner as cave systems.

Soils

The soil survey conducted by the SCS in 1971 included the Wupatki portion of the study area and ten different soil types were defined and mapped. All ten types are described as very shallow to shallow soils derived from basalt, limestone, or calcareous sandstone. All are moderately to well drained, and rated from very poor to fair in plant and wildlife potential. The soil texture is clay loam, with varying amounts of sand,

cinders, and cobbles. Although there is no published soil survey for the Coconino portion of the study area, personal observation indicates that the limestone exposures diminish, while lava flows and cinder cover increase in traveling south towards Sunset Crater.

Climate

There are no long-term climate data for the study area. The two closest weather stations are located at the Wupatki NM Visitor Center at the base of Woodhouse Mesa (1,500 m/4,920 ft), and at the Sunset Crater Volcano NM Visitor Center (Figure 3.1), at an elevation of 2,121 m (6,960 ft). Daily weather data have been collected at the Wupatki Visitor Center since 1948 and at the Sunset Crater Volcano Visitor Center since 1960 (Western Regional Climate Center 2005). The weather data for these two stations are summarized in Table 3.1.

In 1958, Colton published the results of a study that analyzed precipitation data from 1932 to 1956 at several sites around San Francisco Mountain. While some authors assume Wupatki lies in the rain-shadow of San Francisco Mountain (Cinnamon 1988), Colton's study suggests that this may not be the case. Generally, Colton found the pattern one would expect, given the prevailing southwest winds: precipitation higher to the south of San Francisco Mountain than to the north, and higher to the west than to the east (Figure 3.3). However, Colton also found that precipitation was higher at Deadman's Wash, directly south of Wupatki NM, than at a similar elevation at Angell. Angell, a former freight railroad station located some 32 km (20 mi) east of Flagstaff, is clearly outside any rain-shadow effect created by the San Francisco Mountain.

Table 3.1. Summary of weather data.
(Adapted from data acquired from the Western Regional Climate Center)

Station	Average Temp	Average Max Temp	Average Min Temp	Average Total Precipitation	Average Total Snowfall
Sunset Crater	7.7 °C 45.9 °F	17.4 °C 63.4 °F	-2.1 °C 28.3 °F	421.64 mm 16.60 in.	1,521.5 mm 59.9 in.
Wupatki	14.4 °C 57.9 °F	22.1 °C 71.8 °F	6.6 °C 43.9 °F	207.01 mm 8.15 in.	170.2 mm 6.7 in.

Monthly Averages : Wupatki NM

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg Max Temp	8.4 °C 47.2 °F	12.7 °C 54.8 °F	20.1 °C 62.8 °F	22.0 °C 71.6 °F	27.3 °C 81.2 °F	33.3 °C 91.9 °F	35.2 °C 95.3 °F	33.3 °C 92.0 °F	29.9 °C 85.8 °F	23.1 °C 73.6 °F	14.6 °C 58.3 °F	8.3 °C 47.0 °F
Avg Min Temp	-4.2 °C 24.5 °F	-1.7 °C 29.0 °F	1.4 °C 34.6 °F	5.3 °C 41.5 °F	10.0 °C 50.0 °F	15.3 °C 59.6 °F	18.6 °C 65.5 °F	17.3 °C 63.1 °F	13.6 °C 56.4 °F	7.3 °C 45.1 °F	0.6 °C 33.1 °F	-4.1 °C 24.7 °F
Avg Total Precip	11.43 mm 0.45 in.	10.92 mm 0.43 in.	15.49 mm 0.61 in.	9.39 mm 0.37 in.	8.89 mm 0.35 in.	7.62 mm 0.30 in.	35.31 mm 1.39 in.	40.13 mm 1.58 in.	24.13 mm 0.95 in.	17.78 mm 0.70 in.	13.46 mm 0.53 in.	12.70 mm 0.50 in.
Avg Total Snow	35.6 mm 1.4 in.	25.4 mm 1.0 in.	30.5 mm 1.2 in.	5.1 mm 0.2 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	12.7 mm 0.5 in.	55.9 mm 2.2 in.

Monthly Averages : Sunset Crater Volcano NM

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Avg Max Temp	6.6 °C 43.9 °F	8.2 °C 46.8 °F	11.7 °C 53.0 °F	16.2 °C 61.1 °F	21.6 °C 70.9 °F	27.7 °C 81.9 °F	29.2 °C 84.5 °F	27.4 °C 81.4 °F	24.2 °C 75.5 °F	17.9 °C 64.3 °F	11.1 °C 51.9 °F	7.0 °C 44.6 °F
Avg Min Temp	-10.7 °C 12.7 °F	-8.8 °C 16.2 °F	-6.3 °C 20.7 °F	-3.4 °C 25.9 °F	0.6 °C 33.1 °F	4.6 °C 40.3 °F	8.7 °C 47.6 °F	7.9 °C 46.2 °F	3.9 °C 39.0 °F	-2.3 °C 27.8 °F	-7.5 °C 18.5 °F	-10.8 °C 12.6 °F
Avg Total Precip	31.24 mm 1.23 in.	31.24 mm 1.23 in.	33.78 mm 1.33 in.	20.32 mm 0.80 in.	16.26 mm 0.64 in.	11.18 mm 0.44 in.	60.45 mm 2.38 in.	74.17 mm 2.92 in.	48.51 mm 1.91 in.	34.29 mm 1.35 in.	32.26 mm 1.27 in.	33.53 mm 1.32 in.
Avg Total Snow	363.2 mm 14.3 in.	274.3 mm 10.8 in.	269.24 mm 10.6 in.	101.6 mm 4.0 in.	2.54 mm 0.1 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	0.0 mm 0.0 in.	40.6 mm 1.6 in.	152.4 mm 6.0 in.	322.6 mm 12.7 in.

In 1971, the Soil Conservation Service estimated an annual precipitation of 152 to 254 mm (6 to 10 in.) for Wupatki NM at its lowest elevation to about 380 mm (15 in.) at the higher, western edge. The portion of the study area located within the Coconino NF is slightly higher in elevation and, hence, may receive more precipitation. The SCS (1971) report indicated that rain has been recorded in all months of the year, and snow in all months except June and July. Normally, more than half of the precipitation falls from monsoonal thunderstorms between July and September (Colton 1958; SCS 1971;

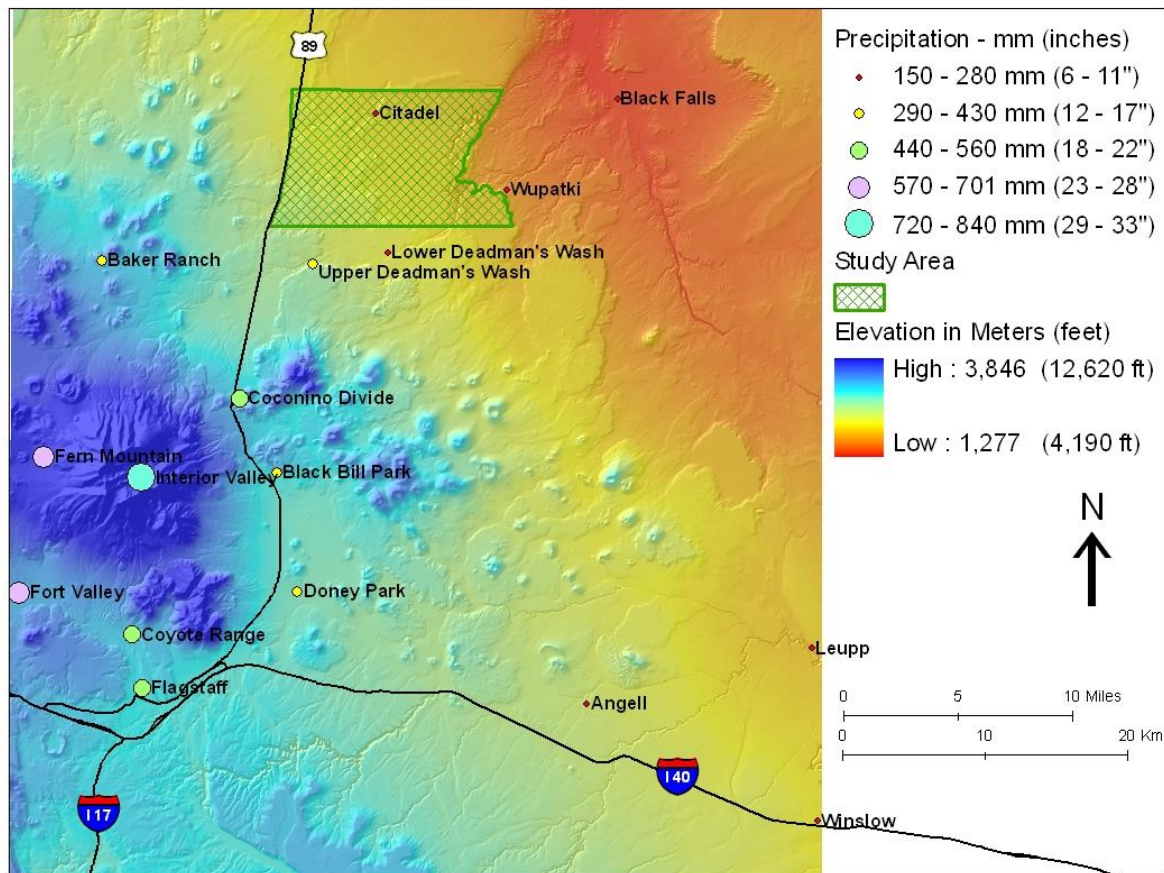


Figure 3.3. Precipitation data for the San Francisco Mountain area.

This figure shows the precipitation patterns for various elevations on and around San Francisco Mountain, as analyzed by Harold Colton in 1958.

Western Regional Climate Center 2005). Average minimum temperatures for December through February can fall well below freezing (Table 3.1), and summer temperatures over 38°C (100°F) are not uncommon (from Wupatki Visitor Center climate records). The growing season (frost free days) at Wupatki is approximately 190 days (Pape 1968, in Cinnamon 1988).

Vegetation

Wupatki NM is bisected by the Doney Cliffs, a 61 to 91 m (200 to 300 ft) drop, which effectively separates the desert scrub vegetation type in the lower Wupatki Basin from the grassland and woodland vegetation found above the cliffs (Figure 3.2). Due to this division of vegetation types, it was decided that the study area would only include the western portion of the Monument.

The study area, bordered by mature woodland on the south and arid grassland on the north, is a mosaic of native grassland, one-seed juniper (*Juniperus monosperma*) savanna, and one-seed juniper woodland, with the bulk of the grasslands located in the Wupatki portion. As is common throughout the Four-Corners Region, the study area presents the aridity of the Great Basin but with the precipitation pattern of the Great Plains (primarily summer rain) (Brown 1994). Due to the long-term climatic conditions, the study area contains a mixture of Plains and Great Basin species and fall into Brown's (1994) definition of a Transitional Plains/Great Basin Grassland. The Plains-grassland species belong to the short-grass association and include perennial sod-forming blue and black gramas (*Bouteloua gracilis* and *B. eriopoda*, respectively). The Great Basin species

include galleta grass (*Pleuraphis jamesii*) and Indian ricegrass (*Achnatherum hymenoides*).

Brown (1994) describes Plains-Grasslands as typically having an upslope woodland contact with juniper-pinyon or oak. In this case, the upslope contact is juniper with a few scattered Colorado (two-needle) pinyon (*Pinus edulis*). The pinyons are primarily found on northern slopes and in protected drainages at the higher elevations. Composed primarily of juniper trees, the woodland and savanna categories fit into Brown's Great Basin Conifer Woodland. As this woodland type is found in areas with varying precipitation patterns, cold winter temperatures provide the unifying climatic feature. These woodlands are located where the number of freezing days per year is relatively high (150 or more) and preclude the presence of warm-temperature vegetation types. While some reports (e.g., Hansen *et al.* 2004) state that temperatures in the study area rarely fall below freezing, the data from the Western Regional Climate Center show average minimum temperatures for December through February well below freezing, and those for November and March as barely above freezing (Table 3.1).

As part of the National Park Service (NPS) Inventory and Monitoring Program, the Agency initiated a joint venture with the USGS in 1999 to map the vegetation around Wupatki NM (Hansen *et al.* 2004). Their results provide a detailed description of the vegetation. Table 3.2 contains a summary of the vegetation types found in the study area, while the most common plant species are presented in Table 3.3. Hansen *et al.* (2004) defined vegetation cover types as follows:

- barren areas have no or sparse (<5%) vegetation cover,
- grasslands (herbaceous vegetation) have less than 10% shrub cover,

- shrublands generally have more than 10% vegetation cover with >10% in shrub or dwarf shrub,
 - grassland/shrubland mixed areas have >10% vegetation cover and are “steppe-like” in appearance, and
- woodlands generally have >10% vegetation cover, with >10% cover in trees.

Table 3.2. Vegetation types of the Northern Arizona study area
(adapted from Hansen *et al.* 2004).

Vegetation Type	Hectares			
	Woodland	Rangeland	Barren	Human Use
One-seed Juniper Woodland	7,329			
Apache Plume Cinder Shrubland		353		
Black Grama Coconino Plateau Mixed Shrubland		768		
Black Grama Grassland		98		
Fourwing Saltbush Upland Drainageways		34		
Galleta Grassland		45		
Galleta Mixed Grasslands		3,088		
Galleta Mixed Shrublands		27		
Needle-and-Thread Grassland		298		
Rabbitbrush Shrubland		1,222		
Wupatki Wash System		21		
Cinder Barren			76	
Basalt Outcrop			41	
Human Use (roads, quarries, commercial, etc.)				107
Total hectares	7,329	5,951	117	107
Percent cover	54.27%	44.07%	0.87%	0.79%

Table 3.3. List of the most common plants species found in the Northern Arizona study area.

Family	Scientific Name	Common Name
Anacardiaceae	<i>Rhus trilobata</i>	skunkbush sumac
Asclepiadaceae	<i>Asclepias</i> sp.	milkweed
Asteraceae	<i>Artemisia dracunculus</i>	tarragon
	<i>Artemisia filifoli</i>	sand sage
	<i>Artemisia ludoviciana</i>	white sagebrush
	<i>Brickellia californica</i>	California brickellbush
	<i>Brickellia oblongifolia</i>	narrowleaf brickellbush
	<i>Chaetopappa ericoides</i>	rose heath
	<i>Ericameria nauseosus</i> ssp. <i>nauseosa</i> var. <i>nauseosa</i>	rubber rabbitbrush
	<i>Gutierrezia sarothrae</i>	broom snakeweed
	<i>Isocoma drummondii</i>	Drummond's goldenbush
	<i>Psilostrophe sparsiflora</i>	greenstem paperflower
	<i>Zinnia grandiflora</i>	Rocky Mountain zinnia
Cactaceae	<i>Opuntia</i> sp.	pricklypear
Chenopodiaceae	<i>Atriplex canescens</i>	fourwind saltbush
	<i>Atriplex confertifolia</i>	shadscale saltbush
	<i>Krascheninnikovia lanata</i>	winterfat
Cupressaceae	<i>Juniperus monosperma</i>	oneseed juniper
Ephedraceae	<i>Ephedra</i> ssp.	Mormon tea
Fabaceae	<i>Astragalus</i> sp.	milkvetch
Hydrophyllaceae	<i>Phacelia</i> sp.	phacelia
Liliaceae	<i>Yucca angustissima</i> .	narrowleaf yucca
Malvaceae	<i>Sphaeralcea hastulata</i>	spear globemallow
	<i>Sphaeralcea parvifolia</i>	smallflower globemallow
Pinaceae	<i>Pinus edulis</i>	twoneedle pinyon
Poaceae	<i>Achnatherum hymenoides</i>	Indian ricegrass
	<i>Andropogon hallii</i>	sand bluestem
	<i>Aristida havardii</i>	Harvard's threeawn
	<i>Aristida purpurea</i> var. <i>longiseta</i>	Fendler threeawn
	<i>Aristida purpurea</i>	purple threeawn
	<i>Bouteloua curtipendula</i>	sideoats grama
	<i>Bouteloua eriopoda</i>	black grama
	<i>Bouteloua gracilis</i>	blue grama
	<i>Elymus elymoides</i> ssp. <i>elymoides</i>	squirreltail
	<i>Hesperostipa comata</i>	needle and thread
	<i>Muhlenbergia porteri</i>	bush muhly
	<i>Muhlenbergia torreyi</i>	ring muhly
	<i>Sporobolus airoides</i>	alkali sacaton
	<i>Sporobolus contractus</i>	spike dropseed
Rosaceae	<i>Fallugia paradoxa</i>	Apache plume
Solanaceae	<i>Lycium andersoni</i>	water jacket
Verbenaceae	<i>Tetradlea coulteri</i>	Coulter's wrinklefruit

In Table 3.2, the grasslands, shrublands, and grass/shrubland mixed areas have been combined to represent a general rangeland type. According to the Hansen *et al.* (2004) report, 54% of the area is covered in one-seed juniper woodland, 44% in grasses and shrubs, 1% is barren (cinder deposits or basalt outcrops), and 1% is completely altered due to anthropomorphic activities, such as roads, quarries, cattle tanks, and buildings.

Although all the species listed in Table 3.3 are native to the area, the Hansen *et al.* (2004) survey also found a number of exotic invasive species. The primary invaders are Russian thistle (*Salsola spp.*) and brome grasses (*Bromus spp.*), primarily cheatgrass (*B. tectorum*), and red brome (*B. rubens*).

Fire History

Although the fire history for the study area is not well documented, fire historically has been a natural component of Transitional Plains/Great Basin Grasslands (Brown 1994). As is typical for this type of grassland, the study area is situated in an open, exposed landscape, which is subject to high insolation and persistent windy periods. Historically, these conditions, coupled with grasses that cure into excellent fine fuels, would likely have helped lightning-ignited fires to carry for miles. Cinnamon (1988) hypothesized that frequent fires were historically a key component in keeping the juniper in the study area restricted to rocky outcrops and higher elevations, and in maintaining the grassland areas. Although current research into carbon deposits on grass phytoliths shows promise as a potential technique in tracking grassland fire history (Boyd 2002), to date there is no accepted means of reconstructing historical fire regimes for grasslands.

Within the wooded parcels of the study area, tree mortality known to be caused by fire can be found in several locations. Hassler (2006), performed a dendrochronological study of the study area and determined a mean mortality of 55% in areas affected by the four most recent wildfires within Wupatki NM. This mortality is found in junipers of all sizes, including trees taller than the 1-m (3 ft) height commonly assumed to render junipers fairly unsusceptible to fire mortality (Johnsen 1962, Arnold *et al.* 1964). Hassler also found fire evidence in the more heavily wooded portions of the study area, but all these fires were restricted to either single trees or small groups (<5) of trees. This fire mortality was apparently due to lightning-ignited fires.

The negative correlation between grazing and grass fires is also widely accepted (Leopold 1924; Sauer 1950; Humphrey 1958; Pyne 1982). In the last several decades, NPS Resource Managers have noted a marked increase in the number and extent of grass fires since the exclusion of grazing in 1989 (Paul Whitefield, NPS Resource Manager, pers. comm. 2007). Although all wildland fires are still actively suppressed, four fires have burned a total of 1,237 ha (3,053 acres) since cattle were removed from the Wupatki NM grasslands in 1989. Table 3.4 summarizes these fires, while Figure 3.4 shows the location and extent of each fire. Prior to 1989, no fires of this scale had been recorded (Hough 2006).

Table 3.4. Recent fire activity in Wupatki NM

Name	Year	Hectares	Acres	Cause
West	1995	374	923	Lightning
Moon	2000	223	550	Lightning
State	2002	73	180	Lightning
Antelope	2002	567	1,400	Cigarette

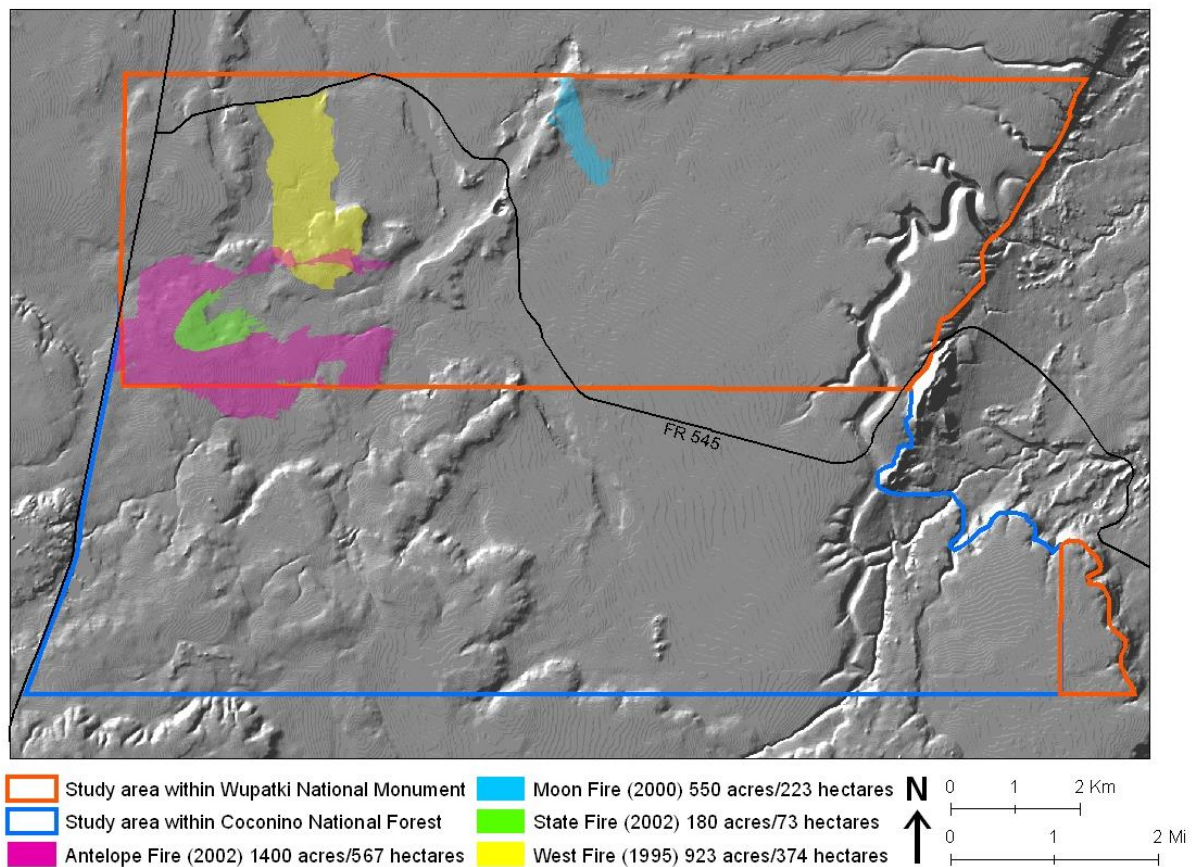


Figure 3.4. Recent fires within the Northern Arizona study area.
This figure shows the four fires that have burned in the study area since 1989.

Cultural History

The study area has a long history of human occupation. A Clovis point, found in 1984, extends human presence to 11,000+ years ago (Downum 1993). Other points, including a few provisionally dated to late Paleo-Indian (ca. 8500-7900 B.C.) and Archaic (ca. 8000–1000 B.C.) periods suggest evidence of continuing post-Clovis human presence (Anderson 1990). Thousands of archeological sites⁹ found in and around the study area indicate the region may have been used seasonally (Nabhan *et al.* 2004) until

⁹ An archeological site could be a multi-room pueblo, a field house, an ancient camp site, a check dam, or a scattering of lithics or pot sherds.

early Sinaguan year-round settlements started to appear at the end of the Basketmaker III period (ca. 500–675 A.D.) (Anderson 1993 in Nabhan *et al.* 2004). The use of large prehistoric agricultural fields, 100 acres or more, appear to have accompanied a marked increase in permanent population during the late Pueblo II period (ca. 900-1100 A.D.). Moisture climatic conditions, coupled with the moisture holding characteristics of the newly added Sunset Crater volcanic ash (Colton 1960, Berlin and Salas 1990), may have supported this increase in agriculture and population. Region-wide outward migrations that resulted in a nearly complete vacancy of the area occurred in the late 1200s and early 1300s. Although this occurred during a period of severe and persistent drought, the reasons for the evacuation of the region are not fully understood (Anderson 1990).

Several contemporary tribes, including the Hopi, Navajo/Diné, and Apache, feel a homeland connection with this area (Nabhan *et al.* 2004). Some Hopi and Diné clans continue to use the area for the collection of food and medicinal and ceremonial items, as their ancestors have done for centuries (National Park Service 2002).

Grazing History

The grazing history of the study area is not well documented. The Diné may have used the area for sporadic livestock grazing as early as 1830 (Nabhan *et al.* 2004). Mormons began settling in the Little Colorado River area from 1870 to 1898 and may have also used this area for livestock grazing. The arrival of the Atlantic and Pacific Railroad in Flagstaff in 1882 was soon followed by an influx of large-scale cattle operations. By 1886, the Babbitt family had established the CO Bar Ranch. A portion of the CO Bar Ranch, Spider Web Camp, borders Wupatki to the north, and is still a working ranch.

Cattle grazing, primarily by the Babbitt Ranches, continued in the Wupatki portion of the study area until 1989 (National Park Service 2002). Wupatki NM now protects one of the largest native grasslands in the Southwest that is not being grazed. The Coconino NF portion of the study area is administered by the USFS, which still allows grazing on its lands. This area is located within the Dove Tanks Pasture of the Peaks¹⁰ grazing allotment (Michael Hanneman, USFS Range Staff, Peaks Ranger District, pers. comm., August 2004). This pasture was not grazed by livestock from the 1970s until 1996. Specific grazing history prior to 1970s is not known. From 1996 to the present, the pasture has been grazed by cattle, but grazing has been relatively light (100-200 head at a time), with an average of 555 head months and 732 animal unit months (AUMs) per year¹¹.

¹⁰ “The Peaks” is the local nickname for San Francisco Mountain. This grazing allotment takes its name from this nickname.

¹¹ A head month is a value determined by multiplying the number of animals by the number of months each animal was grazed in the pasture. An AUM is the amount of forage required for one cow (with or without a nursing calf) for 30 days.

CHAPTER 4

METHODOLOGY

Research Objective

The objective of this thesis was to quantify the change in juniper canopy cover for an area in north-central Arizona between 1936 and 1997 (Figure 3.1). The primary data set consists of two sets of aerial photographs, the first acquired during the 1936 Soil Conservation Service (SCS) survey and the second by the United States Geological Survey (USGS) in 1997. The airphotos of the study area were divided into grids of one hectare (ha) cells. Every cell from each set of airphotos was then classified into one of six classes of canopy cover using visual classification methods. The results were compared and evaluated to quantify the change that had occurred during this 61-year period.

Methods

This project used the digitized images of historical and modern aerial photographs to quantify the change in tree canopy cover between 1936 and 1997. In remote sensing, the terms “*photograph*” and “*image*” have very specific definitions. An *image* is a general term that refers to a pictorial depiction of a scene recorded on any type of medium, including film, camera memory cards, or electronic sensors. A *photograph*, on the other hand, refers specifically to a scene recorded onto a film medium (Avery and Berlin 1992). A photograph is a type of image, but an image is not necessarily a photograph. In this project, the only photographs used were the ones taken during the 1936 SCS (Soil Conservation Survey) aerial survey. Once those photographs were scanned, they became

digital images. Depending upon where in the process the description is being used, either term can be applied to the 1936 dataset. The original data set used for the USGS DOQQs were also aerial photographs, but the product used in this project were images that had already been digitized. Only the term image will be used to refer to the DOQQ dataset.

IMAGE DESCRIPTIONS

The 1997 image set consisted of eleven panchromatic 1:12,000 USGS DOQQs that are available in the public domain (USGS 2001). The photographs used for these digitized images were taken in October 1997 and the digital files have a 1-meter pixel resolution. The DOQQs used for this study are listed in Table 4.1.

Table 4.1. 1997 DOQQs used in this study.

Quadrant Name	Quarter Quadrants Used	DOQQ Name
East of SP Mountain	NE and SE quadrants	easpmone.bil easpmose.bil
Wupatki SW	all quadrants	wupaswne.bil wupaswnw.bil wupaswse.bil wupaswsw.bil
Wupatki SE	SW quadrant	wupasenw.bil
O'Leary Peak	NE quadrant	olepeane.bil
Strawberry Crater	NE and NW quadrants	strcrane.bil strcranw.bil
Roden Crater	NW quadrant	rodcranw.bil

The 1936 image set consists of twelve 10-by-10 inch SCS panchromatic aerial photographs retrieved from the National Archives and Records Administration (NARA⁹). The photographs were selected from SCS photo indexes 119 and 120 (Figure 4.1). These film products were archived as negative transparencies. Each transparency was scanned by a private vendor at 1,200 dots-per-inch (dpi), which provided a digital image with a pixel resolution of approximately 60 cm. Each negative was tonally reversed to provide a positive grayscale image and saved as a .TIF file¹⁰. Figure 4.2 shows the images used for this project.

The name of each image starts with the film spool identifier, while the last 4 digits are the photo identification number found on the photo indexes. For ease of reference, these images will be referenced by their identifying numbers.

The SCS aerial photographs were taken on October 7, 1936. They were taken with a 4-lens camera from a flight height that provided a nominal photo scale of about 1:31,680. Although the manufacturer of the camera used to acquire the airphotos is not known, 4-lens cameras were commonly used by the SCS in the 1930s (Lattman and Ray 1965). These cameras were designed to take four simultaneous exposures through four separate lenses, with the optical axes tilted obliquely toward the terrain. How much optical tilt is present is not known, but it appears to be only a few degrees off vertical (Avery and Berlin 1992). This tilt was normalized to a vertical view during processing with a transforming printer. The four photographs were then pieced together to produce a single,

⁹ National Archives and Records Administration, 8601 Adelphi Road, College Park, MD 20740-6001.

¹⁰ These images are on file at the Flagstaff Area NPS Headquarters building in Flagstaff, Arizona.

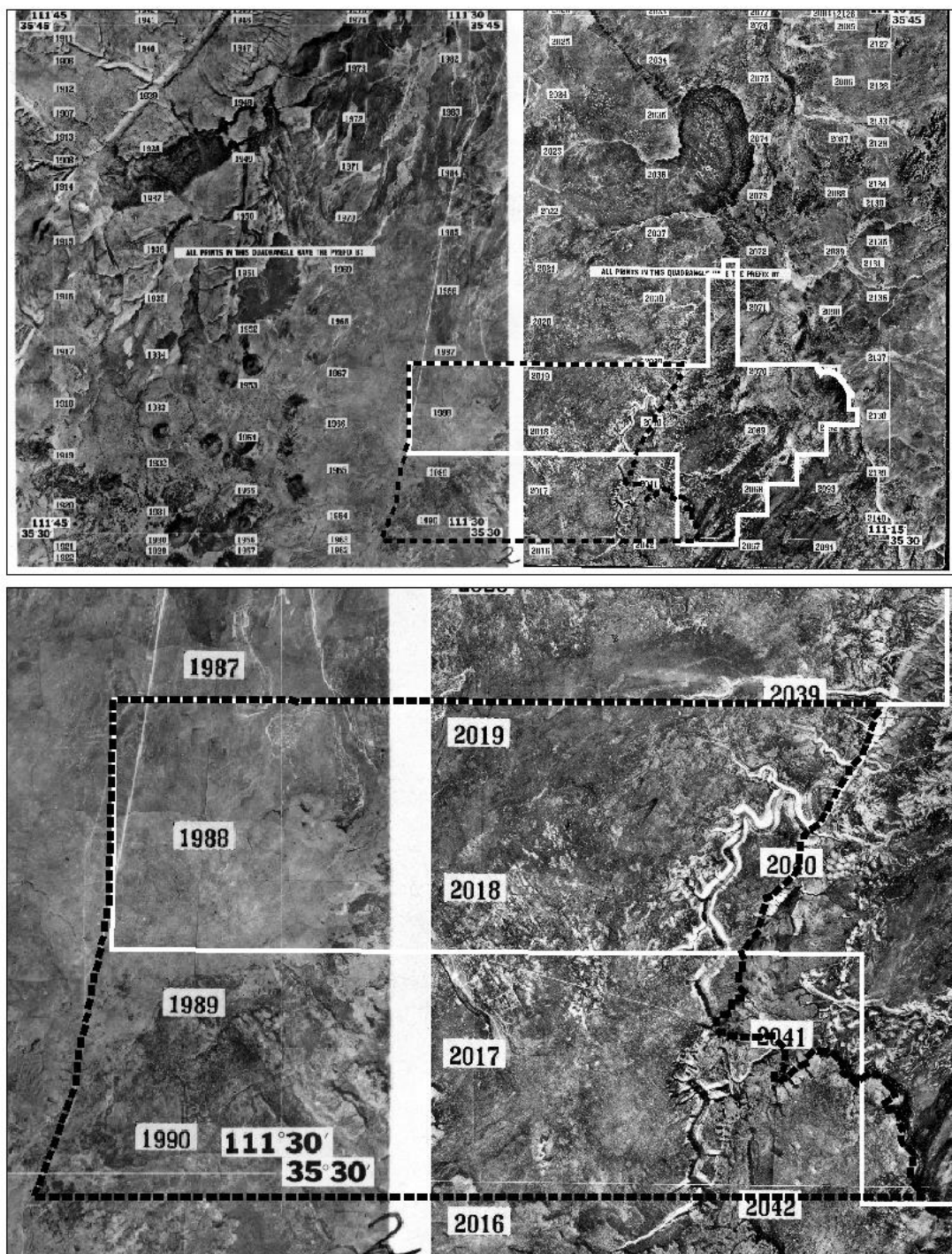


Figure 4.1. 1936 SCS photo indexes covering the Northern Arizona study area.

*Index 119 is shown on the left and index 120 is on the right.
The white line shows the outline of Wupatki National Monument.
The dashed black line shows the study area.*

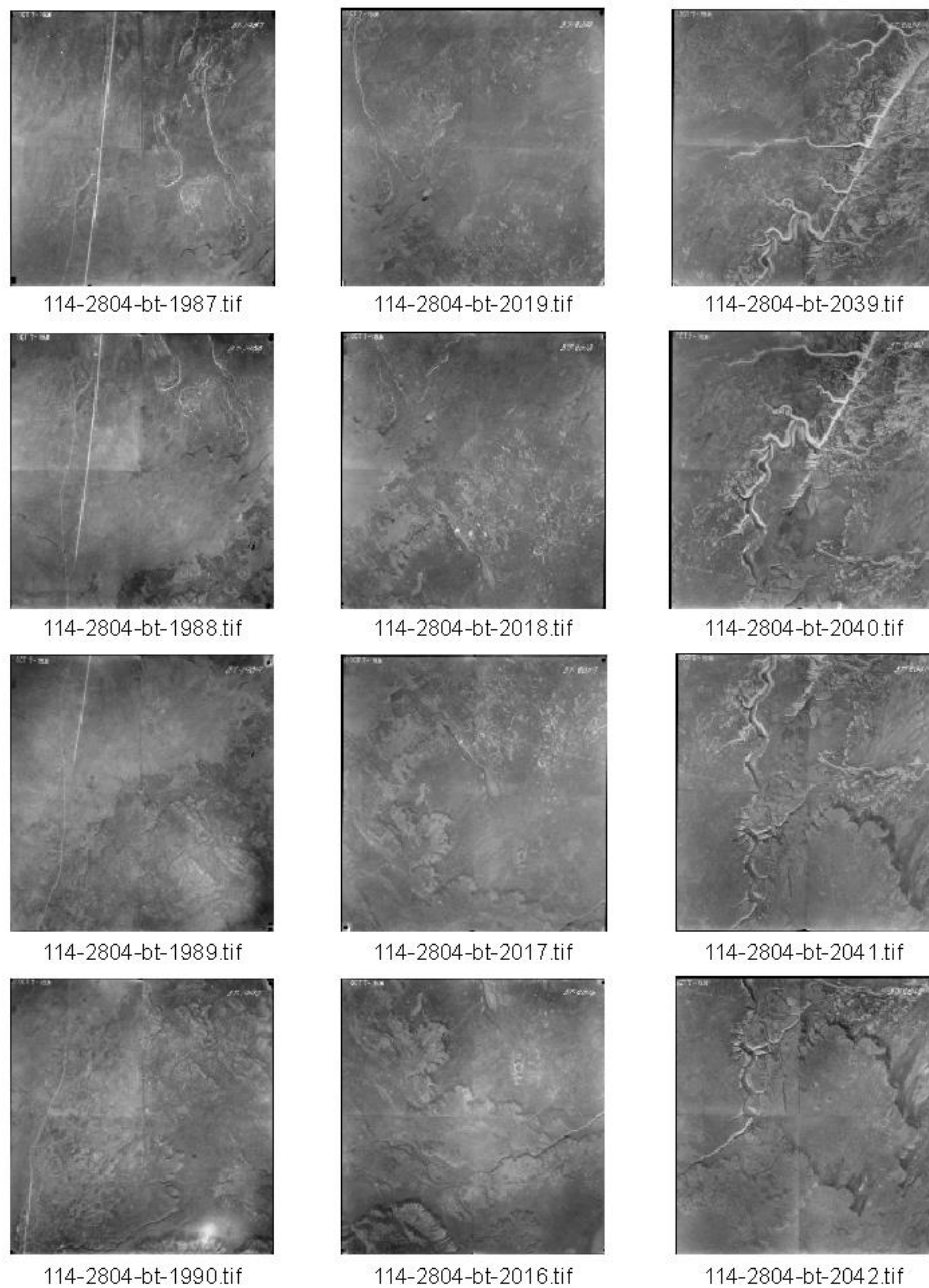


Figure 4.2. 1936 digitized aerial photographs used in this study.
The tonal variation between, and within, the 1936 images is quite evident.

10-by-10 inch vertical-equivalent view (Lattman and Ray 1965). Joint lines are often visible on the final assembled product.

There were several challenges associated with using the SCS airphotos. The most troublesome is tonal variation. The amount of sunlight incident on the landscape and at the camera can either enhance or degrade the quality of a photograph (Avery and Berlin 1992). A loss of information can occur due to either too little illumination (low contrast) or too much illumination (saturation). This is influenced by both the angle at which the sunlight strikes the earth's surface and the angle of the camera's optical axis. The angle of the illumination provided by the sun is a function of time-of-day, season, and latitude. The angle of light incident on the film is a function of the angle of the sun's illumination and the angle of the camera's projected optical axis to the earth's surface. Each SCS photograph is a mosaic of four exposures taken at the same time, but with different optical axes. This resulted in four different illumination angles within each image. These different angles produced considerable tonal variations.

A tonally balanced image has a fairly even set of tonal parameters through the image (Castleman 1996). In a tonally balanced panchromatic image, for example, two patches of ground with the same reflectance values will have approximately the same digital gray-tone values. Figure 4.3 shows image #1988, which is a good example of uneven tonation. The upper left quadrant, for example, is clearly more saturated than the remaining quadrants. The tonal variation is also evident in the histograms presented in Figure 4.3. The left-hand histogram shows the digital gray-tone values for three different grassy areas within this image. In a tonally balanced image, the peaks of these histograms

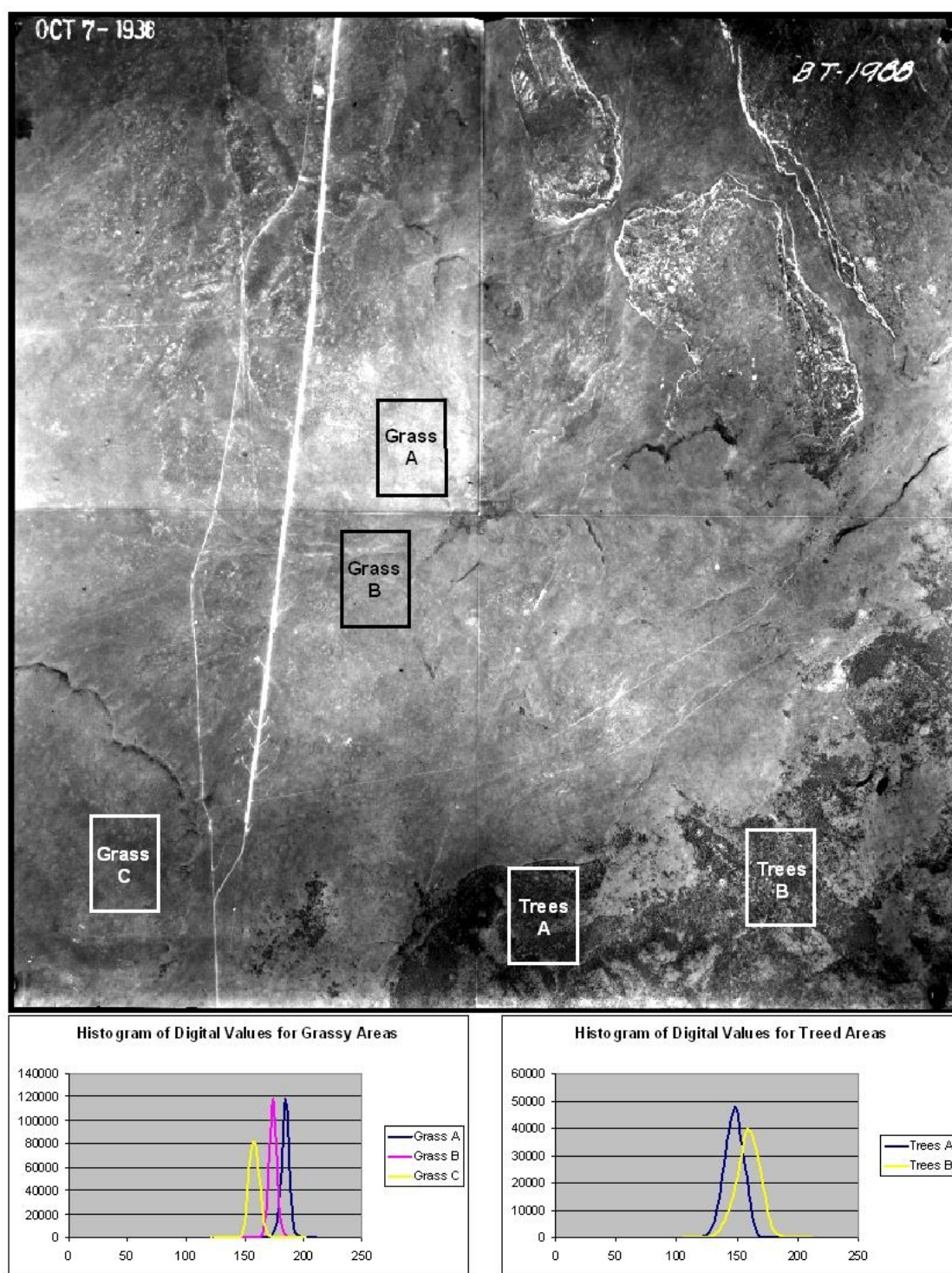


Figure 4.3. Tonal variation within image #1988.

This image shows the high level of tonal variation in the 1936 photographs. The two histograms show how much variation exists within the digital gray-toned values in this single image.

would closely overlap, such that a single, small range of digital values would represent grassy areas throughout the entire image. This is not the case in image #1988.

A second problem is the number of defects in the SCS photographs. Some defects, like fingerprints, could easily be identified. Other defects either obscure or mimic natural features. Figure 4.4 provides examples of these defects. Arrow **A1** points to a cinder dune, while **A2** points to an unknown type of defect. **B1** points to a scattering of actual trees, while the **B2** arrows point to black spots of unknown origin – perhaps ink splatters. **C1** points to a mudflat, while **C2** points to a defect – possibly representing a hole in, or a piece of lint on, the negative.

Another problem with the SCS images is the lack of geometric fidelity. The optical axis of a camera is the perpendicular line that extends out from the center of the film plane, through the lens, and intersects with the object being photographed. This point is also called the principle point. In a true vertical aerial photograph this point aligns with the nadir point, the point on the ground directly beneath the camera's principal point (Avery and Berlin 1992). Even with today's technology, geometric accuracy is only close to perfect at the nadir point of a vertical image (Lattman and Ray 1965; Avery and Berlin 1992). The further away from the nadir, the more the angle of view becomes tilted. Because the angle of view radiates out in all directions from the center of the photograph, this distortion is called radial displacement. All vertical photographs contain some amount of radial displacement. The SCS images are a composite of four tilted, or oblique, photographs. There is no true nadir on these photographs. In tilted photographs the objects being recorded are displaced from the position they would occupy in a true vertical photograph by what is called tilt displacement. The point between the optical axis

of the camera and the true nadir is call the isocenter. In the upper half of a tilted photograph objects are displaced radially toward the isocenter, while in the lower half, objects are displaced radially away from the isocenter. Although a transforming printer, the best technology of the day, was used to correct these distortions, some amount of distortion usually remains.

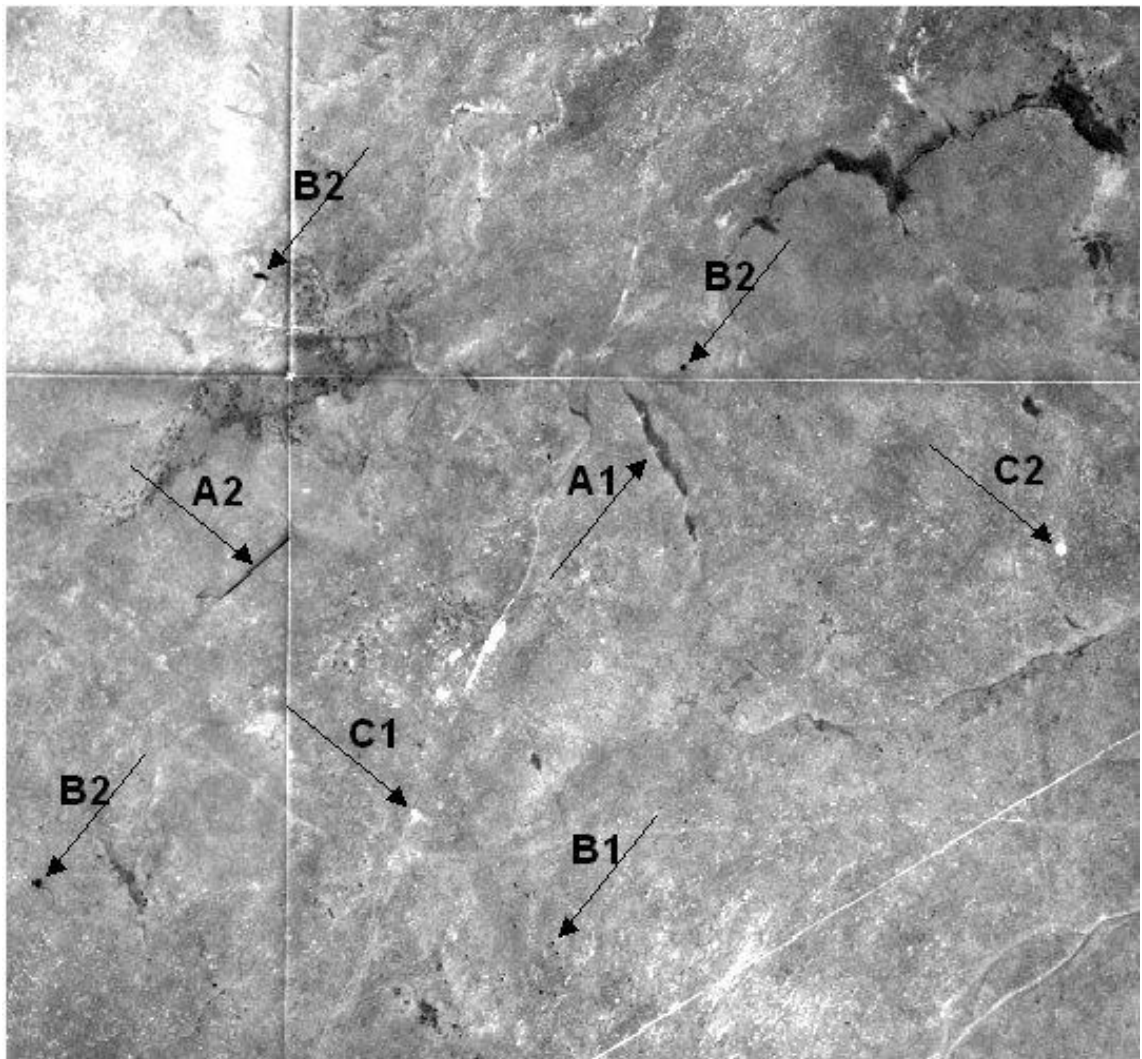


Figure 4.4. Defects on image #1988.

This image gives examples of the defects that were present in the 1936 SCS images. Annotated features are described in the text.

IMAGE PROCESSING

Orthorectification is the process of correcting an image so that all geometric distortions and vertical displacements have been removed. The geometry across an orthorectified image is as uniform and accurate as a map at the same scale (Avery and Berlin 1992; USGS 2001). Georeferencing, also called rectification, is the process of converting the pixel coordinate system of an image to a map coordinate system.

The 1997 DOQQs were already georeferenced, orthorectified, and tonally balanced so no pre-processing was required. They were geo-referenced to the North American Datum of 1927 (NAD27) and cast on the Universal Transverse Mercator (UTM) projection system (USGS 2001). This datum and projection were used for all geo-located data in this project.

The 1936 images needed to be georeferenced before any other processing could be performed. The modern standards for aerial photography include ~60% forward overlap and 20 to 30% sidelap for adjacent flight lines (Avery and Berlin 1992). It appears these standards were adhered to with the 1936 photo set. There is always greater distortion along the edge of a vertical photograph (Avery and Berlin 1992). The forward and side overlap allowed the less distorted center portion of each image to be extracted for use. The 1936 images were georeferenced by performing image-to-image registration (Jensen 1996) with the DOQQs using ESRI ArcMap 8.3.

Ideally, fixed angular cultural features, such as road intersections or corners of buildings, are used as control points for image-to-image registration (Avery and Berlin 1992; ERDAS 1998). When cultural features are absent, permanent natural features can be used (Jensen 1996). The number of control points needed to produce acceptable results

will vary according to what the images depict. When using two modern images of an urban area, for example, as few as 6 to 10 control points can produce satisfactory image registration (ERDAS 1998). Due to the inherent geometric distortion of the SCS photographs, georeferencing was expected to be a challenge. It was decided to start with a minimum of 25 control points for each image. This would provide more than twice the number of points typically used to accomplish image registration. It turned out, however, that the distortion of the SCS photographs was such that many more control points were required. To obtain the best registration possible, 200 control points per photograph were typically used. These points were distributed along the edges, and scattered as evenly as possible across the interior of the image (Richards and Jia 2006). USGS topographic maps were used to find the highest and lowest areas in each image and control points were placed at these locations as well.

The study area contains almost no angular cultural features. Arizona State Highway 89 had been redesigned and widened between 1936 and 1997 and did not provide good control point locations. Other roads are visible but not all were usable. Asphalt roads seen in the DOQQs had not been built in 1936. Most of the roads used in 1936 were unpaved roads or two-tracks, which had been closed and partially overgrown by vegetation by 1997. The power transmission lines and quarry in the DOQQs were not present in 1936.

As many reliable control points as possible were used. Whenever they were available, cultural features were used. When no cultural features were available, natural features were used. Unpaved roads are not considered as reliable as concrete or asphalt roads, but they can be used when necessary. Even though they do not typically provide good edges, geologic features, such as basalt outcroppings, were used when available. In open, grassy

areas it was sometimes impossible to locate the same feature on both sets of images.

Although vegetation is typically considered one of the least reliable features to use for control points, where trees were the only indefinable features, they were used. The guidelines and assumptions used in control point selection are listed below.

1. Unless there is reason to suggest otherwise, unpaved roads that could be identified on both sets of images were assumed to be in the same location and were used.
2. Canyons, arroyos, and other geomorphic features were assumed to not have changed since 1936 and were used.
3. Historic or prehistoric cultural features that have the same apparent location, such as locality to a geologic feature, were assumed to be in the same location.
4. Individual trees that would be identified in both sets of images were assumed to be the same tree, and were used.
5. Small areas of high reflectance that could be identified on both sets of images, and which had a similar shape and size, were assumed to be exposed bedrock or stable mudflats and were used.

Once control point selection was complete, each image was geometrically corrected. There is generally less overall distortion when lower order transformations are used (Richards and Jia 2006). Each image was corrected using the second-order polynomial transformation algorithm provided by the geo-referencing feature of ArcMap. Finally each image was resampled using the nearest-neighbor algorithm to keep data loss at a minimum (Avery and Berlin 1992). Because camera parameters, such as focal length and camera tilt, were not available, it was not possible to orthorectify the 1936 images.

EXTRACTION OF TREE DATA FROM THE IMAGES

The layers of data contained within modern, multi-band spectral images make them particularly amenable to computer analysis. The single-band data available from panchromatic images, on the other hand, are often better suited to visual interpretation (Jensen 1996). In situations where computers are used to perform gray-scale classification, that classification is typically double-checked by human analysts. Since the DOQQs had been tonally balanced, the computer extraction of tree data from these images would have been reasonably accurate. This technique, however, proved to be practically impossible on the poor quality 1936 images. Correcting for the variation in tonation and number of defects would be a sizable task in and of itself (Figure 4.3). It would require considerable digital manipulation (Phil Mlsna, School of Engineering, Northern Arizona University, pers. comm., January 2006) and extensive manual verification. Further, as georeferencing of the SCS images is not exact, image-to-image comparisons would still not be feasible, even if the tonation and defect difficulties could be overcome.

This being the case, both sets of images were analyzed using traditional photo interpretation techniques. The human mind is particularly proficient at discerning complex features in photographs and images (Jensen 1996). While computers can be programmed to isolate certain patterns within digital images, human interpreters are able to recognize a much larger set of identifying characteristics. These include shape, size, pattern, tone, texture, shadow, and site/object association (Avery and Berlin 1992, Jensen 1996). Human interpreters are also adept at utilizing collateral information, personal

experience, and real-world knowledge of the area to aid in the identification of objects and patterns (Avery and Berlin 1992).

Continuous Quadrat Grid

Continuous quadrats were used to quantify canopy change. The ideal quadrat size takes into account both the scale of the pattern of interest as well as the scale and purpose of the study (Dale 1999). As the study area is over 13,500 ha, it was determined that a cell size of 1 hectare would be sufficient to capture the patterns of change. To avoid introducing a directional bias, it is traditional to use square cells when using contiguous quadrats. A 100 m x 100 m (1 ha) polygon grid shapefile was generated and geo-located over the study area. It was located at an even meter boundary to make measurements in the field easier. The rows and columns of the grid were numbered for ease of reference. The attribute table for this shapefile includes fields for the row and column identifiers, and for both 1997 and 1936 classification values. In this way, all the geographic and canopy cover classification data are contained within one file.

Classification System

Many approaches to class definition exist, including equal-interval, defined-interval, and natural breaks. For this project a 6-class defined-interval system of tree canopy cover was devised that took several issues into account, including visual natural breaks. Numeric values were assigned to each class to make the mathematics associated with tracking the changes easier. These values were selected so that the difference between any two classes would be a unique number that defined the change. These values were

used in the shapefile attribute table to assign a class to a hectare cell. Class definitions are listed in Table 4.2 and an explanation follows.

Table 4.2. Classification system definitions.

Description	Treeless	One-or-Two Trees	Scattered Trees	Savanna	Open Woodland	Closed Woodland
Class Number	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Percent Canopy Cover	0 - 0.05%	0.06 - 0.5%	0.51 - 5%	5.01 - 15%	15.01 - 30%	> 30%
Attribute Table Value	1	2	5	14	25	50

According to the literature, definitions of grasslands, savannas, shrublands, woodlands, and forests differ widely (Platou and Tueller 1988). Definitions vary according to the type of woody plant involved (tree, shrub), species of plant (oak, juniper, acacia, mesquite), location (Africa, Australia, Southwest US), and what the management concerns and practices are (wildlife habitat preservation, ranching). Even the definition of what distinguishes a tree from a shrub is “fuzzy”. Trees are typically considered to be single-stemmed woody plants that reach some minimum height, while shrubs are usually defined as multi-stemmed and shorter (Platou and Tueller 1988). Johnsen (1962) describes the one-seed juniper as a shrubby tree that is typically multi-stemmed, but occasionally single stemmed. While one-seed junipers can obtain a height of 10.5 m (35 ft), they are typically shorter, even at full maturity.

The growth pattern of the one-seed juniper tends to keep the canopy in contact with the ground. As these junipers reach old age, however, the canopy tends to open up and lift off the ground (Schott and Pieper 1984). Although Hassler (2006) found trees up to

700 years old in the study area, personal observation indicated that the majority of trees in the study area had canopies on, or near, the ground. This interferes with visibility and produces a closed woodland perspective when viewed laterally, even when tree density is relatively low. This limited visibility could have a profound effect on the habitation patterns of wildlife that prefer open areas, such as the pronghorn (Ockenfels *et al.* 1994).

The National Vegetation Classification Standard (NVCS 1994) is widely used by the USGS, NPS, and US Forest Service (USFS). It uses the following criteria to define wooded areas:

<u>Type</u>	<u>Canopy Cover</u>	<u>Crown Pattern</u>
forest	60 – 100%	interlocking
woodland	25 – 60%	not touching
sparse woodland	10 – 25%	widely spaced

These definitions, however, did not seem appropriate for this study area. From previous field work it was known that the southern portion of the study area was fairly heavily and uniformly wooded. It was suspected, however, that even these wooded areas would not have the level of canopy cover found in other areas defined as pinyon-juniper woodlands (e.g., 42% at Bandelier NM, Arno and Fiedler 2005). Personal observation also showed that the juniper in the study area often grew in a clumping pattern that resulted in interlocking canopies, even in areas with only a moderate number of trees.

Arno and Fiedler (2005) found that, in some areas of the West, even with canopy cover as low as 20%, juniper trees could dominate an ecosystem, pushing out grasses and shrubs. In drier areas, they found that stands with no more than 40% cover were not only dominated by juniper trees, but also showed signs of being moisture stressed. Hansen *et*

al. (2006) estimated much of the juniper woodland in the Wupatki area had approximately 25% juniper canopy cover. Platou and Tueller (1988) used a canopy cover limit of 30% to distinguish between open and closed shrublands. Pilot studies suggested that this 30% limit would also capture the most heavily wooded areas of this study area. Class 6, the most heavily wooded class used in this study, was thus defined to include all areas with >30% canopy cover.

On the other end of the canopy cover spectrum, defining areas that had absolutely no trees, as well as the initial appearance of trees in previously treeless areas was important. The shift from a treeless area to one or two trees per hectare is not a huge habitat change. It does, however, invite other changes that can have considerable impact, at least locally. This is most evident in the avian population. With the introduction of even one tree, perching birds start to appear, which shifts the dynamics of such processes as seed dispersal and predation (Vibe-Petersen *et al.* 2006). To capture this change, Class 1 was defined as having no trees, and Class 2 as having one-to-two trees per hectare. Class 1 not only defines treeless grassland areas, but also large treeless cinder fields. The canopy data collected by Hassler (2006) was used to calculate the size of an average tree. From these data, it was determined that a canopy range of 0.06 to 0.50% would capture the presence of one-to-two trees per hectare.

As discussed in Chapter 1, impact on wildlife tends to be more pronounced along the edge of habitat change. To highlight this change, the classes with lower levels of canopy cover were kept small, while the upper classes were allowed to include a wider range of cover. Using this consideration, and naturally occurring visual breaks, Class 3 was defined as 0.51 to 5.0% cover. This definition would include areas that have more than

two trees, but are still quite open. As the upper boundary for Class 5 had already been defined as 30%, the difference between these two remaining classes was split down the middle. Class 4 as 5.01 to 15.0% and Class 5 as 15.01 to 30.0%.

Manual Classification

Manual classification was performed at a screen resolution of 1:9,000 using ArcMap 9. Since only the classification of the DOQQs could be assessed for accuracy, that classification was performed first. Several trips to the field were made to verify and refine the manual classification technique.

Some areas had been so modified by human activity that they were unusable for this study. These areas include the power transmission line easement, the Antelope Trading Post, and a pumice quarry. None of these areas had been modified in 1936. All cells that overlapped these modified areas by more than 10% were excluded.

The accuracy of a photo interpreter can be improved by comparing temporally separate photos (Avery and Berlin 1992). During manual classification, the screen views were swapped between the two sets of images as necessary to resolve ambiguity issues. This was mostly necessary with the 1936 SCS images. In some areas, for example, there appeared to be trees in the early images where no trees, snags, or stumps are today. Since studies at Mesa Verde NP have found that juniper snags in arid environments can persist for centuries (Floyd *et al.* 2000), the 1997 images were used to distinguish between trees and defects in the 1936 images.

The spatial distribution of the trees sometimes made overall cell classification a challenge. The “cramming” method described by Hays *et al.* (1981) was used to increase

the accuracy and consistency of the results. Cramming is a visual technique wherein the interpreter mentally moves all the canopies into one corner of the cell and then uses that new mental picture to estimate the percent cover. Border trees were included if they were on the north or west sides, and excluded if they were on the east or south sides. Figure 4.5 provides an example of this technique.

Roads were another issue that needed to be addressed. In 1936, there was a network of unpaved roads and two-tracks in the study area. By 1997, most of these features had been abandoned, although many are still faintly visible on the DOQQs. The main road through the park (Forest Service Road 545) had been paved and a few US Forest Service roads outside the park were formalized. Since even a paved road does not take up a major portion of a hectare cell, the roads were ignored and the cell was classified as if the road was not there.

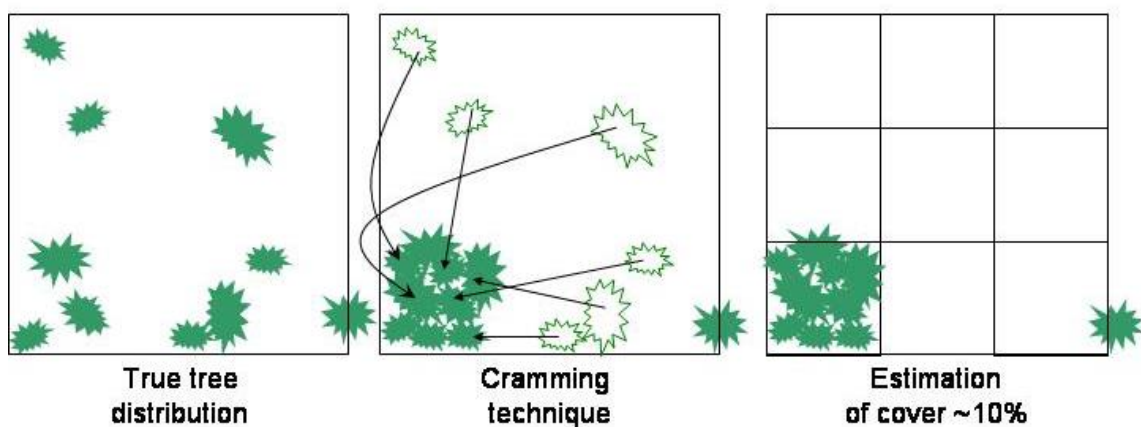


Figure 4.5. Example of tree cramming.
(Adapted from Hays *et al.* 1981)

There were a few areas on the DOQQs that appeared to have been deforested. All were in the Coconino NF, and appeared to have been “pushed”, most likely during earlier federal range improvement programs. Pushing is one of several techniques used to remove short stature trees like juniper and pinyon. It is typically performed with the intent of removing tree competition; increasing herbaceous plants, and improving grazing. Pushing is accomplished with bulldozers that literally push the trees over and then, typically, into piles. Sometimes these piles are burned, but often they are simply left in place. Figure 4.6 shows piles of juniper slash that had been pushed to the edge of an area cleared for grazing.

Although the roads were ignored, these intentionally deforested areas were not. Roads are built to improve transportation while areas are pushed with the intent to change the



Figure 4.6. Evidence of “pushed” juniper.

The two piles of juniper slash on the right side of the photograph were pushed into place by a bulldozer decades ago to create the open area to the left. Small juniper trees in the center of the photo suggest trees are beginning to move back into this area.

habitat from a wooded area to an open grassland. It seemed important to capture this land-use legacy. Although the habitat around the quarry area had also been considerably modified by mining activity, habitat change was not the goal or intention. For these reasons, the roads were ignored and the quarry excluded, but the intentional habitat change of the pushed areas was included.

Some of the assumptions made, and limitations encountered, during manual classification are listed below.

1. Both sets of photographs were taken in October. It is customary to perform aerial imaging within two hours of local noon, unless the details in the area being studied would be enhanced by larger shadows (Avery and Berlin 1992). It was assumed that this was true for both sets of images used in this project. The sun angle was assumed to be similar in both cases, and any obscuring effect caused by shadows could be discounted.
2. Trees with canopies smaller than $\sim 1 \text{ m}^2$ often do not show up on the images. When a cell was perceived as a borderline case, it was assumed that there were more trees rather than less, and the cell was assigned to the higher class.
3. Due to the poor rectification of the 1936 images, trees that fell on the cell edge in one set of images may fall within a different cell on the other set. The DOQQs were used as the base reference, and then best judgment was then employed on how to resolve these situations.

ACCURACY ASSESSMENT

In order to quantify the range of error in interpreting the cover within each cell in the classification grid, an accuracy assessment was performed on the classification of the DOQQs. Canopy data were collected in the field to calculate confidence intervals and standard error for each of the classification classes.

Field Data Collection Site Selection

Chris Lauver, a Quantitative Ecologist for the NPS, was consulted to select cells for field examination. The Generalized Random-Tessellation Stratified (GRTS) algorithm was used to select spatially balanced, random test cells. Lauver used the R-Project for Statistical Computing (also called R-stats), a free statistical program that can be downloaded from the Internet¹¹. This program is controlled by an input script, and the script that was used is shown in Figure 4.7. The input script needs to include the number of classification categories (classes), prioritization of these classes, and the number of points to be generated per class/per polygon. The output of this program is a point shapefile, which can be used with a GIS program. This point file placed a point within each hectare cell that had been selected for accuracy assessment. Fifty points were generated for each cover class. Although only 20 cells were going to be used, extra points were generated in case some points needed to be discarded due to unforeseen circumstances in the field. All points generated by the GRTS algorithm are listed in Table 4.3, and the locations of all points are shown in Figure 4.8. A glance at the script shows

¹¹ The address on the World Wide Web for R-stats is <http://www.r-project.org/>.

that Class 2 was accidentally entered before Class 1, so the numbering sequence starts with Class 2 rather than Class 1.

```
## Testing (WUPA) - Equal Prob with stratification - Using R 2.2.1
##

#####
# Load sp library
#####
# Load psurvey.design library
#####

# Read dbf file attribute table from shapefile, in same directory
that R is started from
att <- read.dbf("sites")
#header
head(att)

##### Stratified GRTS survey design.
Stratdsgn <- list("2"=list(panel=c(PanelOne=50), seltype='Equal'),
                 "1"=list(panel=c(PanelOne=50), seltype='Equal'),
                 "5"=list(panel=c(PanelOne=50), seltype='Equal'),
                 "14"=list(panel=c(PanelOne=50), seltype='Equal'),
                 "25"=list(panel=c(PanelOne=50), seltype='Equal'),
                 "50"=list(panel=c(PanelOne=50), seltype='Equal'))

sample(100000000,1)
# run to get random seed
set.seed(4447864)

# create design
Stratsites <- grts (design=Stratdsgn,
                   src.frame='shapefile',
                   in.shape='sites',
                   att.frame=att,
                   type.frame='area',
                   stratum='CLASS97',
                   DesignID='test',
                   shapefile=TRUE,
                   prj='sites',
                   out.shape='GRTS_sites')

# summarize sites selected
addmargins( table( Stratsites$stratum,Stratsites$panel) )
```

Figure 4.7. R-Stats script used to generate coordinates of accuracy assessment field sites.

Table 4.3. Accuracy assessment site numbers by class.

Class	Test Site Numbers
Class 1	51 – 100
Class 2	1 – 50
Class 3	101 – 150
Class 4	151 – 200
Class 5	201 – 250
Class 6	251 - 300

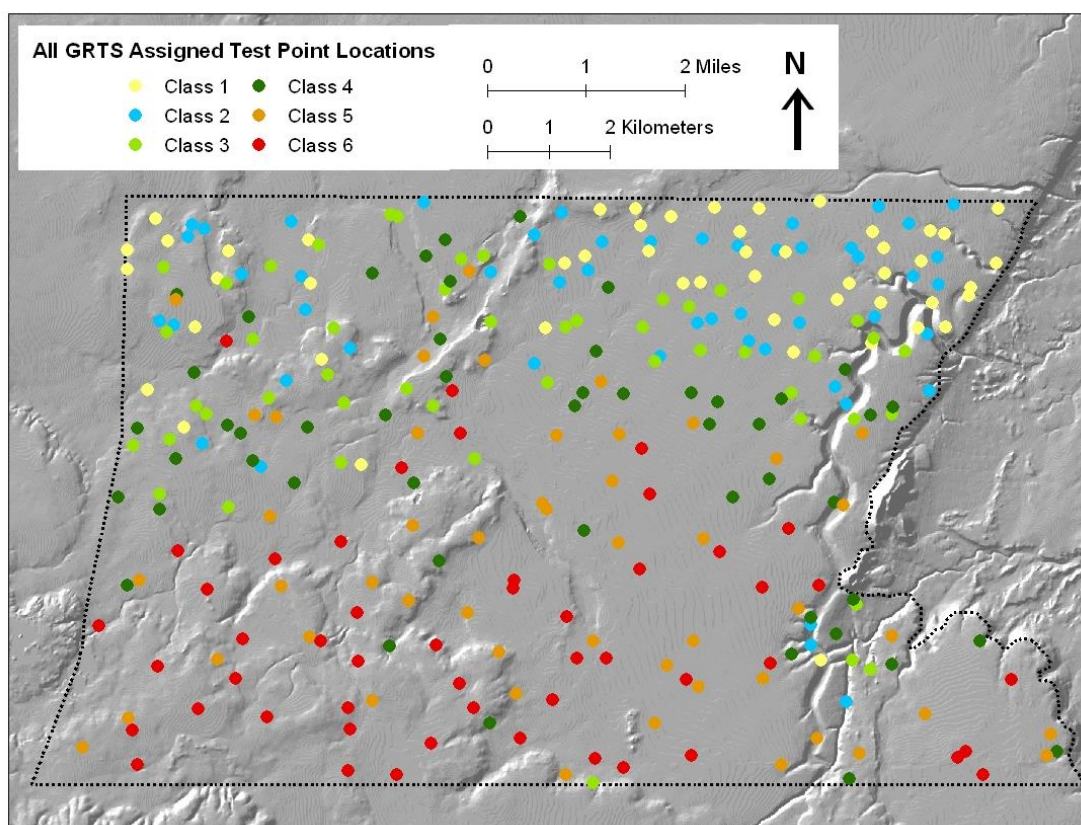


Figure 4.8. Location of all accuracy assessment points generated by the GRTS algorithm.

Field Data Collection

As canopy cover is the primary attribute assigned during the image interpretation, and as funding was not available to support field data collection, only the canopy of trees in a subset of each hectare test cell was measured. A systematic approach was used to select four 30 m x 30 m subplots. The layout of these subplots is shown in Figure 4.9.

To ensure proper field location of the plots and subplots, a field map was generated for each test cell. Row/column and the UTM coordinates for the center of the test cell were included. An example of a field map is shown in Figure 4.10. Three images at different scales were included in each map to aid in plot location. Although a GPS unit was used to determine the final locations, the smaller scale images helped with such issues as where to park, and how to avoid cliffs and gullies while navigating to the test cell. The field map was also used to define which trees fell into each subplot.

Field information was recorded on both field maps and field forms. An example of a field form is shown in Figure 4.11. Each tree was numbered on both the field form and field map to aid in tree location during any future study. All trees that were clearly within the subplot were measured. Trees that were on the edge were included if they were on the north and west edges, and excluded if they were on the south and east edges. To calculate the area of each canopy two radial, or drip line, measurements were taken using a homemade height pole. The measurements taken were first the widest radius of the tree, and then a second radius at 90° from the first in a clock-wise direction. The average of these measurements was used to calculate the area of the canopy. Whether the tree could be seen on the image or not was noted on the field form. The height pole was also used to get a gross-scale estimate of tree height.

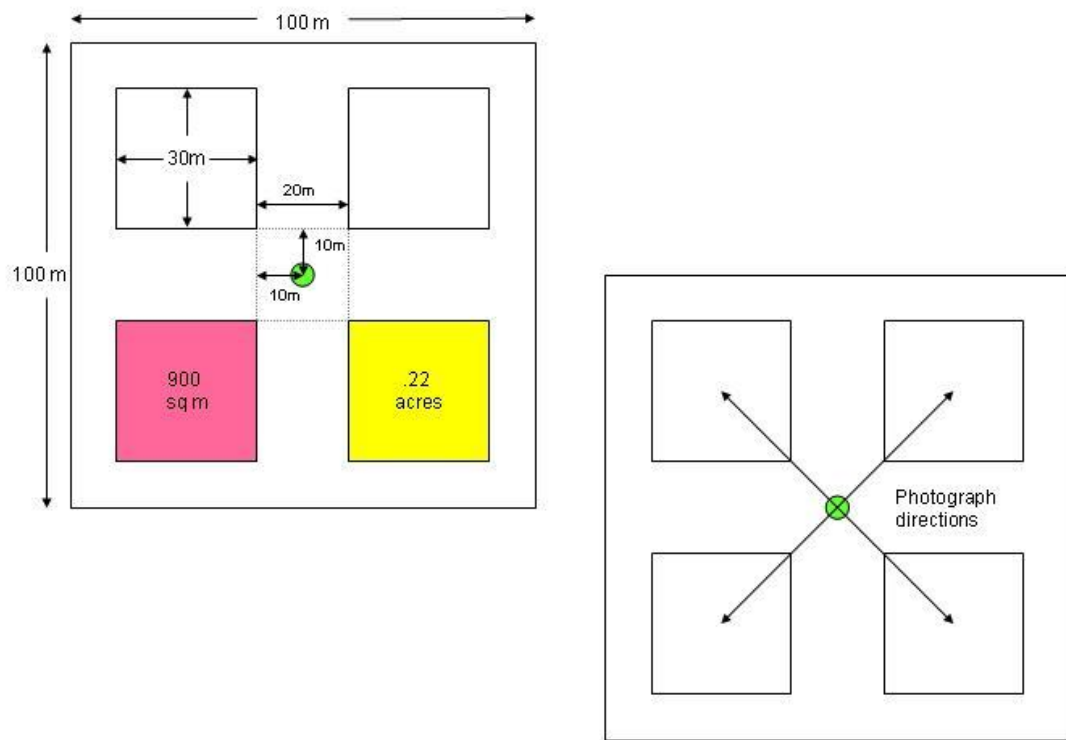


Figure 4.9. Subplot layout and photograph directions.

The figure on the left shows the dimensions and layout of the subplots used to measure canopy cover. The figure on the right shows the direction the photographs for the photo-record were taken.

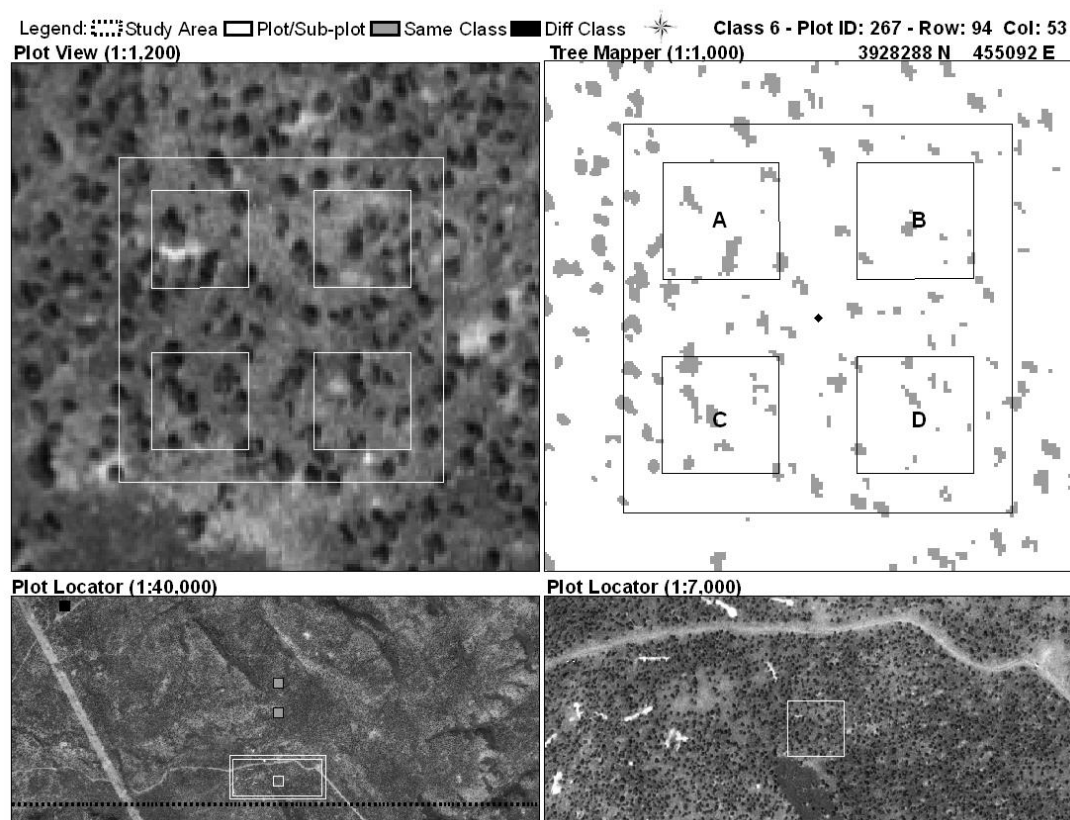


Figure 4.10. Field map.

Field maps were used to both help locate the plot in the field and to help determine which trees fell into which subplots.

Field Work Sheet – Juniper Study – Cindy Parker

Plot ID: _____ Plot Row: _____ Plot Column: _____ Date: _____ Page _____ of _____

Field Worker(s): _____ Class _____

Plot Understory:	grass/shrub dominated	grass/shrub dominated (except around trees)	sparse grass	cinder dominated
1	1	1	1	1
2	1	1	1	1
3	1	1	1	1
4	1	1	1	1
5	1	1	1	1
6	1	1	1	1
7	1	1	1	1
8	1	1	1	1
9	1	1	1	1
10	1	1	1	1
11	1	1	1	1
12	1	1	1	1
13	1	1	1	1
14	1	1	1	1
15	1	1	1	1
16	1	1	1	1
17	1	1	1	1
18	1	1	1	1
19	1	1	1	1
20	1	1	1	1
21	1	1	1	1
22	1	1	1	1
23	1	1	1	1
24	1	1	1	1
25	1	1	1	1
26	1	1	1	1
27	1	1	1	1
28	1	1	1	1
29	1	1	1	1
30	1	1	1	1
31	1	1	1	1
32	1	1	1	1
33	1	1	1	1
34	1	1	1	1
35	1	1	1	1
36	1	1	1	1
37	1	1	1	1
38	1	1	1	1
39	1	1	1	1
40	1	1	1	1
41	1	1	1	1
42	1	1	1	1
43	1	1	1	1
44	1	1	1	1
45	1	1	1	1
46	1	1	1	1
47	1	1	1	1
48	1	1	1	1
49	1	1	1	1
50	1	1	1	1
51	1	1	1	1
52	1	1	1	1
53	1	1	1	1
54	1	1	1	1
55	1	1	1	1
56	1	1	1	1
57	1	1	1	1
58	1	1	1	1
59	1	1	1	1
60	1	1	1	1
61	1	1	1	1
62	1	1	1	1
63	1	1	1	1
64	1	1	1	1
65	1	1	1	1
66	1	1	1	1
67	1	1	1	1
68	1	1	1	1
69	1	1	1	1
70	1	1	1	1
71	1	1	1	1
72	1	1	1	1
73	1	1	1	1
74	1	1	1	1
75	1	1	1	1
76	1	1	1	1
77	1	1	1	1
78	1	1	1	1
79	1	1	1	1
80	1	1	1	1
81	1	1	1	1
82	1	1	1	1
83	1	1	1	1
84	1	1	1	1
85	1	1	1	1
86	1	1	1	1
87	1	1	1	1
88	1	1	1	1
89	1	1	1	1
90	1	1	1	1
91	1	1	1	1
92	1	1	1	1
93	1	1	1	1
94	1	1		

[illegible]

Figure 4.11. Field form.

Since this study examined changes to grasslands and stands of trees over time, it was decided that tree age would be a useful parameter to include. For some species, the physical form of the tree can be used to make a gross estimate of age. Keen (1943), for example, devised a classification system for ponderosa pines that estimates both tree age and vigor. More recently, Romme *et al.* (2006) devised an aging technique using tree form for juniper and pinyon trees at Mesa Verde NM. Their guidelines include tree form, branch structure, amount of dead wood present, and bark condition. Hassler also found a general change in form that appeared to correlate with age (pers. comm. 2005). Combining the observations of these researchers with personal experience in the field, a system was devised which defined very young trees as being conical, middle-aged trees as being round, and old trees as being gnarled. Since many trees did not fall easily into these three categories, the in-between categories of conical/round and round/gnarled were also included. When a particularly old and gnarled tree was found, this was noted.

Categorizing trees by form is a subjective process, which is further complicated by the fact that juniper trees appear capable of taking on an endless variety of shapes, depending upon growing conditions. By adhering to consistent guidelines, however, this type of aging system can be a useful tool. The criteria used for each class are listed in Table 4.4. Example photographs are shown in Figures 4.12a and 4.12b.

Shape	Conical	Conical/Round	Round	Round/Gnarled	Gnarled
Approx. Age	very young to young	young to juvenile	juvenile to mature	mature to old	old to very old
Shape	conical, square, or round	conical, square, or round	typically round, but conical or square are also common	typically still rounded, but irregularity, and sometimes spreading, becoming pronounced	typically irregular, can be extremely spreading
Foliage	typically uniform from ground to tree top	typically uniform from ground to tree top	typically uniform from ground to tree top	becoming non-uniform, often starting to lift off the ground, becoming more sparse and clumped	not uniform, almost always lifted off the ground, tends to be bunched at branch ends
Height	short – typically under 1 m	variable, but typically 1-2 m	variable, but typically 2-3 m	variable, but typically 3-5 m	variable, but typically 3-5 m
Bark	relatively smooth, typically supple, no dead wood	relatively smooth, typically supple, no dead wood	shaggy, no dead wood on main stems	shaggy, typically noticeable dead wood on main stems	distinctively shaggy, typically considerable dead wood on main stems
Dead Branches	typically none	typically none	typically none or very little	often noticeable dead portions	often considerable dead portions

Table 4.4. Juniper age class criteria.



Figure 4.12a. Examples of tree-age classification.

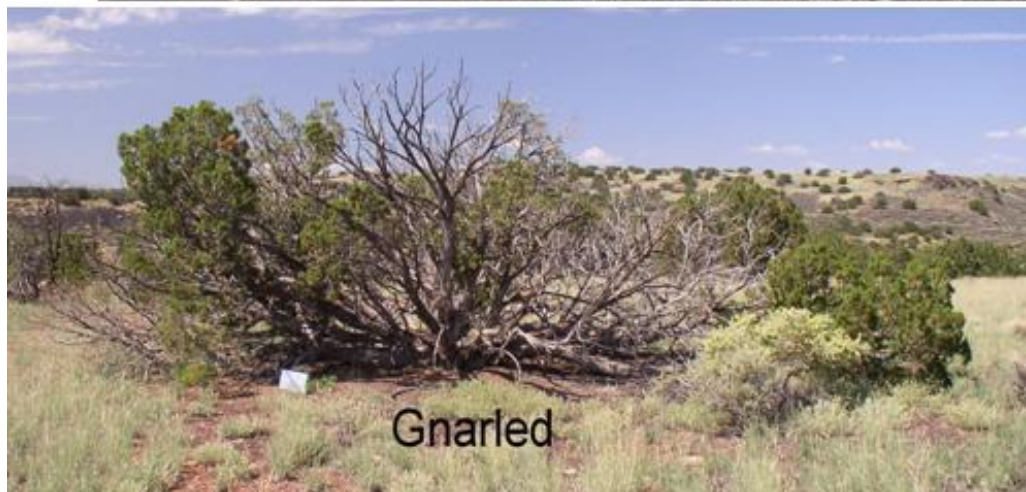
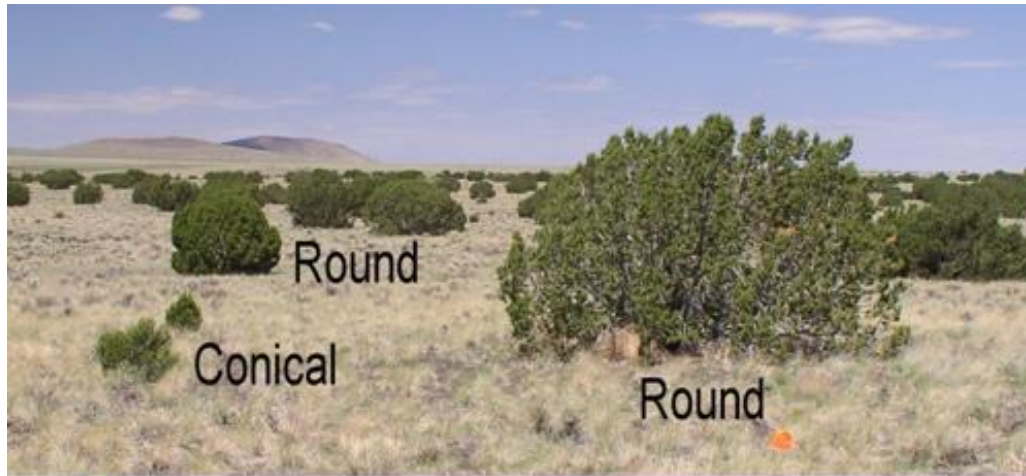


Figure 4.12b. Examples of tree-age classification.

The dominant tree species was the one-seed juniper. When the rare pinyon tree was encountered, this was noted on the field form. Although Romme *et al.* (2006) used the same criteria for both juniper and pinyon, the same criteria did not appear to be applicable for the few pinyon trees found in this study area. To avoid devising a separate system for so few trees, tree size and stem diameter were visually estimated and used to approximate the age of these trees.

A baseline terrestrial photo-record was created for each test cell. A digital photograph was taken of each subplot from the center of each hectare cell. Photo directions are shown in Figure 4.9. If a tree was in the center of the hectare cell the camera was moved to whatever side was necessary to get a clear view of each subplot. If a tree at the corner of a subplot obscured the rest of the subplot, the camera was moved to the left until a good view of the remainder of the subplot was obtained. A second photograph was taken from that position. Likewise, if there was a major topographic feature, such as a slope or cliff, the camera was moved to an appropriate vantage point to make a good visual recording of the subplot.

Ancillary Data

Although the following additional field data would not be used in the analysis of this project, interesting observations made in the field were also placed in the margins of the field forms. For example, many trees had interlocking canopies. Since NVCS uses this parameter to delineate woodlands and forests, I noted which canopies were joined.

As there is interest in how juniper trees influence understory plants, four gross-scale understory categories were added to the field form. These categories were defined as follows:

- 1) grass/shrub dominated,
- 2) grass/shrub dominated, except around and between the trees,
- 3) primarily cinder dominated, but with some sparse grass/shrubs, and
- 4) completely cinder dominated.

Another interesting issue is that the study area is currently experiencing a long-term drought. Since how much of a tree is alive and vigorous versus dead or dying could be an indication of drought stress, such observations were noted on the field form. Determining vigor of junipers is a challenge. Some amount of dead wood, especially on older trees, is common and does not necessarily suggest health problems with the tree. There are several common pests that plague pinyon and juniper trees, and can produce a variety of symptoms, including dieback. The juniper twig pruner (*Styloxus bicolor*), for example, is one of several boring insects that are part of the natural juniper ecosystems throughout the Southwest (Fairweather *et. al* 2006). While this insect causes obvious twig dieback, it typically does little damage to the overall tree. The dead twig commonly falls off shortly after the emergence of the grub and does not persist on the tree as long-term deadwood. Damage that was clearly due to twig pruners was ignored.

Three gross-scale ages of dieback were recorded: (1) very recent, (2) recent and (3) old (i.e., dieback had occurred long ago). Branches that were considered as having died “very recently” still had bright orange/brown foliage attached. It was estimated that these branches had died in the last couple of years. Branches that had died “recently” had little

or no foliage, and what foliage remained was frequently gray with age. Many of the small twigs and most bark were typically still attached, although often in the process of being shed. Using scorch damage examples from the Antelope and State Fires, which are known to have occurred seven years ago, it was estimated that these branches had died sometime in the last six to eight years. Branches that had died “long ago” had shed all foliage, small twigs, and bark. These branches were typically bare wood, and frequently bleached white with age. It was estimated that these branches died ten or more years ago. Some have perhaps persisted on the tree for decades.

All stumps and standing snags found within a test cell were recorded. If a tree within a subplot was dead, the DOQQ was used to determine if the tree had been alive in 1997. If not, then the dead tree was recorded on the field map but was not considered for canopy cover. If the tree had been alive in 1997, and if the tree was still substantially present, then its canopy was measured. This included trees that had been killed in the 2002 Antelope and State Fires, as well as trees that apparently died due to the current drought. In most of these cases the dead foliage was still present, and it was determined that a reasonable measurement of the canopy could be made. If the tree had been recently harvested, then a different decision had to be made. If the tree had not been substantially harvested (often just one large branch is taken) then what was left of the tree was measured. If the tree had been substantially harvested and it was determined that a major amount of the canopy was missing, the hectare cell would be excluded and the next one on the list would be used.

CHAPTER 5

RESULTS AND ANALYSIS

Image-to-Image Registration Results

The geo-referencing feature of ESRI ArcMap 8.3 was used to register the digitized 1936 SCS aerial images to the 1997 DOQQ images. As this software registers an image pair, it also calculates how closely it is able to warp the image to the reference image. This accuracy is expressed by the root mean square error (RMSE), which is calculated for each control point using the following equation (Jensen 1996):

$$\text{RMSE} = \sqrt{(X' - X_{\text{ref}})^2 + (Y' - Y_{\text{ref}})^2}$$

Where: X' = X coordinate of the control point on the image being registered,
 X_{ref} = X coordinate of the control point on the reference image,
 Y' = Y coordinate of the control point on the image being registered,
 Y_{ref} = Y coordinate of the control point on the reference image.

An average RMSE is also calculated for the overall image. The RMSE is typically expressed in the same units as the ground resolution cell size of the reference image (Jensen 1996). Ideally an image is warped until the overall RMSE represents a smaller spatial mismatch between images than the size of the ground resolution cell of the reference image (Richards and Jia 2006). If the ground resolution cell size of two images being registered is one meter, then the overall error in matching would ideally be one

meter, or less. This standard is fairly easily met with images taken by modern, high-resolution mapping cameras that contain reliable, “non-moving” control points, such as the corners of buildings. It can be difficult to meet this standard with images depicting natural subjects. When registering images with only natural subjects, a RMSE of ± 3 to ± 5 meters is considered acceptable (Welch and Remillard 1996). Sometimes errors larger than this are unavoidable (Hudak and Wessman 1998; Kambiz and Lawrence 1998; Welch and Remillard 2002).

A control point with a particularly large RMSE is often caused by poor operator placement of the control point. In this case, repositioning it more carefully will usually result in a smaller RMSE and a more accurate registration (Richards and Jia 2006). Sometimes, however, distortion of an image cannot be resolved, and the RMSEs of all control points in a particular area of the image remain unfavorably large. This is not uncommon when performing image-to-image registration with old photographic images. Although deleting points with large error values will reduce the overall RMSE, it will also remove any attempt to register the portion of the image that the difficult control points were removed from. Leaving these points, however, allow for at least a partial correction. The priorities of a particular investigation typically drive the choice between forcing a small RMSE value by removing control points with large error values and attempting what image correction is possible, even if it results in an unfavorable overall RMSE (Richards and Jia, 2006).

The priority of this project was to register the SCS images to the DOQQs as accurately as possible. During the registration of each image, a minimum of 25 control points were initially selected. Care was taken to ensure that these points were well

distributed across the entire study area (Avery and Berlin 1992). The resulting registration was evaluated both numerically, via the RMSE, and visually. For this project, visual verification is defined as the practice of manually determining when the closest match of point A' to A_{ref} had been obtained. Since manual visual classification was to be performed on these images, preference was given to visual verification, regardless of the size of the overall RMSE. Additional control points were added until it was determined that the best possible registration was achieved.

As each assembled SCS photograph was originally taken at four slightly oblique angles, large errors were expected. Indeed, some of the final RMSE values for this study are quite large. Although every attempt was made to reduce the error size, the priority to register each area of the image as accurately as possible was adhered to. The decision was made to accept high error values rather than to force a small RMSE by simply not registering difficult areas. The final registered 1936 images and the DOQQs these images were registered to are shown in Figure 5.1.

Table 5.1 summarizes the registration process for this project. The table shows (1) which DOQQ(s) each SCS image was registered to; (2) how many control points were used for each SCS image; (3) the resulting RMSE for each image, and (4) the average RMSE for all images. It is to be expected that with greater topographic relief there will be greater geometric distortions within an image (Avery and Berlin 1992; Warner 1997). This held true for this study. The images with lower RMSE values depict areas of gently rolling terrain. The images with the highest RMSE values all include the Doney Cliffs, an important relief feature.

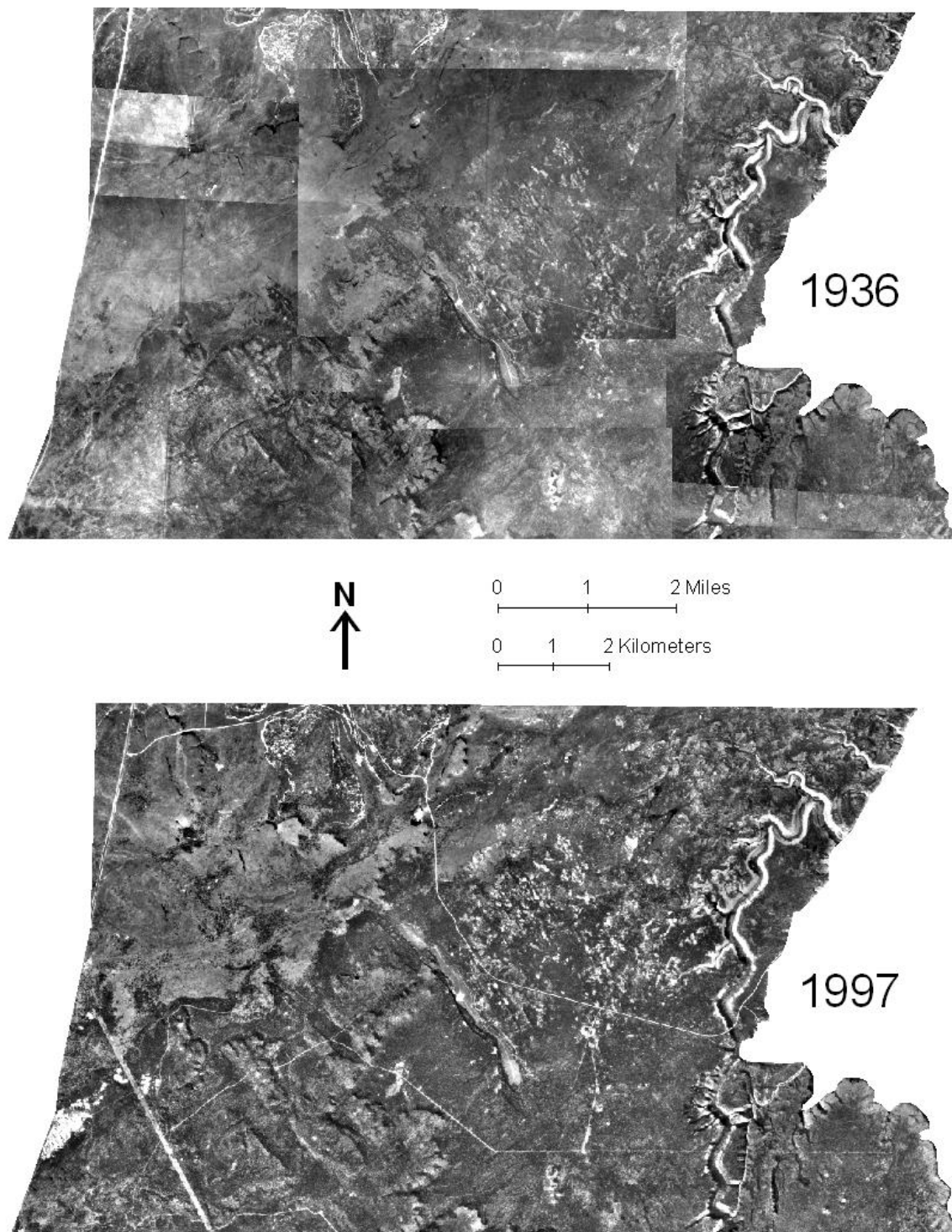


Figure 5.1. Registered images of the study area in 1936 and 1997.

The top image shows the final mosaic of the registered, digitized 1936 airphotos. The variation in tonation is evident. The lower image is the original DOQQ set as produced by the USGS.

Table 5.1. Image-to-image registration results.

SCS Image ID	DOQQs	Number of Control Points	RMSE (m)
1987	easpmone, wupaswnw	79	26.75
1988	easpmone, easpmose, wupaswsw, wupaswnw	75	20.29
1989	easpmose, wupaswsw	112	28.06
1990	easpmose, wupaswsw, olepeane, strcranw	66	17.89
2016	strcrane, strcranw, wupaswsw, wupaswse	99	21.84
2017	wupaswsw, wupaswse	87	11.16
2018	wupaswsw, wupaswse, wupaswnw, wupaswne	62	11.04
2019	wupaswnw, wupaswne, wupaswsw, wupaswse	74	10.24
2039	wupaswne, wupasenw	201	42.78
2040	wupaswne, wupasenw, wupaswse, wupasesw	154	38.85
2041	wupaswse, wupasesw	230	41.96
2042	wupaswse, wupasesw, rodcranw, strcrane	162	35.55
Total Number of Control Points: 1,401 Mean RMSE: 25.5 m			

Classification Results

The study area consists of 13,584 one hectare cells. Ninety-four of these cells (<1%) were excluded due to extensive anthropogenic alteration. Excluded areas include stock tanks, the Antelope Hills Trading Post, portions of a high-power line easement, and a pumice quarry. The remaining cells numbered 13,490. These cells were manually classified twice; once using the digitized 1936 SCS airphotos and once using the 1997 DOQQs. Classification results are presented in Figure 5.2.

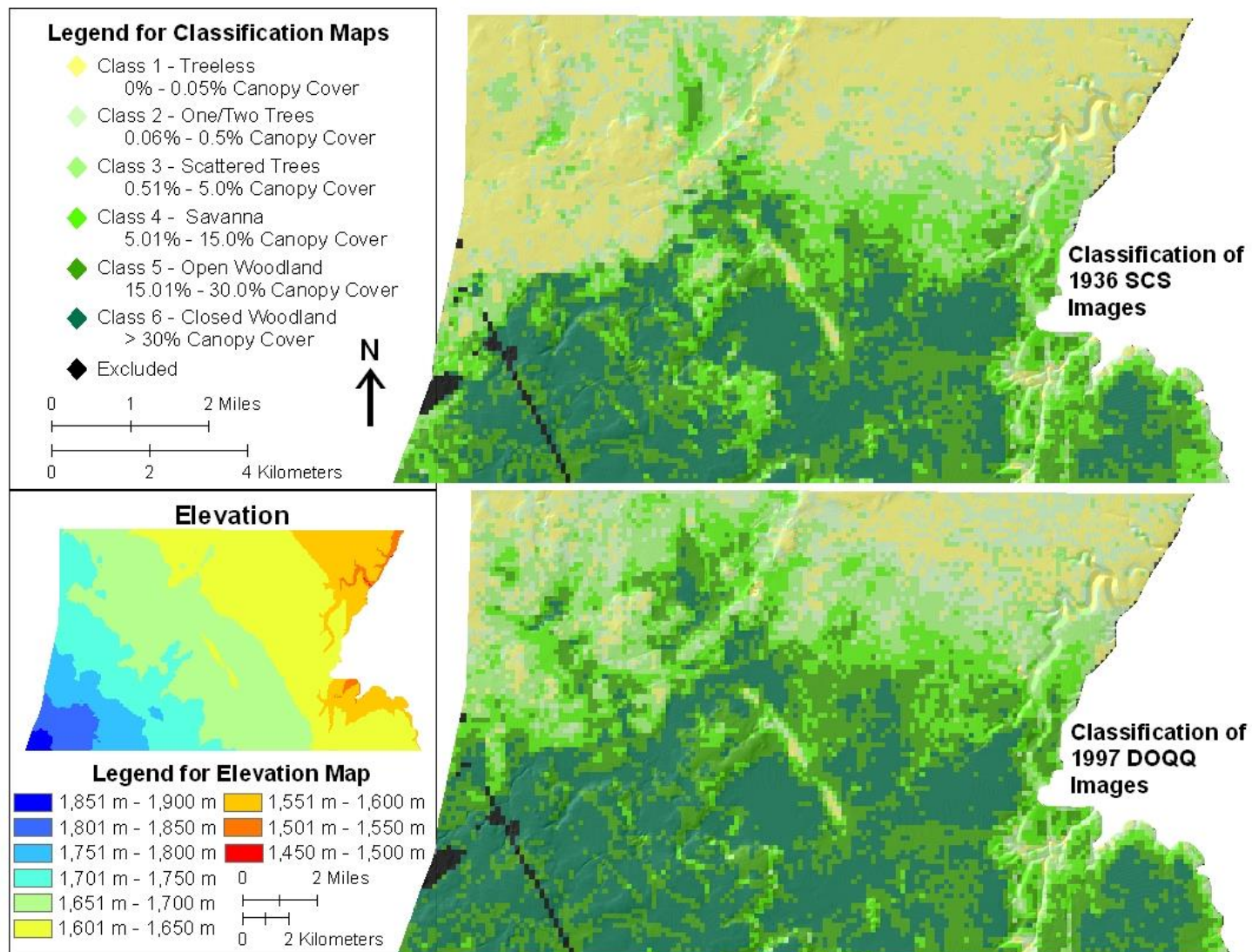


Figure 5.2. Classification of the study area in 1936 and 1997.

This figure shows the final classification of the 1936 and 1997 images. Elevations for the study area are also shown. The progression of woodland northward, and generally downslope, is evident.

Table 5.2 and Figure 5.3 summarize the classification results in tabular and graphic form, respectively. Proportionally, the largest number of hectare cells from the 1936 images fell into the two extreme classes: Class 1, treeless areas (27.20%), and Class 6, closed woodland (21.56%). By 1997, the majority of cells fell into the two most heavily wooded Classes; Class 5, open woodland (23.59%) and Class 6, closed woodland (28.49%). Whereas 27.20% of the study area was treeless in 1936, only 9.50% was treeless in 1997. Similarly, whereas 39.37% was classified as open/closed woodland in 1936, 52.08% was open/closed woodland by 1997. This represents a reduction in treeless areas of 17.64%, and a smaller, but notable, increase in woodlands of 12.71%. Classes 2,

Class	Canopy Cover	Definition	Number of Hectare Cells per Class			Percent of Total per Class		
			1936	1997	Change	1936	1997	Change
-	-	Excluded	94	94	0	0.69%	0.69%	0.00%
1	0-0.05%	Treeless	3,695	1,290	-2405	27.20%	9.50%	-17.70%
2	0.06-0.5%	One/Two Trees	1,131	1,292	161	8.33%	9.51%	1.19%
3	0.51-5%	Scattered Trees	1,743	1,971	228	12.83%	14.51%	1.68%
4	5.01-15%	Savanna	1,573	1,863	290	11.58%	13.71%	2.13%
5	15.01-30%	Open Woodland	2,419	3,204	785	17.81%	23.59%	5.78%
6	>30%	Closed Woodland	2,929	3,870	941	21.56%	28.49%	6.93%
		Totals	13,584	13,584	0*	100.00	100.00	0.00*

Table 5.2. Summary of manual classification for 1936 and 1997.

This table includes the excluded cells, so the values are somewhat different from the tables that follow, which that do not include these cells.
** These values are zero because the overall number of cells did not change.*

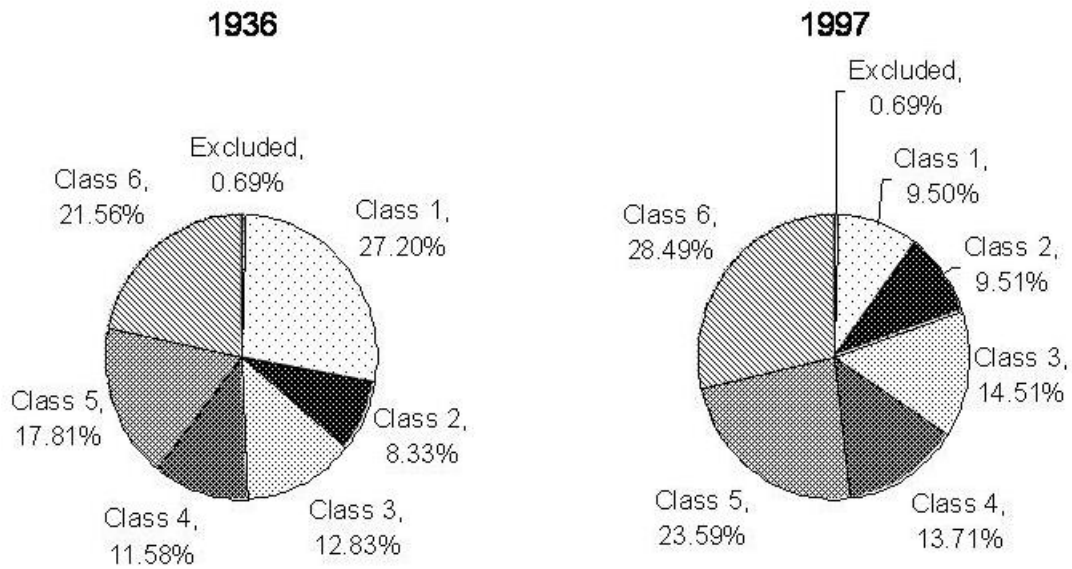


Figure 5.3. Pie charts of canopy class change from 1936 to 1997.

3, and 4 also increased in area (1.18%, 1.68%, and 2.13% respectively). The only class that decreased in area was Class 1, treeless areas.

CHANGE ANALYSIS

The number of hectare cells classified and analyzed for change was 13,490 (13,584 minus the 94 excluded cells). Of this number, 7,368 cells (54.62%) stayed in the same class, while 6,122 cells (45.38%) changed sufficiently to be placed into a different class.

Even a casual examination of the 1936 and 1997 images suggests a considerable increase in treed areas (Figure 5.1). The classification results in Figure 5.2 confirm this increase, showing a general south-to-north/ downslope progression of the tree line. What is not as evident is the spatial distribution of the change. Figure 5.4 provides a spatial

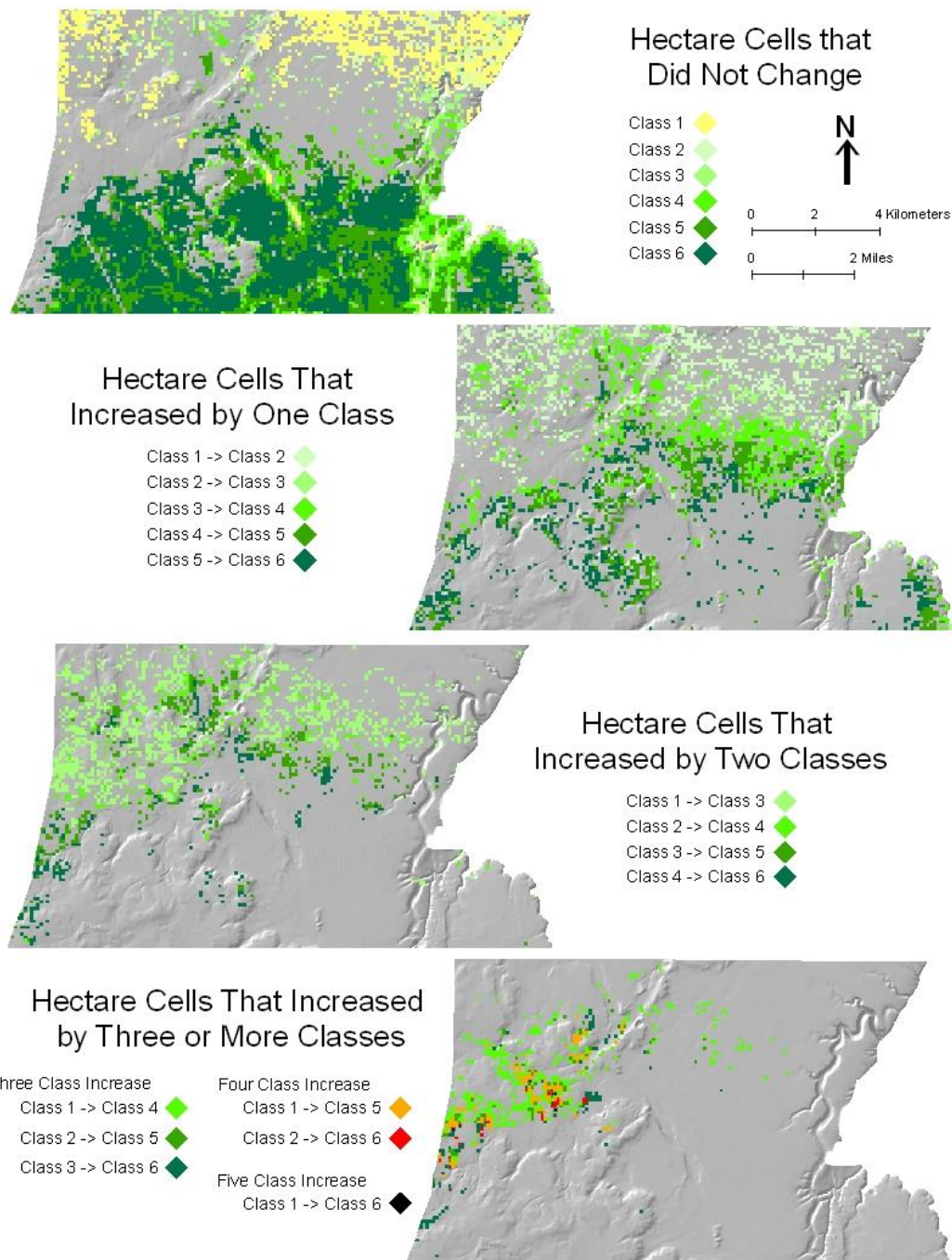


Figure 5.4. Spatial patterns of canopy class change.

These maps provide a spatial depiction of where changes occurred in canopy cover between 1936 and 1997.

view of this change. The first map shows the areas that did not change class. The three remaining maps show the locations of hectare cells that changed by one, two, and three or more classes, respectively. As might be expected, the areas that show no change are at the two extremes, both geographically and in class definition. The areas that show change are dispersed, but are primarily located within the transition zone inbetween these extremes.

The bulk of the treeless cells (Class 1) that did not change are in the northernmost/down-slope areas of the study area, while the majority of closed woodland areas (Class 6) that did not change are in the southernmost/up-slope areas. Areas that changed by one class appear to be fairly evenly distributed, with the notable exception of the areas in the south that have been wooded since 1936 and have not changed. Areas that increased by two classes appear in an east-west trending transitional band that runs through the northern portions of the study area. Areas that increased by three or more canopy cover classes are primarily found in the Big Hawk Valley area (Figure 3.2), a swath that trends from the southwest corner of the study area towards the northeast.

The change matrix table is a useful tool for analyzing the vegetation changes. Tables 5.3, 5.4, and 5.5 show the final classification results in a change matrix format. Table 5.3 provides a summation of the classification results in hectares; Table 5.4 takes a closer look at the cells that actually changed, and Table 5.5 provides two different temporal perspectives into these changes. In each of these tables, the 1936 classification results are displayed in the columns, while the 1997 classification results are displayed in the rows. Each table also has two sub-tables: one that shows the number of hectare cells, and a second that expresses those cells as percentages of all cells analyzed for change. The diagonal table cells (blue) indicate the number of hectares that did not change. The table

Table 5.3a. Classification change matrix in numbers of hectare cells.

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Totals
Class 1	1,269	13	8	0	0	0	1,290
Class 2	912	370	9	1	0	0	1,292
Class 3	1,024	459	485	3	0	0	1,971
Class 4	353	196	752	554	6	2	1,863
Class 5	126	73	398	792	1,789	26	3,204
Class 6	11	20	91	223	624	2,901	3,870
Totals	3,695	1,131	1,743	1,573	2,419	2,929	13,490
Total number of hectare cells that show no change:						7,368	
Total number that show decrease in canopy cover:						68	
Total number that show increase in canopy cover:						6,054	

Table 5.3b. Classification change matrix expressed as percentages of all hectare cells analyzed for change.

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Totals
Class 1	9.41%	0.10%	0.06%	0.00%	0.00%	0.00%	9.56%
Class 2	6.76%	2.74%	0.07%	0.01%	0.00%	0.00%	9.58%
Class 3	7.59%	3.40%	3.60%	0.02%	0.00%	0.00%	14.61%
Class 4	2.62%	1.45%	5.57%	4.11%	0.04%	0.01%	13.81%
Class 5	0.93%	0.54%	2.95%	5.87%	13.26%	0.19%	23.75%
Class 6	0.08%	0.15%	0.67%	1.65%	4.63%	21.50%	28.69%
Totals	27.39%	8.38%	12.92%	11.66%	17.93%	21.71%	100.00%
Percent that show no change:						54.62%	
Percent that show decrease in canopy cover:						0.50%	
Percent that show increase in canopy cover:						44.88%	

Table 5.4a. Number of hectares that changed class from 1936 to 1997.

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Total Decrease	Total Increase
Class 1	-	13	8	0	0	0	21	-
Class 2	912	-	9	1	0	0	10	912
Class 3	1,024	459	-	3	0	0	3	1,483
Class 4	353	196	752	-	6	2	8	1,301
Class 5	126	73	398	792	-	26	26	1,389
Class 6	11	20	91	223	624	-	-	969
Total Decrease	-	13	17	4	6	28	68	-
Total Increase	2,426	748	1,241	1,015	624	-	-	6,054
Total number of hectare cells that changed:								6,122
Number that show reduction in canopy cover:								68
Number that show increase in canopy cover:								6,054

Table 5.4b. Hectares that changed class
as percent of all cells that changed from 1936 to 1997.

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Total Decrease	Total Increase
Class 1	-	0.21%	0.13%	0.00%	0.00%	0.00%	0.34%	-
Class 2	14.90%	-	0.15%	0.02%	0.00%	0.00%	0.16%	14.90%
Class 3	16.73%	7.50%	-	0.05%	0.00%	0.00%	0.05%	24.22%
Class 4	5.77%	3.20%	12.28%	-	0.10%	0.03%	0.13%	21.25%
Class 5	2.06%	1.19%	6.50%	12.94%	-	0.42%	0.42%	22.69%
Class 6	0.18%	0.33%	1.49%	3.64%	10.19%	-	-	15.83%
Total Decrease	-	0.21%	0.28%	0.07%	0.10%	0.46%	1.11%	-
Total Increase	39.63%	12.22%	20.27%	16.58%	10.19%	-	-	98.89%
Total number of hectare cells that changed:								6,122
Percent that show reduction in canopy cover:								1.11%
Percent that show increase in canopy cover:								98.89%

Table 5.5a. Classification change matrix in number of hectare cells.
(This table is identical to Table 5.3a - it is repeated as reference for the following tables.)

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Totals
Class 1	1,269	13	8	0	0	0	1,290
Class 2	912	370	9	1	0	0	1,292
Class 3	1,024	459	485	3	0	0	1,971
Class 4	353	196	752	554	6	2	1,863
Class 5	126	73	398	792	1,789	26	3,204
Class 6	11	20	91	223	624	2,901	3,870
Totals	3,695	1,131	1,743	1,573	2,419	2,929	13,490

Table 5.5b. Change to the 1936 cell classification by 1997
by percent of class.

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Totals
Class 1	34.34%	1.15%	0.46%	0.00%	0.00%	0.00%	-
Class 2	24.68%	32.71%	0.52%	0.06%	0.00%	0.00%	-
Class 3	27.71%	40.58%	27.83%	0.19%	0.00%	0.00%	-
Class 4	9.55%	17.33%	43.14%	35.22%	0.25%	0.07%	-
Class 5	3.41%	6.45%	22.83%	50.35%	73.96%	0.89%	-
Class 6	0.30%	1.77%	5.22%	14.18%	25.80%	99.04%	-
Totals	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	-

Table 5.5c. Percent change to the 1997 cell classification from 1936
by percent of class.

1936 1997	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Totals
Class 1	98.37%	1.01%	0.62%	0.00%	0.00%	0.00%	100.00%
Class 2	70.59%	28.64%	0.70%	0.08%	0.00%	0.00%	100.00%
Class 3	51.95%	23.29%	24.61%	0.15%	0.00%	0.00%	100.00%
Class 4	18.95%	10.52%	40.37%	29.74%	0.32%	0.11%	100.00%
Class 5	3.93%	2.28%	12.42%	24.72%	55.84%	0.81%	100.00%
Class 6	0.28%	0.52%	2.35%	5.76%	16.12%	74.96%	100.00%
Totals	-	-	-	-	-	-	-

cells above the no-change diagonal (yellow) indicate the hectares that lost tree canopy cover over time. The table cells below the no-change diagonal (green) indicate hectares that increased in tree canopy cover.

The largest values in Table 5.3 are those that show no change in Class 6 (2,901 ha), Class 5 (1,789 ha), and Class 1 (1,269 ha). These three non-changing classes comprise 44.17% of the cells that did not change. The remaining 10.45% are represented in the non-change cells in Classes 2, 3, and 4. The cells which indicate a reduction in tree canopy cover (yellow) account for only 0.50% of all hectares analyzed for change. The cells which represent tree canopy cover increase (green), on the other hand, include 44.88% of all hectare cells analyzed for change. Overall, a total of 6,122 hectare cells (45.38%) changed class, with the majority showing an increase in tree canopy cover.

Table 5.4 provides a closer look at the 6,122 hectare cells that changed. The largest change occurred for cells that had been classified as Class 1 in 1936. Of the 3,695 hectare cells classified as Class 1 in 1936, 2,426 showed enough increase in tree canopy cover by 1997 to be reclassified into denser classes. This shows an increase in tree canopy cover to 65.66% of the 1936 Class 1 cells. This increased tree canopy cover in formerly treeless areas represents 39.63% of all the change that occurred in all cells from all classes.

In this study, it appears that the most common change was for the tree canopy cover to have increased, or decreased, by one tree canopy cover class value. The second most common change is for the tree canopy cover to have increased/decreased by two classes. For example, while 12.28% of the hectare cells classified as Class 3 in 1936 show a one class increase in canopy cover by 1997, only 6.50% show a two class increase, and even fewer (1.49%) show a three class increase. The exception to this is that more hectare cells

classified as Class 1 in 1936 made a two class leap to Class 3 (16.73%) than the one class shift to Class 2 (14.90%). Indeed, this change outpaces any other change in classification value observed.

Table 5.5 provides two different temporal perspectives of the change recorded in Table 5.3. The first perspective (Table 5.5b) is from a 1936 vantage point, and describes what happened to the 1936 landscape over time. The second perspective (Table 5.5c) is from the vantage point of 1997, looking back in time. This table describes where the 1997 cells came from. For ease of reference, the data from Table 5.3 are repeated in Table 5.5a.

Table 5.5b (the 1936 perspective) shows that of the 3,695 hectare cells classified in 1936 as Class 1, only 34.34% of these cells (1,269 ha) are still classified as Class 1 in 1997. From the 1997 perspective, however, Table 5.5c shows that 98.37% of the hectare cells classified as Class 1 in 1997 were also classified as Class 1 in 1936. In other words, while the majority of the treeless areas in 1997 were also treeless in 1936, only slightly more than one third of the treeless areas in 1936 were still treeless in 1997. This indicates a remarkable reduction in treeless areas between 1936 and 1997. At the other extreme, while 99.04% of the closed woodland areas in 1936 are still closed woodland in 1997, only 75% of the closed woodland areas in 1997 were closed woodland in 1936. A full 25% of the closed woodland areas in 1997 had less canopy cover in 1936. Table 5.5c also shows what classes that 25% came from:

- 16.12% came from Class 5,
- 5.76% came from Class 4,
- 2.35% came from Class 3,
- less than 1% came cumulatively from Classes 1 and 2.

This suggests savanna and woodland fill-in has occurred. Figures 5.5 and 5.6 show these changes in graphical form.

Accuracy Assessment

Accuracy assessment was performed with the goal of determining a map accuracy of at least 80%, the accepted standard of the National Park Service/National Biological Survey Vegetation Mapping Project (NPS IandM 2008). Canopy cover data were collected from 1,695 trees in the field to provide reference data with which to perform this accuracy assessment. Other stand data were also collected and are discussed in detail in the Stand Data section.

FIELD WORK RESULTS

Field data were collected from 120 (0.88%) of the 13,490 hectare cells that comprise the study area. These data were collected in 38 trips to the study area between June 2007 and February 2008. Accuracy assessment was performed on less than 1% of the population because time and budgetary limitations prohibited the verification of more cells.

Upon examination in the field, three data collection cells were eliminated from the study: two because they were on the cliffs of Antelope Wash, and one because it had been too heavily harvested to use. In each case, the next numbered data collection cell of the same class from the list generated by the GRTS algorithm was used. The summary of this replacement is listed in Table 5.6.

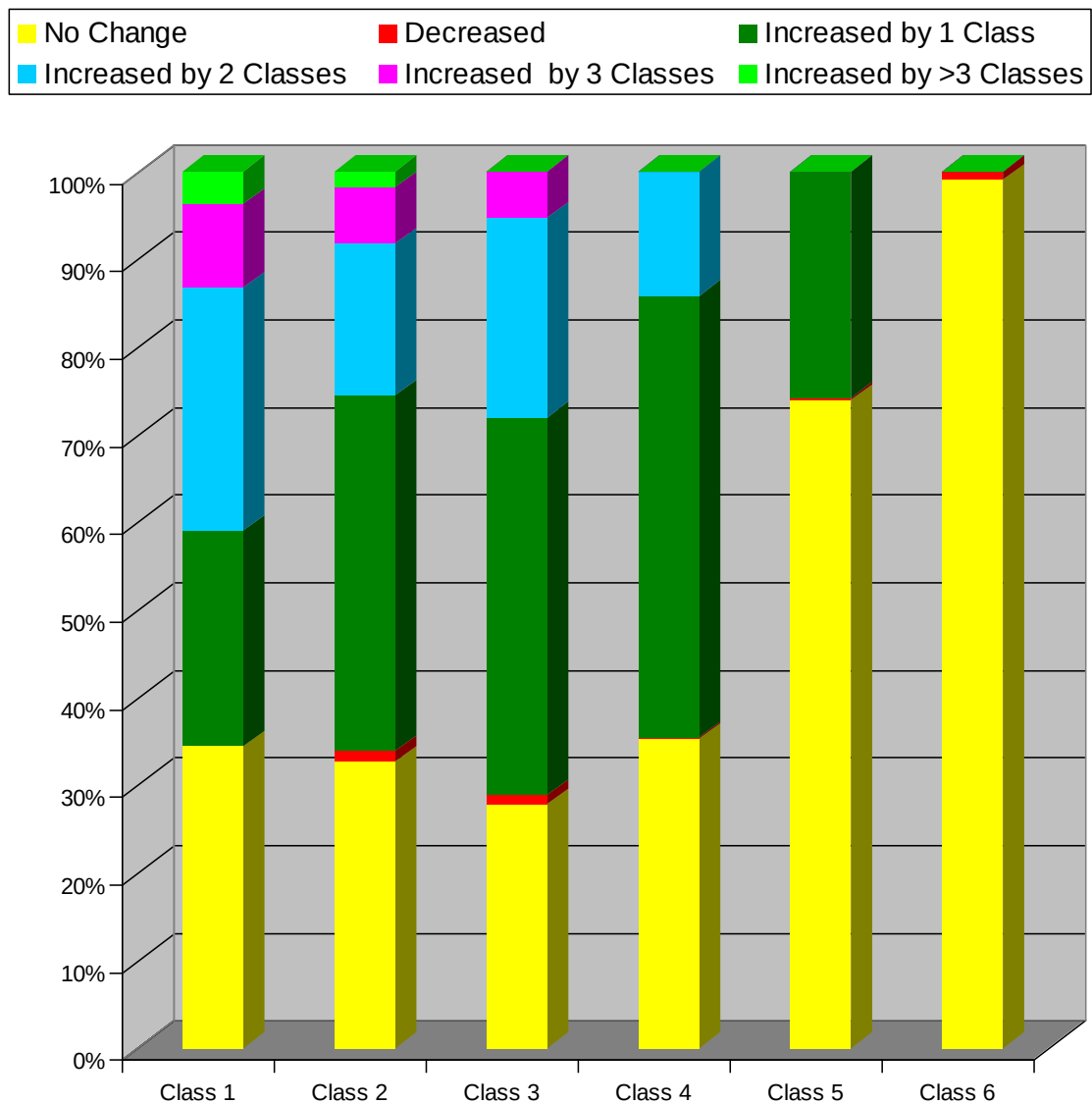


Figure 5.5. Graphic depiction of how the 1936 landscape changed.

This graphic clearly shows how much of the 1936 landscape changed over time. While most of the closed woodland areas (Class 6) remained the same, the vast majority of the treeless (Class 1) and more lightly treed areas (Classes 2-5) show a notable increase in canopy cover by one or more classification class values.

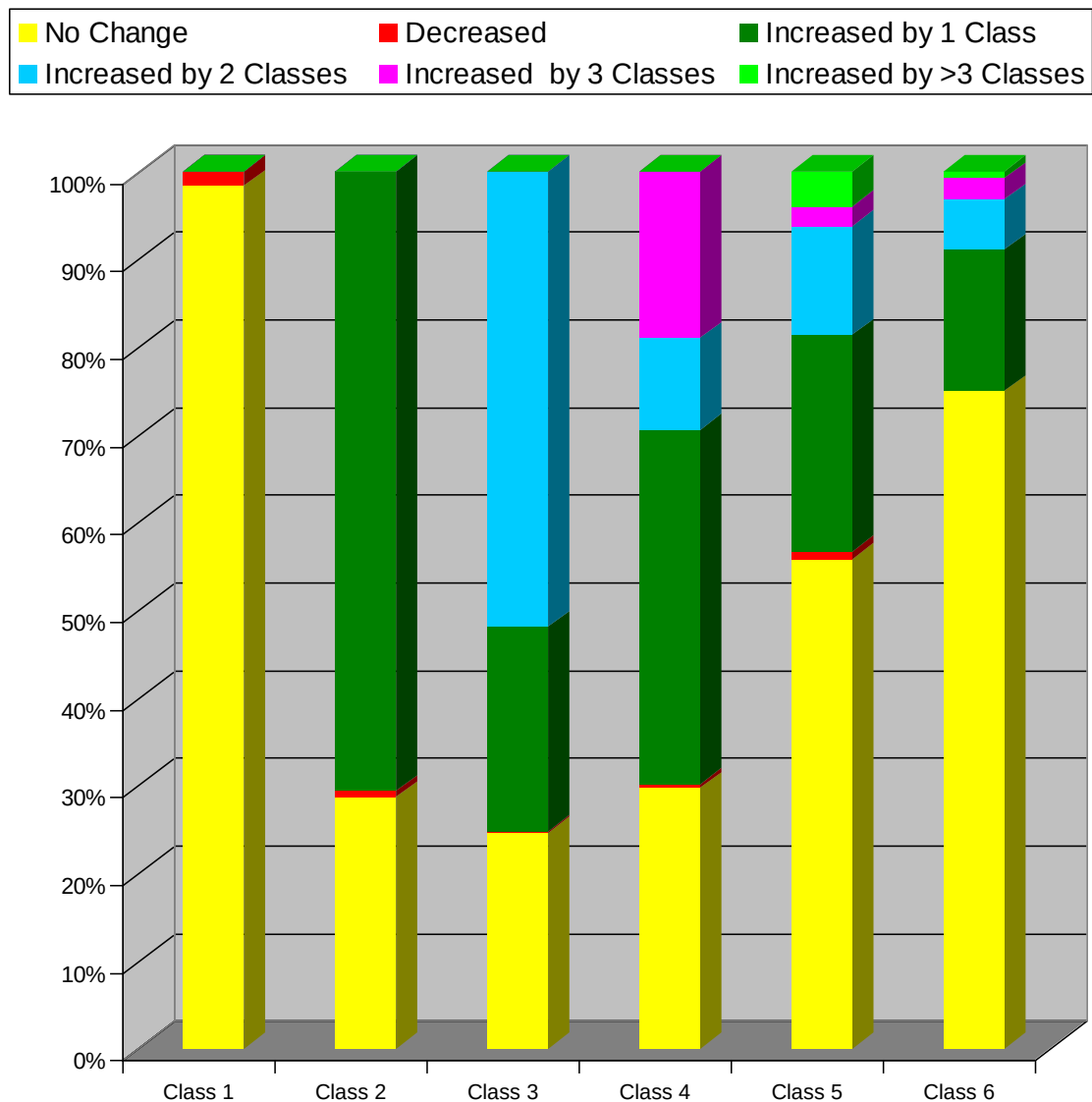


Figure 5.6. Graphic depiction of where the 1997 landscape came from.

This graphic shows the history of the 1997 landscape. While, clearly, the majority of the treeless areas (Class 1) in 1997 had also been treeless in 1936, a significant percentage of the variously wooded areas (Classes 2-6) previously had notably fewer trees. Most notable is the two class increase in over 50% of the areas classified as Class 3 in 1997.

Table 5.6. Summary of eliminated field data collection cells.

Class	Original Cell Number	Replacement Cell Number	Reason
3	106	121	Cliff
4	158	171	Cliff
6	260	271	Harvested

The canopy cover for each field data collection cell was calculated and then translated into a classification value according to the percent canopy cover definition values. The field classification was then compared to the manual classification for each cell to determine how accurately the manual classification reflected what was actually measured in the field.

ACCURACY ASSESSMENT RESULTS

When evaluating the field classification results, an unexpectedly high number of hectare cells were found to have been misclassified. While some of these misclassifications are simply wrong, the reasons for many of the errors are understandable. Small trees are a particular challenge in this type of classification. There is a size threshold below which a tree will not appear distinctly in an airphoto. While the pixel size of the DOQQs is one meter, it is not simple geometry that determines whether a one meter wide tree will be visible as a distinct dark feature. Tree detection is also affected by where the tree falls within the pixel geometry (e.g., in the center or along the edge), the health of the foliage (full or sparse), and the background material. Trees that have sparse

or unhealthy foliage may not appear on the image. If a tree is large, but has very sparse foliage, it may look similar to a mottled patch of cinders. The type of background material can highlight or mask the presence of trees. Trees, even small trees, growing in the cracks of limestone, or in fields of thick, continuous grass, are typically easy to see because of the “bright” background. Trees growing in areas that are mottled by cinders or large shrubs (e.g., saltbush, rabbitbrush, sumac, or Apache plume) may also be hard to detect. When the cinder deposits are thick over a large area, such as on leeward slopes, even large trees can be completely obscured. Basalt outcrops that extend for some distance can typically be discerned, but a large, isolated basalt boulder can be mistaken for a tree.

Other researchers have found similar types of confounding ground conditions (Klopfer *et al.* 2002, Hansen *et al.* 2004). To address this, it is becoming common to perform an accuracy assessment for vegetation mapping at different levels: (1) the standard criteria of exact match; (2) some number of “fuzzy” categories of error; and (3) a final level of simply incorrect. The first assessment of this study used the standard criteria of exact match. Since this effort produced unexpectedly low results, the decision was made to re-access the results using fuzzy criteria defined appropriately for this study area and project objectives. Four levels of accuracy criteria were defined and are listed in Table 5.7. Accuracy assessment was then performed according to three sets of criteria: (1) Criteria 4 alone; (2) Criteria 3 and 4; and (3) Criteria 2, 3, and 4.

Appendix A lists the field results for this project and how the classification/misclassification of each cell was evaluated against these four criteria. Of the 120 field data collection cells that were verified, 34 (28.33%) were misclassified according to

Criteria 4. If the Acceptable level of error defined in Criteria 3 is allowed, the number of misclassified cells drops to 25 (24.83%). If the Understandable level of error in Criteria 2 is used, the number of misclassified cells falls to 20 (16.67%). These results are summarized in Table 5.8.

A standard tool for assessing map classification accuracy is the error matrix (Congalton 1991, Jensen 1996). Table 5.9 shows the accuracy assessment error matrix for this project according to Criteria 4, Table 5.10 for Criteria 3 and 4, and Table 5.11 for Criteria 2, 3, and 4.

The rows of each error matrix show the manual airphoto classification results, while the columns show the results of the field classification (Congalton 1991). Producer's (omission) and user's (commission) accuracies were also computed. The producer's accuracy indicates how consistently a certain area was classified by the producer of the map. The user's accuracy indicates how often a user will actually find in the field the same classification as shown on the map. For example, Table 5.9 indicates that 80% (producer's accuracy) of the times that a hectare cell had one to two trees in it, that cell was classified as Class 2 on the map. However, only 40% (user's accuracy) of the Class 2 cells on the map actually correspond to hectare cells on the ground that have one to two trees. Conversely, while only 69% of the times that a hectare cell on the ground that has no trees was properly classified as a Class 1 on the map, a user can be 100% certain that every Class 1 cell on the map will have no trees.

Table 5.7. Accuracy assessment criteria definitions.

Criteria 4:	Exact Match - Manual classification and field results match exactly.
Criteria 3:	Acceptable - Misclassification occurred because either (1) sufficient tree canopy existed within the hectare cell but did not fall within the subplots (typically resulting in a lower canopy class field classification), or (2) a considerable number of trees were obscured by cinders (typically resulting in a higher canopy cover class field classification).
Criteria 2:	Understandable - Misclassification occurred because some type of non-tree object on the ground clearly looked like a tree in the images. Objects included large shrubs (typically saltbush, three-leaf sumac, or Apache plume), isolated patches of cinders, or isolated basaltic boulders. Also, included in this level of error is the over-evaluation of canopy cover due to cinder rings ¹⁵ around trees.
Criteria 1:	Complete Error – Hectare cell was misclassified.

¹⁵ The processes that cause cinder rings are not well understood. Cinder rings may be created by the juniper tree out-competing the grass for water resources, or as an aeolian feature.

Table 5.8. Summary of accuracy assessment according to three levels of error criteria.

Criteria	Criteria Description	Overall Accuracy	90% Confidence			Kappa Coefficient ¹⁶
			Interval	Lower Limit	Upper Limit	
4	Exact Match	70.8%	6.8%	64.0%	77.7%	0.65
3 and 4	Plus Acceptable Error	79.2%	6.1%	73.1%	85.3%	0.75
2, 3, and 4	Plus Understandable Error	83.3%	5.6%	77.7%	88.9%	0.80

Although the study area was fairly well known to the investigator before the study began, the variety of ground conditions that caused visual confusion during manual classification was clearly underestimated. According to the classification rules defined for this project, when a cell was perceived as a borderline case, it was assumed there were more trees, rather than less, and the cell was placed in the higher canopy cover class. In retrospect it appears that this was not the best decision. Some number of the erroneously classified cells can be attributed to this decision.

Another issue that had a noticeable impact on the results was the spatial variability of the trees. Although this variability is evident with even a casual glance at the images, the real impact of this variability did not become evident until the field data were analyzed.

¹⁶ The Kappa coefficient statistic accounts for correct classifications due simply to chance.

Table 5.9. Accuracy assessment error matrix – Criteria 4 – exact match.

	Field Reference Data							Total	User / Commission Accuracy	90% Confidence		
Manual Classification Results		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	N	Correct	Interval	Upper	Lower
	Class 1	20	0	0	0	0	0	20	100%	0.0%	100%	100%
	Class 2	8	8	4	0	0	0	20	40.0%	18.0%	58.0%	22.0%
	Class 3	1	2	17	0	0	0	20	85.0%	13.1%	98.1%	71.9%
	Class 4	0	0	8	11	1	0	20	55.0%	18.3%	73.3%	36.7%
	Class 5	0	0	1	6	13	0	20	65.0%	17.5%	82.5%	47.5%
	Class 6	0	0	0	0	4	16	20	80.0%	14.7%	94.7%	65.3%
	Total	N	29	10	30	17	18	16	Total Sampled Points: 120 Total correct: 85 Overall Accuracy: 70.8% Kappa coefficient: 0.65 90% Confidence Interval: 6.8% (64.0%, 77.7%)			
90% Confidence	Producer/ Omission Accuracy	Correct	69.0%	80.0%	56.7%	64.7%	72.2%	100%				
	Interval	Interval	14.1%	20.8%	14.9%	19.1%	17.4%	0.0%				
		Upper	83.1%	100.8%	71.5%	83.8%	89.6%	100%				
		Lower	54.8%	59.2%	41.8%	45.6%	54.9%	100%				

Table 5.10. Accuracy assessment error matrix – Criteria 3 and 4 – acceptable.

	Field Reference Data							Total	User / Commission Accuracy	90% Confidence		
Manual Classification Results		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	N	Correct	Interval	Upper	Lower
	Class 1	20	0	0	0	0	0	20	100%	0.0%	100%	100%
	Class 2	6	13	1	0	0	0	20	65.0%	17.5%	82.5%	47.5%
	Class 3	1	0	19	0	0	0	20	95.0%	8.0%	103.0%	87.0%
	Class 4	0	0	7	12	1	0	20	60.0%	18.0%	78.0%	42.0%
	Class 5	0	0	1	5	14	0	20	70.0%	16.9%	86.9%	53.1%
	Class 6	0	0	0	0	3	17	20	85.0%	13.1%	98.1%	71.9%
	Total	N	27	13	28	17	17	Total Sampled Points: 120 Total correct: 95 Overall Accuracy: 79.2% Kappa coefficient: 0.75 90% Confidence Interval: 6.1% (73.1%, 85.3%)				
90% Confidence	Producer/ Omission Accuracy	Correct	74.1%	100%	67.9%	70.6%	77.8%					
	Interval	Upper	87.9%	100%	82.4%	88.8%	93.9%					
		Lower	60.2%	100%	53.3%	52.4%	61.7%					

Table 5.11. Accuracy assessment error matrix – Criteria 2, 3 and 4 – understandable.

	Field Reference Data							Total	User / Commission Accuracy	90% Confidence		
Manual Classification Results		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	N	Correct	Interval	Upper	Lower
	Class 1	20	0	0	0	0	0	20	100%	0.0%	100%	100%
	Class 2	2	17	1	0	0	0	20	85.0%	13.1%	98.1%	71.9%
	Class 3	1	0	19	0	0	0	20	95.0%	8.0%	103.0%	87.0%
	Class 4	0	0	6	13	1	0	20	65.0%	17.5%	82.5%	47.5%
	Class 5	0	0	1	5	14	0	20	70.0%	16.9%	86.9%	53.1%
	Class 6	0	0	0	0	3	17	20	85.0%	13.1%	98.1%	71.9%
	Total	N	23	17	27	18	18	17	Total Sampled Points: 120 Total correct: 100 Overall Accuracy: 83.3% Kappa coefficient: 0.80 90% Confidence Interval: 5.6% (77.7%, 88.9%)			
90% Confidence	Producer/ Omission Accuracy	Correct	87.0%	100%	70.4%	72.2%	77.8%	100%				
	Interval	Upper	98.5%	100%	84.8%	89.6%	93.9%	100%				
		Lower	75.4%	100%	55.9%	54.9%	61.7%	100%				

Since accuracy assessment data was collected by the author alone, these data were gathered from four 30x30 meter subplots, rather than from the full one hectare cells. The impact of whether a tree fell within a subplot, however, turned out to be important, especially in sparsely treed cells. In Classes 2 and 3, for example, by definition there should only be a “handful” of trees within the hectare. If these trees did not fall within the subplots, the percent canopy cover calculated for that plot would suggest that the hectare was treeless, when, in fact, there were trees present (Figure 5.7).

Even in the more heavily treed hectares, which trees fell within the subplots had a noticeable effect. If a number of large, visible trees used to determine the cell classification did not fall within the subplots, the canopy cover calculation for that hectare would be low. Conversely, if all the large trees fell within the subplots, the canopy cover calculation for that hectare would be high. In retrospect, the decision to measure the canopy in subplots may have biased the extrapolated results for the entire hectare. Measuring canopies of all trees within each hectare cell would have produced better results. Regardless of the impact on the results, however, the field data provide an interesting measure of the variability of canopy cover at both the hectare and subplot-scales. This variability is discussed in more detail in the Stand Data section that follows.

Field Data Collection Cell: 12 (Row 21, Col 22)

1936 - Manually Classified as Class 1

1997 - Manually Classified as Class 2

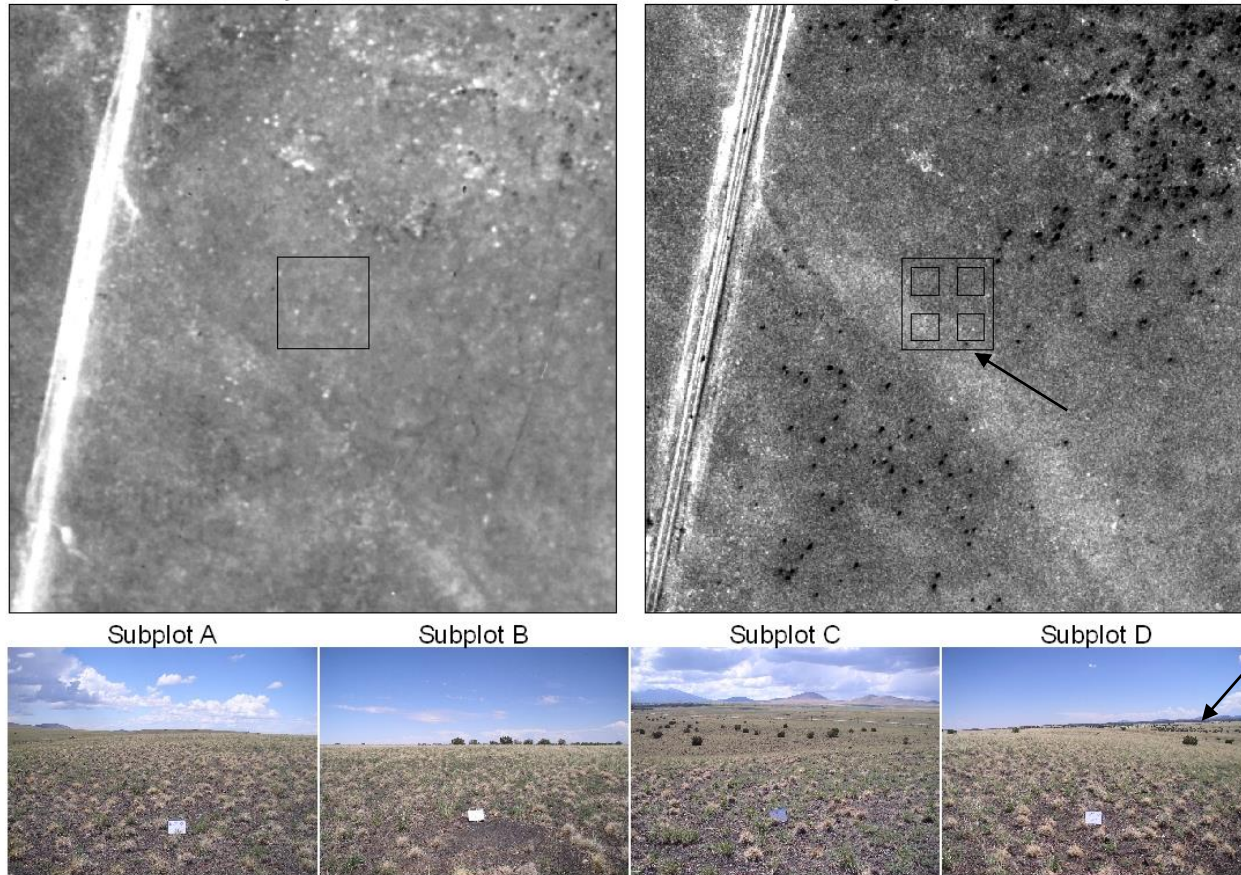


Figure 5.7. Example of cell manually classified as Class 2 that field tested as Class 1

In this example there is clearly a tree in the field collection cell that simply did not fall within the subplots. This tree can be seen in the right hand portion of subplot D.

STAND DATA

During this study, the canopy cover for 1,695 trees was measured and used for accuracy assessment. These trees were also evaluated for species type, estimated age class, and estimated vigor. Of all the trees evaluated, only 1.5% were identified as pinyons (24), the remaining (1,671) were juniper (*Juniperus monosperma*). Interestingly, the pinyons were only found in the two most heavily wooded canopy classes, Class 5 and 6. Table 5.12 provides a summary of these trees by age class and species.

Table 5.12. Summary of trees by species and age.

Form	Estimated Age	Tree Counts by Species			Percentages by Species		
		Pinyon	Juniper	Both	Pinyon	Juniper	Both
Conical	Very Young-Young	8	51	59	33.3%	3.1%	3.5%
Conical/ Round	Young-Juvenile	1	24	25	4.2%	1.4%	1.5%
Round	Juvenile-Mature	6	363	369	25.0%	21.8%	21.8%
Round/ Gnarled	Mature-Old	7	566	573	29.2%	33.9%	33.8%
Gnarled	Old-Very Old	2	667	669	8.3%	39.9%	39.5%
	Totals	24	1,671	1,695	100%	100%	100%

Estimated tree age and tree vigor data by canopy cover class are summarized in Tables 5.13 and 5.14. Table 5.13 shows these data as numbers of trees, while Table 5.14 shows these data as percentages of the condition of the woodlands found in the study area. It shows trees by species and age class. These data provide useful insights into how

many trees were healthy, how many displayed a considerable amount of recent dieback, and how many were dead. Since non-fire related dieback can be considered a proxy of drought stress, the mortality and dieback of trees found in areas known to have recently burned are listed separately. In areas known to have burned, the dieback is attributed to scorch damage and mortality due to fire kill. Figure 5.8 summarizes estimated tree age class by canopy cover class. Figure 5.9 shows tree health by age class and canopy cover class.

Of all the trees evaluated, only 59 trees were placed in the youngest age class (Conical). Eight of these trees were pinyon. This age class contained slightly less than 3.5% of the overall tree sample, but a full one-third of all pinyons. All the young pinyons, and all but three of the young juniper trees appeared to be healthy. Of the three non-healthy junipers, one had been killed in the West Fire, one had been notably scorch damaged in the Antelope Fire, and over 15% of the foliage on the third had recently died, perhaps because of drought stress. Interestingly, most of these very young trees were found in the higher canopy cover classes (Figure 5.8). This suggests two things: 1) woodland fill-in is still occurring, and 2) new trees are not moving into the treeless areas as rapidly as in the past.

Table 5.13. Summary of age class and vigor in number of trees (pinyons are in brackets).

Form (Age)		Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Sums	Total
Conical (Very Young to Young)	Number in Class	-	2	8	10	10 (5)	21 (3)	51 (8)	59
	Mostly Healthy	-	2	6	9	10 (5)	21 (3)	48 (8)	56
	Notable Recent Dieback	-	-	1	-	-	-	1	1
	Recently Dead	-	-	-	-	-	-	-	-
	Notable Portions Scorched	-	-	-	1	-	-	1	1
	Recently Dead due to Fire	-	-	1	-	-	-	1	1
Conical/ Round (Young to Juvenile)	Number in Class	-	2	-	5	11	6 (1)	24 (1)	25
	Mostly Healthy	-	1	-	3	11	6 (1)	21 (1)	22
	Notable Recent Dieback	-	-	-	1	-	-	1	1
	Recently Dead	-	1	-	-	-	-	1	1
	Notable Portions Scorched	-	-	-	-	-	-	-	-
	Recently Dead due to Fire	-	-	-	1	-	-	1	1
Round (Juvenile to Mature)	Number in Class	1	14	55	92	87 (1)	114 (5)	363 (6)	369
	Mostly Healthy	1	13	50	75	83 (1)	114 (4)	336 (5)	341
	Notable Recent Dieback	-	-	-	2	2	-	4	4
	Recently Dead	-	1	-	-	2	(1)	3 (1)	4
	Notable Portions Scorched	-	-	3	3	-	-	6	6
	Recently Dead due to Fire	-	-	2	12	-	-	14	14
Round/ Gnarled (Mature to Old)	Number in Class	-	4	11	57	164 (1)	330 (6)	566 (7)	573
	Mostly Healthy	-	2	11	49	139 (1)	295 (5)	496 (6)	502
	Notable Recent Dieback	-	2	-	6	21	35	64	64
	Recently Dead	-	-	-	2	4	(1)	6 (1)	7
	Notable Portions Scorched	-	-	-	-	-	-	-	-
	Recently Dead due to Fire	-	-	-	-	-	-	-	-
Gnarled (Old to Very old)	Number in Class	-	1	1	29	146 (1)	490 (1)	667 (2)	669
	Mostly Healthy	-	1	1	16	108 (1)	342 (1)	468 (2)	470
	Notable Recent Dieback	-	-	-	11	37	147	195	195
	Recently Dead	-	-	-	2	1	1	4	4
	Notable Portions Scorched	-	-	-	-	-	-	-	-
	Recently Dead due to Fire	-	-	-	-	-	-	-	-
Totals		1	23	75	193	418 (8)	961 (16)	1,671 (24)	1,695

Table 5.14. Summary of age class and vigor in percentage per species per age class.

[illegible]

The smallest age group was the Young-Juvenile (Conical/Round) group. Only 25 of all trees evaluated were placed into this group. This represents less than 1.5% of the overall tree sample, and included only one pinyon (4% of all pinyons). The single pinyon, and all but three of the junipers, appeared to be healthy. Of the three non-healthy juniper trees, one had been killed in the Antelope Fire, one had died of an unknown cause, and most of the foliage on the third had recently died. Again, almost all of these trees were found in the higher canopy cover classes (Figure 5.8).

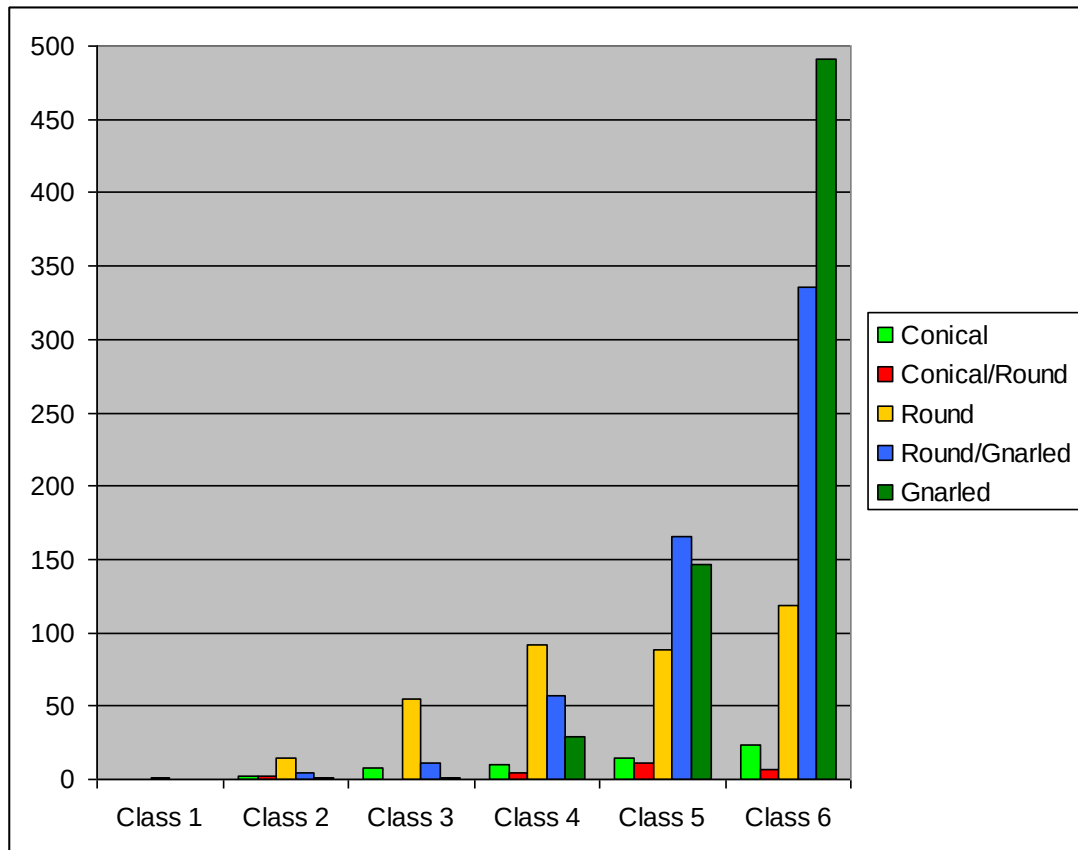


Figure 5.8. Estimated tree age sorted by canopy cover class.

This graph shows that the majority of both very old trees and very young trees are found in the densest canopy cover classes (Classes 5 and 6). The mid-range canopy cover classes (Classes 3 and 4), on the other hand are primarily comprised of middle-aged trees (Round). This suggests a period of tree population increase into areas that were previously treeless or only sparsely populated.

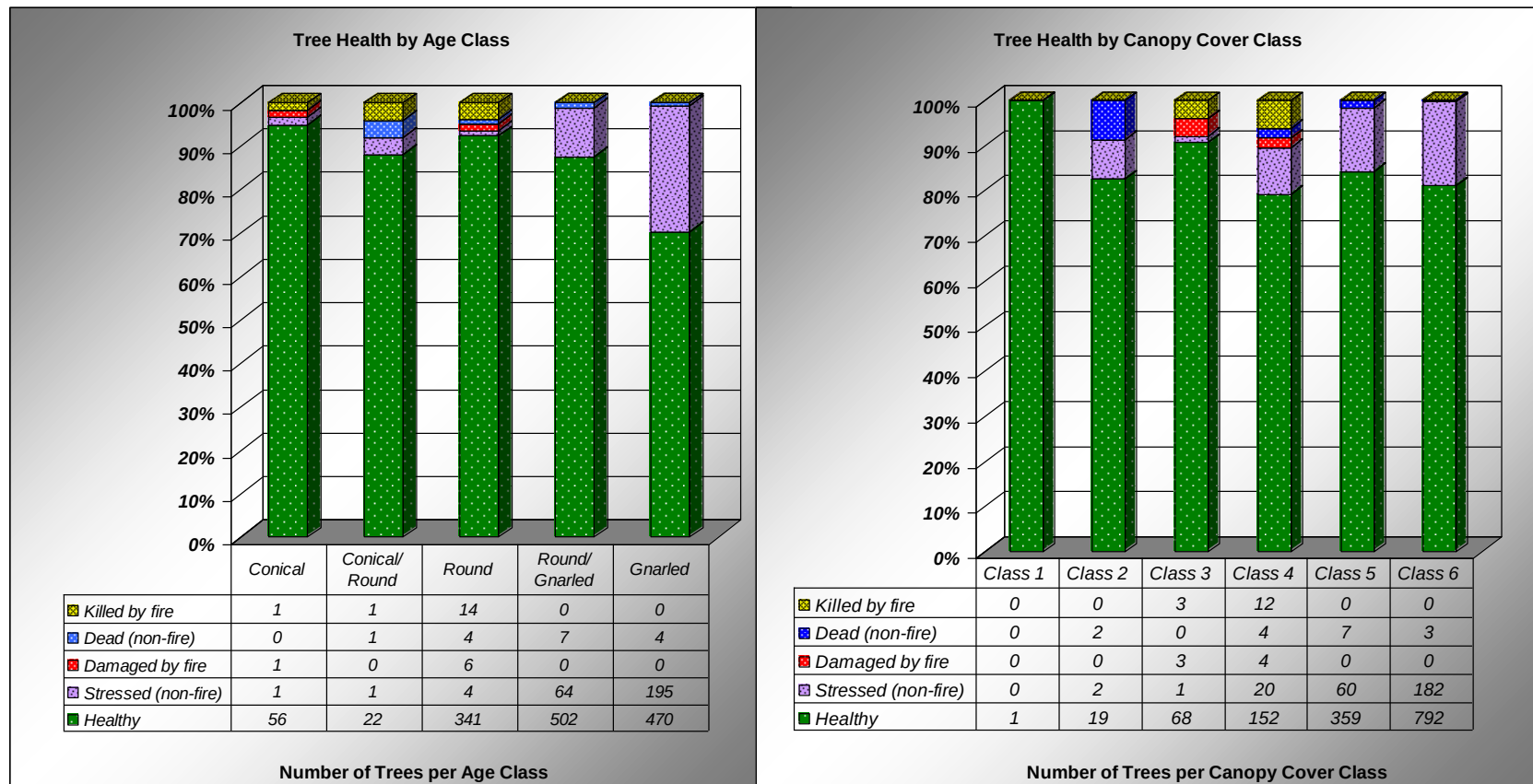


Figure 5.9. Tree health by age class and canopy cover class.

The majority of trees in all categories are apparently healthy. These graphs, however, suggest that the older trees, and those found in the denser canopy cover classes, are showing a fair amount of non-fire related stress. This could indicate drought stress. As Table 22 shows, most of the oldest trees are found in the denser canopy cover classes.

Six pinyon and 369 juniper were placed into the Juvenile-Mature age class (Round). This class contains slightly more than 20% of all the junipers evaluated, and 25% of all pinyons. While Class 6 contained the largest number of juniper in this age group, these trees dominated the mid-canopy cover classes (Classes 3 and 4). All but one of the pinyons in this age group were also found in Class 6. Within this category, 14 juniper had been killed in the Antelope Fire, and six had been notably scorch damaged in the Antelope and West Fires. Four junipers and one pinyon had recently died of apparently non-fire related causes, while an additional four junipers had notable amounts of non-fire related, recently dead foliage. This mortality could be interpreted as drought stress.

Seven pinyons and 573 junipers were identified as Mature-Old (Round/Gnarled). This represents 29% of all pinyons and 34% of all junipers. While some of these older trees were found in the more open canopy classes, the bulk were in the two densest canopy cover classes. The amount of recent, non-fire related dead foliage and tree mortality increases in this age group, especially in the higher canopy cover classes (Figure 5.9). Sixty-four junipers displayed a notable amount of dead foliage, and seven junipers and one pinyon had recently died. None of this age group showed evidence of recent fire damage.

The largest proportion of all the trees evaluated (39%) belonged in the Old-Very Old (Gnarled) age group. Two of these trees were pinyon (8% of all pinyons); the remainder were juniper (40% of all junipers). Although no recent fire damage was found in this age group, a full 30% of the junipers had notable amounts of recently dead foliage (Figure 5.9). Only four very old juniper trees were found to have died recently of non-fire related causes. Both pinyon trees in this age category were healthy.

CANOPY COVER VARIABILITY

The field data provide an interesting measure of the variability of canopy cover at both the hectare and subplot scales. As might be expected, the classes with the tighter limits (e.g., Class 2 with a 0.5% range) show less variability than the classes with broader limits (e.g., Class 5 with a 15% range).

Variability statistics at both the hectare and subplot scales are shown in Tables 5.15 and 5.16. Histograms for these data are shown in Figures 5.10 and 5.11. These tables and graphs give an indication of the variability in spatial distribution of the trees, as well as the impact of scale on measuring. For example, while a hectare cell could have been evaluated as having 10% canopy cover overall, spatial variation could have placed all of this canopy within one subplot. Likewise, the clumping habit of the juniper trees sometimes resulted in subplots with higher canopy cover than any full hectare cell. This can be seen by the >40% canopy cover in Class 5 subplots and the >60% in Class 6 subplots, values that are clearly beyond the definition for the class. When these subplot values are averaged with the others, the overall average falls within the definition of each class.

Table 5.15. Variance statistics for each class,
20 hectare test cells per class – 120 test cells in total.

Statistic	Class 1 0-.05%	Class 2 .06 - 0.5%	Class 3 .51 - 5%	Class 4 5.01 - 15%	Class 5 15.01 - 30%	Class 6 > 30%
Min	0.00	0.00	0.00	0.91	3.59	24.32
Max	0.04	0.61	4.83	17.86	29.78	41.74
Range	0.04	0.61	4.83	16.94	26.19	17.42
Mean	0.00	0.24	1.36	6.15	18.38	33.69
Median	0.00	0.24	0.73	6.40	18.32	34.25
Variance	0.00	0.06	1.44	15.09	57.99	26.22
Std Dev	0.01	0.24	1.20	3.88	7.62	5.12

Table 5.16. Variance statistics for subplots,
4 subplots per hectare test cell – 480 subplots in total.

Statistic	Class 1 0-.05%	Class 2 .06 - 0.5%	Class 3 .51 - 5%	Class 4 5.01 - 15%	Class 5 15.01 - 30%	Class 6 > 30%
Min	0.00	0.00	0.00	0.00	0.00	13.10
Max	0.14	2.46	8.38	34.20	46.39	63.55
Range	0.14	2.46	8.38	34.20	46.39	50.45
Mean	0.00	0.24	1.36	6.15	18.38	33.69
Median	0.00	0.00	0.15	3.72	17.36	32.89
Variance	0.00	0.32	4.06	52.59	104.15	116.00
Std Dev	0.02	0.57	2.02	7.25	10.21	10.77

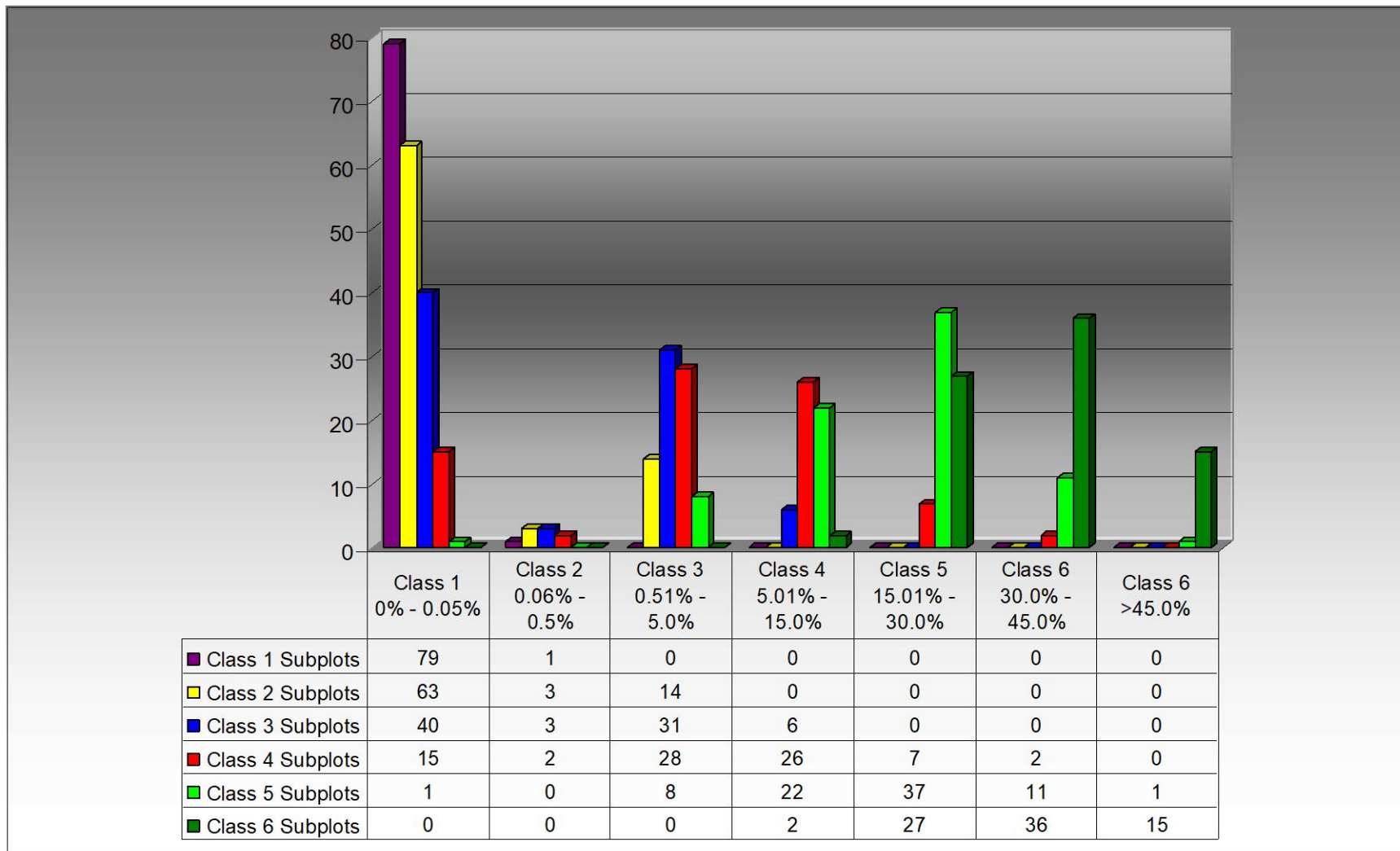


Figure 5.10. Histogram of percent canopy cover for each class at the subplot level.

This graph shows the number of subplots with canopy cover measured to fall within each class canopy cover interval. The variability on the subplot level is evident, with a significant number of subplots falling outside of the class definitions.

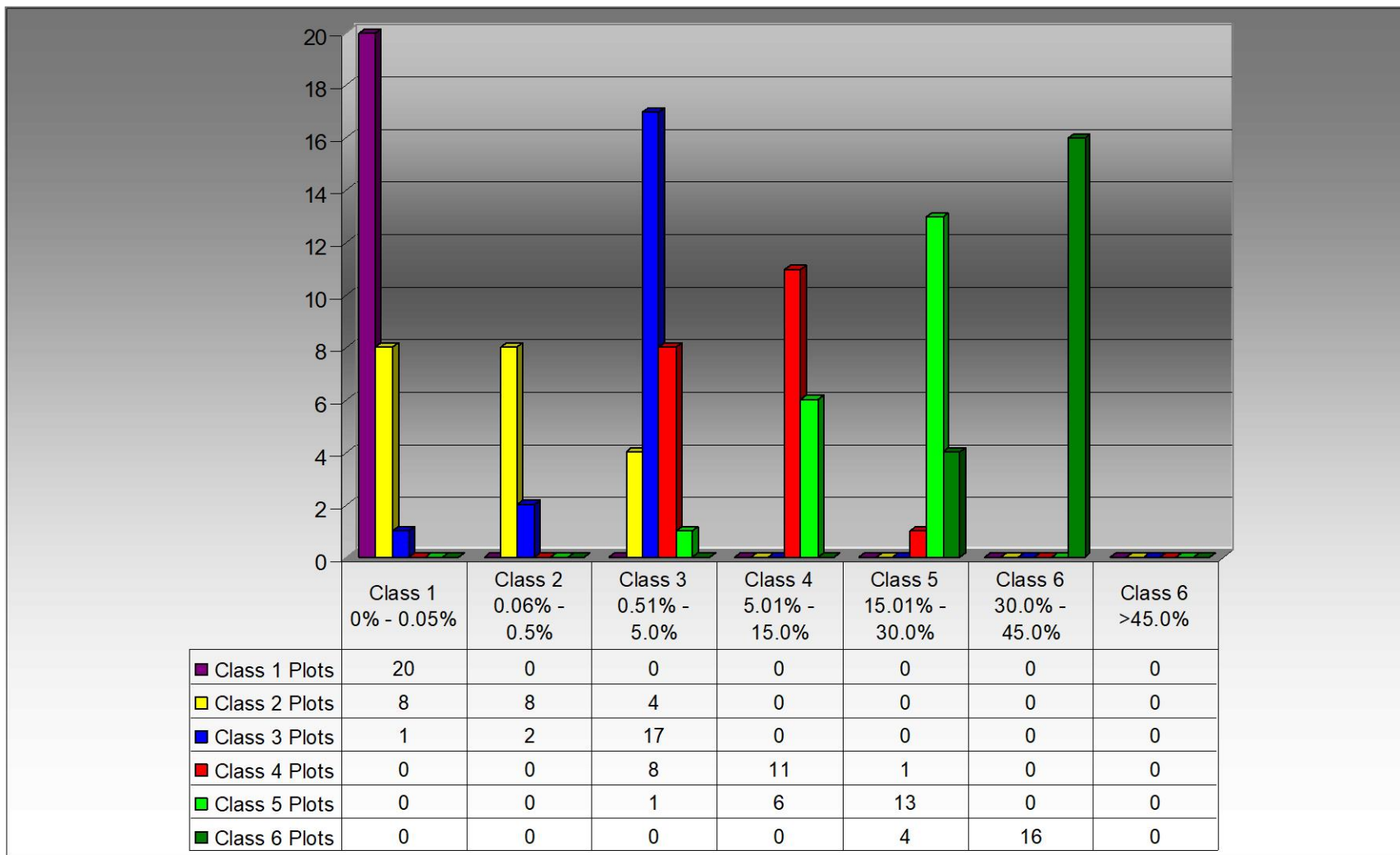


Figure 5.11. Histogram of percent canopy cover for each class at the plot level.

This graph shows the number of plots with canopy cover calculated to fall within each class canopy cover interval. Averaging of the four subplots per plot smoothes out the variability found at the subplot level.

CHAPTER 6

DISCUSSION

Overview of Major Findings of this Study

While the focus of this study was quantification of juniper tree canopy cover change, field observations made while examining the study area were not without merit. These observations are included in this discussion.

CANOPY COVER

A casual examination of the two sets of airphotos used in this study suggest that the results would show a decrease in open, grass areas, and a corresponding increase in wooded areas between 1936 and 1997. What was not expected was just how dramatic the change would be. Although more than half of the study area did not change, almost one-fifth (2,405 ha) of the study area transitioned from treeless to treed in the 61-year span. This averages to a loss of just under 40 treeless hectares per year. Of the hectare cells that did not change, over 63% (4,690 ha) were already heavily treed (Classes 5 and 6) in 1936, while only about 17% (1,269 ha) were treeless (Class 1), and remained treeless.

With the loss of open grassland, one might expect to see an increase in the lightly canopied transitional classes (Classes 2, 3, and 4). This study, however, showed the greatest increases, overall, as occurring in the two most heavily wooded classes. While the three transitional classes together amount to a 5% increase in area (679 ha), Classes 5 and 6 together account for a 13% increase (1,726 ha) – over one-eighth of the study area.

Table 26 provides a summary of the change in per-class area between 1936 and 1997. This table shows the area measured for each class in the 1936 and 1997 classifications, and the difference in overall extent for each class. While all of the treed classes (Classes 2 through 6) increased in size to some extent, there was a 65% decrease in the 1936 treeless areas (Class 1). The greatest increases clearly occur in Classes 5 and 6.

When these changes are examined on a per-class basis, the change is even more dramatic. Although the actual number of cells varies, the percentages of change within each class are impressive. For example, of all the hectare cells classified as treeless (Class 1) in 1936, 66% transitioned into one of the treed classes by 1997. Likewise, 66% of Class 2, 71% of Class 3, and 65% of Class 4 hectare cells increased by one or more canopy cover class values. At the other extreme, while the total number of Class 6 hectare cells increased markedly by 1997 (an increase of 941 cells), 99% of the hectare

Table 6.1. Change in overall area covered by each class,
between 1936 and 1997

Class	Hectares in 1936	Hectares in 1997	Area that Changed, in Hectares	Percent Change in Area from 1936 to 1997
1	3695	1290	-2405	- 65.09%
2	1131	1292	161	+ 14.24%
3	1743	1971	228	+ 13.08%
4	1573	1863	290	+ 18.44%
5	2419	3204	785	+ 32.45%
6	2929	3870	941	+ 32.13%

This table compares the number of hectare cells, per class, that resulted from the 1936 and 1997 manual classifications. Percents were calculated by comparing the number of hectares difference against the total number of hectare cells classified in the 1936 manual classification.

Table 6.2. Percent change, per class, between 1936 and 1997.

Change	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Decreased	-	1.15%	0.98%	0.25%	0.25%	0.96%
No Change	34.34%	32.71%	27.83%	35.22%	73.96%	99.04%
Increased	65.66%	66.14%	71.20%	64.53%	25.80%	-

This table shows the percent change within each individual class. Percents were calculated by comparing the number of hectare cells per class that resulted from the 1997 manual classification against the number of hectare cells per class that resulted from the 1936 manual classification.

cells that were classified as Class 6 in 1936 were still classified as Class 6 in 1997.

Likewise, of the cells classified as Class 5 in 1936, 74% did not change, while 26% increased in canopy cover to the Class 6 level. Table 27 summarizes these changes.

These numbers suggest that there is notable instability at the grassland end of the ecological spectrum found in this study area, and considerable stability at the heavily wooded end. The study conducted by Ironside (2006) concluded that the long-term climatic conditions over the study area have been favorable for tree growth over the last several centuries. This suggests that, barring the introduction of a major disturbance factor such as fire or wood harvesting, the entire area may eventually become wooded. Short-term climatic fluctuations, such as the current drought, could also interrupt this trend. Indeed, notable tree stress and mortality are evident in some locations within the study area.

While there is an overall trend toward an increase in canopy cover, 68 hectare cells (0.5%) showed some amount of canopy reduction. Many of these reductions are due to the intentional clearing of the land for grazing purposes (Figure 6.1). This clearing was

typically accomplished through the process of “pushing”, as described in the Methods Chapter. Other areas appear to be misclassifications due to artifacts in the 1936 airphotos.

STAND STRUCTURE

As a general rule, as one travels south and upslope, treeless grasslands give way to more and more heavily wooded areas. One travels from completely open grasslands, to grasslands lightly speckled with small (<1 m), conical and round trees with no evidence of tree mortality. These small-treed areas transition to open savannas dotted with taller (~ 2 m) trees that are still round and fully foliated. The occasional older, more gnarled tree can be seen. Tree density becomes noticeably heavier as one proceeds south, and the tree forms change markedly. The “average” tree becomes more gnarled, and branch and trunk diameters clearly increase. Foliage becomes sparser and dead branches become more frequent. As judged by tree appearance (Romme *et al.* 2006), the increase in overall tree age as one travels south and upslope is evident. Hassler’s (2006) dendrochronology data generally agrees with this progression. Younger trees are evident, but not prominent. The presence of extremely large, gnarled trees becomes more common, especially on heavily cindered slopes and within washes. Along mesa tops in the southern portion of the study area, tall rounded trees still dominate. Typically, these areas were manually classified as Classes 1, 2, or 3 in the 1936 images, suggesting that they are still in the process of filling in.

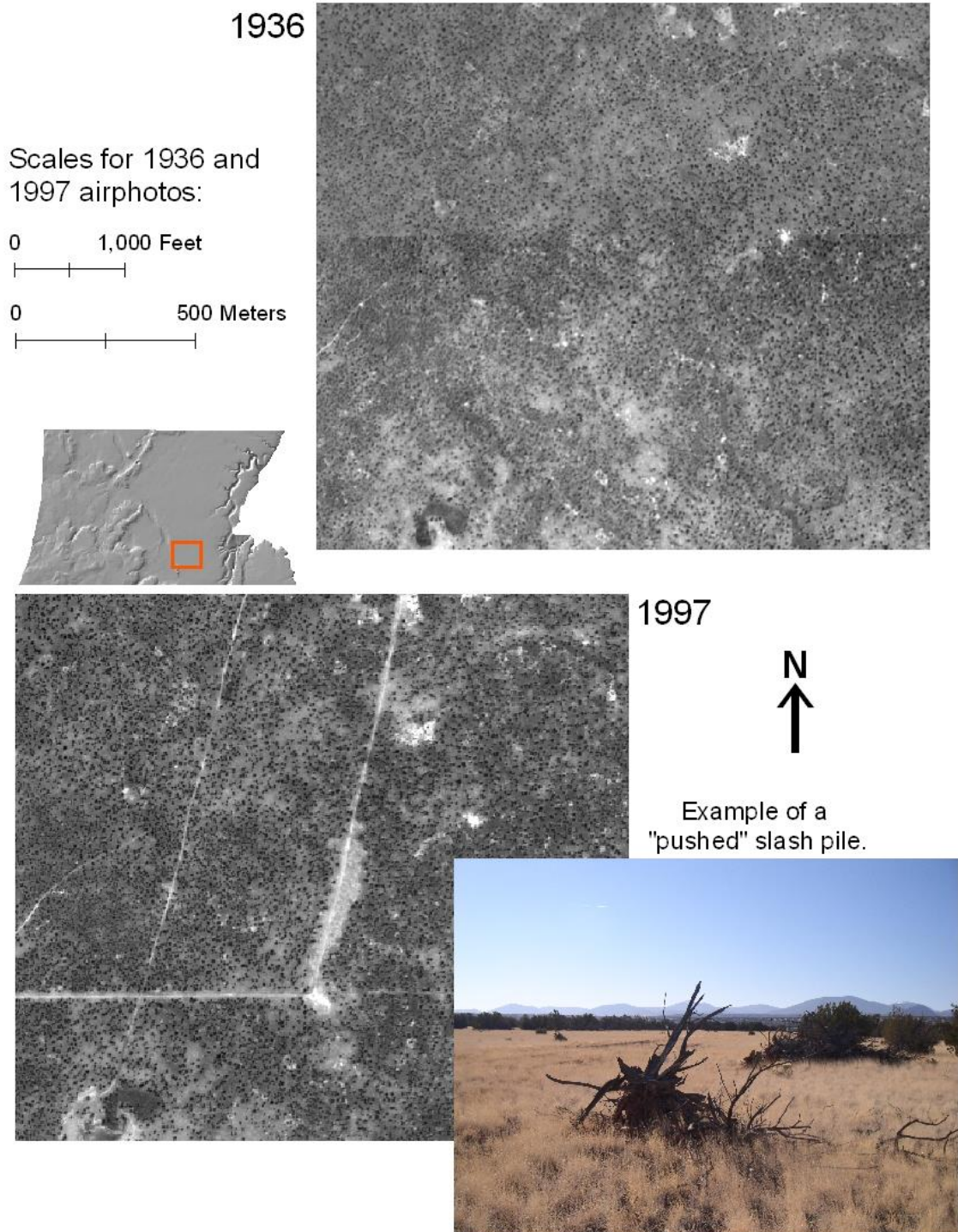


Figure 6.1. Area near Hulls Canyon that has been "pushed" to remove trees for grazing.

The lower photograph shows a several hectare area that has been cleared by "pushing" for grazing purposes. Trees along the road corridor to the West were also "pushed". A photograph of a slash pile is included at the lower left.

What is not commonly found in any portion of the study area is an abundance of standing or downed snags and woody ground litter. In most areas, the only woody ground litter present is slash left from harvesting activities. Snags and accumulated woody litter are two of the criteria used in the Mesa Verde National Monument to define old-growth pinyon-juniper woodlands (Floyd *et al.* 2003). While standing snags do exist, the typical forms found suggest that most died while they were still in middle age (Figures 6.2 and 6.3). Almost no snags were found that looked like they naturally died of old age. Floyd *et al.* (2003) dated most of the Utah junipers (*Juniperus osteosperma*) in the old-growth pinyon-juniper woodlands at Mesa Verde NM at 400 to 600 years. Utah junipers over 1,350 old have been found in areas around Mesa Verde NM (Floyd *et al.* 2003). The oldest one-seed juniper tree dated by Hassler (2006) in the Wupatki-Dove Tank study area was just under 700 years old¹. This age suggests that this woodland might qualify as old-growth, but the stand structure (i.e., lack of snags and litter) could be seen to argue against it. Hassler's data does indicate this woodland dates back to the last large-scale



Figure 6.2. Common snag of a juniper tree that appears to have died in middle age.



Figure 6.3. Less common snag of a juniper tree that was fairly old when it died.

¹ Hassler (2008) determined this tree had become established in the year 1310.

human occupation of the area, which is thought to have ended around 1300 AD (Anderson 1990). Some studies suggest that prehistoric settlements may have been abandoned because local pinyon and juniper resources were depleted (Kohler and Matthews 1988). It may be that these modern woodlands are still in the process of initial regrowth after depletion by the prehistoric inhabitants, or even possible decimation caused by the eruption of Sunset Crater Volcano. They do not appear to have existed long enough to qualify as true old-growth.

As mentioned before, considerable variation in stand structure was found across the study area. At the extremes, such variation was expected. Of interest was the considerable variation between the intermediate classes, and even within individual classes. A good example is the difference in tree structure of Plots 255 and 261 (Figure 6.4). These plots were both manually classified and measured in the field as Class 6. Plot 255, located on Woodhouse Mesa, has a measured canopy cover of 30%. This plot has only 24, very large and very old trees located within the subplot areas. Plot 261 is situated in a cinder basin to the west of Hull's Canyon. This plot has a slightly higher measured canopy cover (32%), but contained considerably more trees: 111 smaller juvenile-to-mature trees were counted within the subplot areas. Table 28 summarizes the variation found between these two plots. Figure 6.5 shows a histogram of the juniper tree canopy diameters for the two plots.

The reason for this variation in stand structure becomes clear when one considers the history of each plot. Essentially all the trees visible in the 1997 airphoto of Plot 255 were already mature enough in 1936 to be visible in that airphoto as well. This plot was manually classified as Class 6 in both sets of airphoto. Only a few of the trees in Plot 261

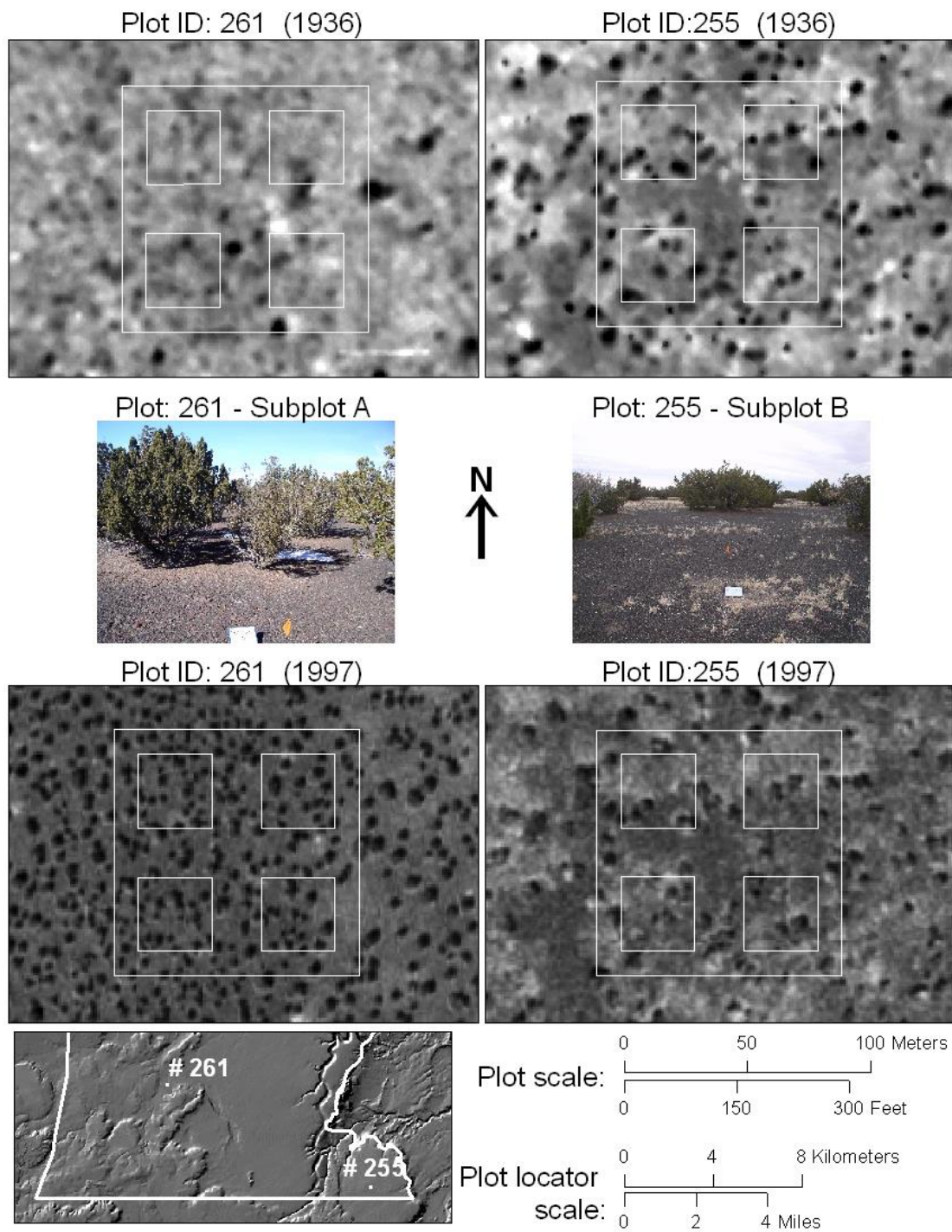


Figure 6.4. Variation between two Class 6 plots: Plot 255 and Plot 261.

Plot 225 has a measured canopy cover of 30.22% from a total of 24 trees. Plot 261 has a measured canopy cover of 32.18% from a total of 111 trees. Plots are shown in both 1936 and 1997. Photographs of the trees found on the plots in 2008 are also shown.

Table 6.3. Variation between Plots 261 and 255.

Plot number	261	255
Number of trees in subplots	111	24
Measured canopy cover	32.18 %	30.22%
Mean canopy diameter	3.5 m 11.4 ft	7.2 m 23.6 ft
Smallest canopy diameter	0.1 m 0.3 ft	0.3 m 1.1 ft
Largest canopy diameter	6.0 m 19.7 ft	11.8 m 38.7 ft
Age class distribution:		
Gnarled (old to very old)	0	13 trees 54.17%
Round/gnarled (mature to old)	70 trees 63.06%	10 trees 41.67%
Round (juvenile to mature)	40 trees 36.04%	0
Round Conical (young to juvenile)	0	0
Conical (very young to young)	1 tree 0.90%	1 tree 4.17%

This table summarizes the difference in tree structure between Plots 261 and 255. Both plots were classified as Class 6 in the 1997 images, but contain significantly different trees in size, age, and number.

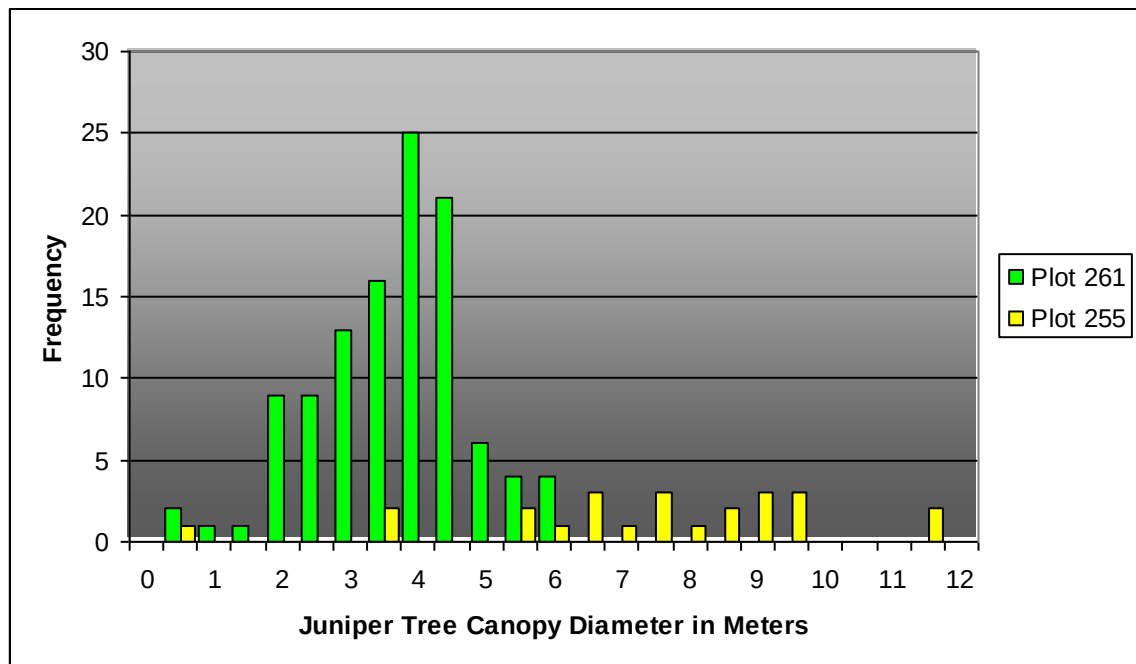


Figure 6.5. Histogram of canopy diameters for Plots 261 and 255.

This histogram shows an example of the variation in stand structure between plots. Plot 261 had 111 small and medium sized juniper trees, while Plot 255 had only 24 large to very large juniper trees.

were visible in 1936, causing this plot to be manually classified as Class 3. It is probable that many of the trees in Plot 216 were present in 1936 but were too small to see.

Nevertheless, it is clear that there has been an increase in tree populations in that cinder basin over the last several decades. It also appears that both plots are at, or close to, their carrying capacity for juniper trees. Each plot only contains one relatively young tree, which suggests that the mature tree populations are stable and that almost no recruitment is occurring.

FIRE

The different effects of fire as one progresses from the lightly treed, grass dominated areas to the denser, older tree and cinder dominated areas are striking. The high tree mortality in the West, Moon, State, and Antelope Fire areas is obvious (Figure 6.6). Hassler (2006) measured this mortality at 96% for the Moon Fire, 55% for the State and Antelope fires, and 46% for the north portion of the West Fire² and 66% for the south portion. All of these fires occurred in areas with a grass matrix.

While the evidence of fire is not uncommon within the heavily wooded areas, fire damage is always limited to a small number of trees (Hassler 2006). Most typically, only a single tree appears to be involved. These woodland fires are usually started by lighting, as were the West, Moon, and State Fires. These lightning strike fires spread readily where there are sufficient fine fuels to carry them, and do not spread where fine fuels are lacking. Additional evidence of this can be seen by examining the areas within the

² Due to differences in bedrock and elevation, Hassler (2008) considered the West Fire area as comprising two separate woodland stands, a north stand and a south stand.



Figure 6.6. Fire damage from the 2002 Antelope Fire.

The tree to the left is still alive and healthy, but shows considerable scorch damage to its lower branches. Several fire killed trees can be seen in the background. Photograph taken near Plot 112.

Antelope Fire that were left unburned (Figure 6.7). This fire, ignited by a cigarette thrown from a car driving along Arizona Highway 89, was clearly driven by the prevailing southwesterly winds. It evidently moved easily where grass was abundant, but where the tree density increased enough to exclude grasses, fire passage was effectively stopped. Although burning embers were likely wind-blown throughout the area, it appears that ignition failed to occur within areas lacking fine fuels.

These observations concur with two of the three pinyon-juniper woodland “types” described by Romme *et al.*(2003). The lightly treed, grass dominated, northern portions of the study area fit well into their description of a *pinyon-juniper grass savanna type*. The heavily wooded areas in the south fit into the *pinyon-juniper forest type*. The open,

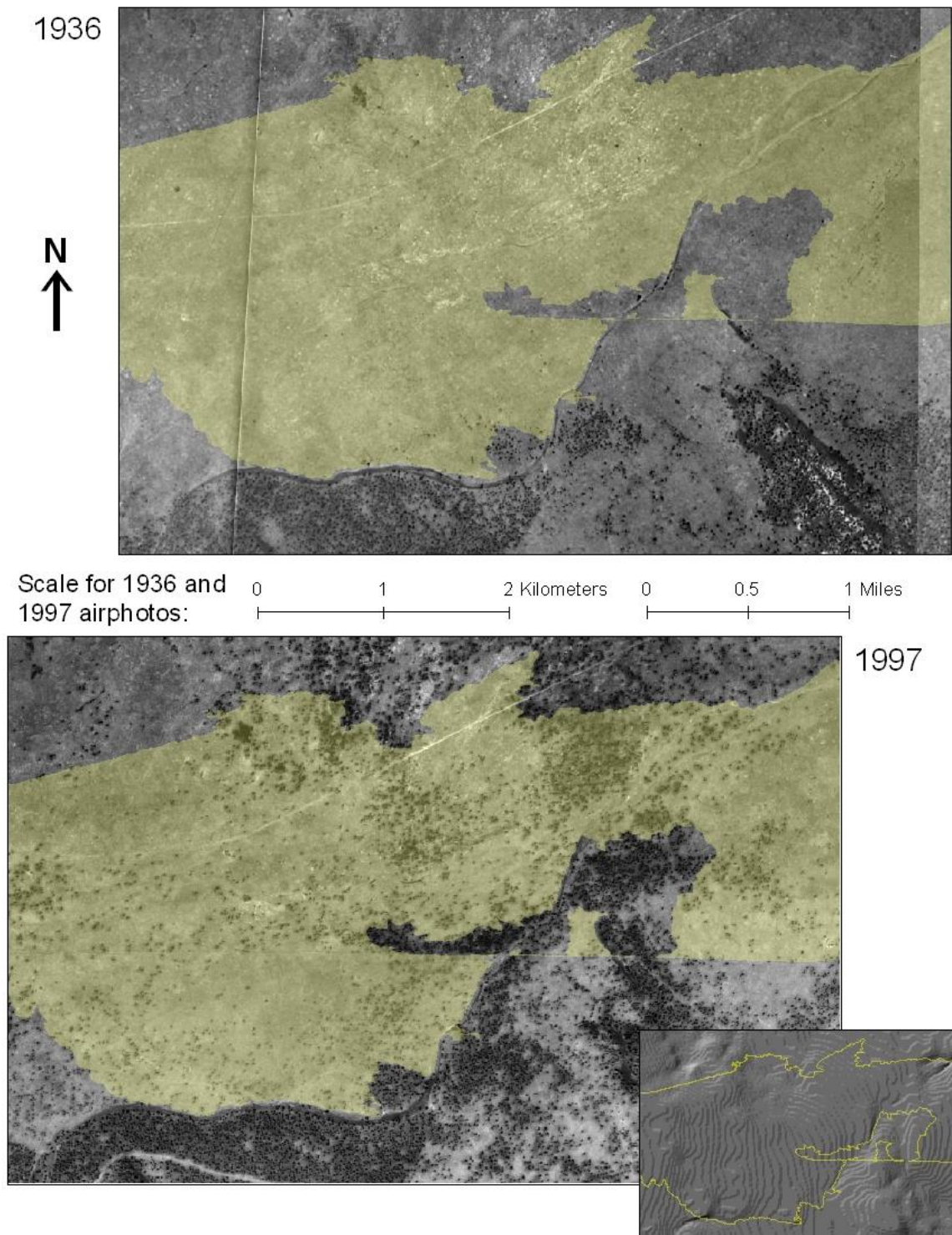


Figure 6.7. Area of Antelope Fire.

The yellow area in these maps show the extend of a portion of the Antelope Fire. The coincidental southern boundary of part of the Antelope Fire with the 1936 tree line along a shallow creek bed is noteworthy. In the 1997 airphoto, the lack of apparent fine fuels in the heavily wooded area the fire moved around is suggestive. The map in the lower right hand corner depicts the topography of the area.

grass areas, which were more prevalent in 1936, are clearly able to carry fire. The tree mortality associated with the recent fires suggest that frequent, low-intensity fires, typically associated with grassland areas, may have kept the historical tree populations low. Although the grazing history is not entirely known, these areas are thought to have been used for sheep pasturage by Navajo families as early as 1830 (Nabhan 2004). Records show this area was grazed by Babbitt Ranch cattle from 1886-1998 (National Park Service 2002, Nabhan 2004). At its peak, between 1909 and 1917, up to 40,000 head of cattle were grazed on the Babbit CO Bar Ranch, a portion of which overlapped the study area (Cinnamon 1988). The reduction of fine fuels by grazing is known to inhibit the ability of a fire to spread. This interaction is suspected, by many scientists, to have an important impact on the increase in tree populations (Johnsen 1962; Ellis and Schuster 1968; Blackburn and Tueller 1970; Burkhardt and Tisdale 1979). Grazing and lack of fire may be, at least partially, responsible for the 1936 to 1997 increase in tree populations in this area.

The lack of wide-spread fire damage in the heavily wooded areas supports the inclusion of this area into the *pinyon-juniper forest type* described by Romme *et al.* (2003). The occasional one-to-few-tree fire damage found within this area suggests that it is reasonably fire resistant. Under the right kind of droughty, windy conditions, however, it is likely these woodlands could experience a severe, stand-replacing fire. Such fires have burned in other pinyon-juniper woodlands within the Coconino National Forest in recent years. The 2003 Mormon (2,600 acres) and Lizard (5,270 acres) fires, and the

2004 Jacket Fire (17,219 acres) are recent examples of this type of fire. All occurred approximately 30 miles to the southeast of the study area³.

Consideration of These Findings in the Light of Other Studies

This study found an increase in canopy cover between 1936 and 1997. This is consistent with both historical accounts of the area and recent research. In 1926, Samuel Barrett visited the Flagstaff area on an information and artifact collecting expedition for the Milwaukee Public Museum. Barrett wrote the following description of the drive from Flagstaff to the Citadel Pueblo area in Wupatki:

“In traveling from Flagstaff to the Citadel group of pueblos, the main highway toward Tuba City is followed, through the Coconino National Forest. It runs in a northeasterly direction until the base of O’Leary Peak has been skirted. Here the pine forests end rather abruptly and we begin to drop rapidly down to a lower level. This drop is accompanied by a very abrupt change in flora, from these stately pines to the short juniper and the many other semi-desert species. Passing through Dead Man’s Flat, we drop again rapidly to a still lower level and to an even more arid plain, which slopes away, mile after mile, to the Little Colorado River canyon. On this plain, there is, as a rule, almost nothing but sage brush, bunch grass and here and there cacti and other strictly desert forms of plant life. *At rare intervals on the plain itself, a small juniper is found [emphasis mine].* However, in the washes and ravines, these trees occur somewhat more frequently and are of larger size. Our branch road leads off over this plain and finally drops down into a wash which we have here called Juniper wash, on account of the presence in it of several fairly large specimens of this tree. The road finally [...] forks, one branch turning eastward and climbing to the foot of the Citadel Mesa, the other passing

³ From the news archives of the Coconino National Forest (www.fs.fed.us/r3/coconino).

on over to the vicinity of T Canyon. Thus, this whole Citadel group is very easily accessible by means of a good automobile road. (Barrett, 1927, p10)”

Historical accounts can be a challenge, as place names sometimes change over time. “T Canyon” is likely what is known as the Box Canyon/Lomoki area today. “Juniper Wash” is probably the currently unnamed wash that runs perpendicular to Cedar Canyon to the west of Citadel Mesa. The description of the lack of large junipers over this area correlates well with the classification of the 1936 airphotos taken 10 years later. Figure 6.8 shows the area of the road through “Juniper Wash” in both 1936 and 1997. The increase in canopy cover across the “arid plain” and within “Juniper Wash” is evident. Figure 1.2 also depicts this area with repeat terrestrial photographs from 1905 and 1985. The location of the tree in Figure 1.2 is also along “the highway toward Tuba City”, approximately 1.5 km (one mile) south of the branch road described by Barrett.

The results of this study also concur with juniper research done throughout the West over the last several decades. Scientists examining western juniper in northern California (Young and Evans 1981), Idaho (Burkhardt and Tisdale 1969) and central Oregon (Soulé *et al.* 2003), redberry juniper in northwest Texas (Ellis and Schuster 1968), Utah juniper in the Great Basin (Miller *et al.* 1999) and central Nevada (Blackburn and Tueller 1970), and one-seed juniper in northern Arizona (Johnsen 1962), all found marked increases in tree densities over the last two centuries. The results of this study agree with three recent studies performed within this study area (Cinnamon 1988, Hassler 2006, Ironside 2006), and could even be seen to support the seemingly dissimilar results of the Deadman Flats study conducted by Ffolliott and Gottfried (2002).

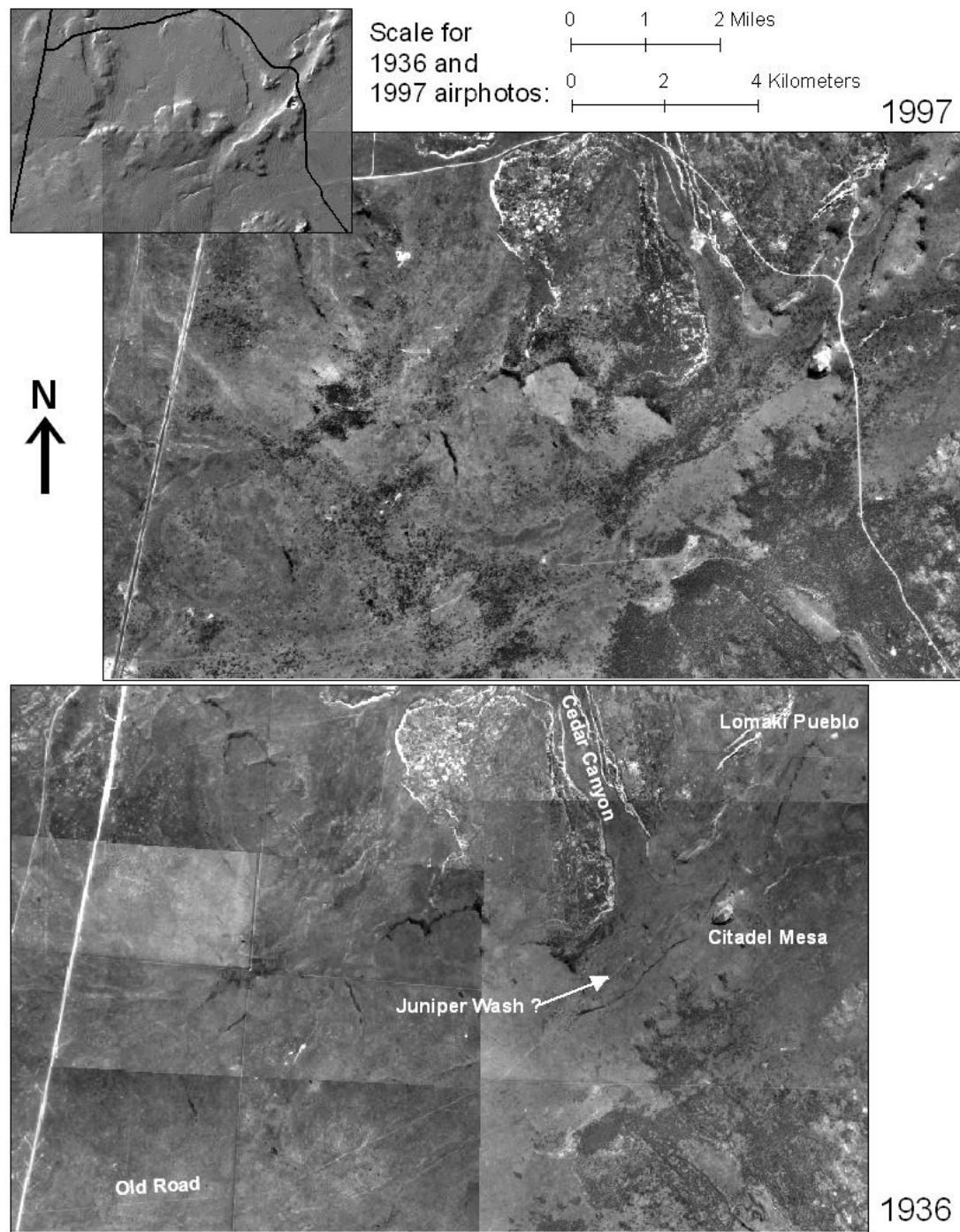


Figure 6.8. Area described in the historical Samuel Barrett account.

In the lower image the old road can be seen branching off “the main highway to Tuba City” – the road now known as Arizona State Highway 89. The “arid plain” described in the historical account is evident. The upper image shows the same area in 1997. The “arid plain” has a significant population of juniper trees on it today.

In the mid-1980's, Cinnamon (1988) studied the pollen record recorded in pack rat middens. The results suggest that there have been pulses of high tree populations from the early-Holocene (~14,000 – 11,000 years BP) to modern day, and that the tree populations are influenced by both climatic conditions and human occupation. The study also shows that there has been a shift in dominant tree species over time. Rocky Mountain juniper (*Juniperus scopulorum*) and Colorado pinyon (*Pinus edulis*) were the primary species in the area until just before the Sunset Crater eruption, approximately 900 years ago. At that time, the one-seed juniper, the dominant species today, begins to appear. The more recent middens studied by Cinnamon (1988) show that, on the modern landscape, the Rocky Mountain Juniper is locally absent, the Colorado pinyon is scarce, and the one-seed juniper population has increased over the last 200 years. The results from this study agree. Cinnamon was particularly interested in the ecological change that occurred in the years between Barrett's exploration of the area in 1926 and his own study. Luckily, Barrett left a small terrestrial photographic record of his trip to the Citadel/Lomoki Pueblos. These areas were rephotographed by Cinnamon in 1986, and again in 2005 for this study. Figure 6.9 shows the camera locations and directions used for this photographic record. Figures 6.10-6.13 show the repeat terrestrial photographs. There is a considerable increase in tree population in the 60-year interval between the first two sets of photographs. The next series of photographs, taken 19 years later, show both additional new trees and a maturing of the trees that had already become established by 1986. The Hassler (2006) and Ironside (2006) studies, both conducted in the same area, are also in agreement with the findings of this study. Ironside (2006) examined both the impact of past climatic conditions and the modeled impacts of future climate change on

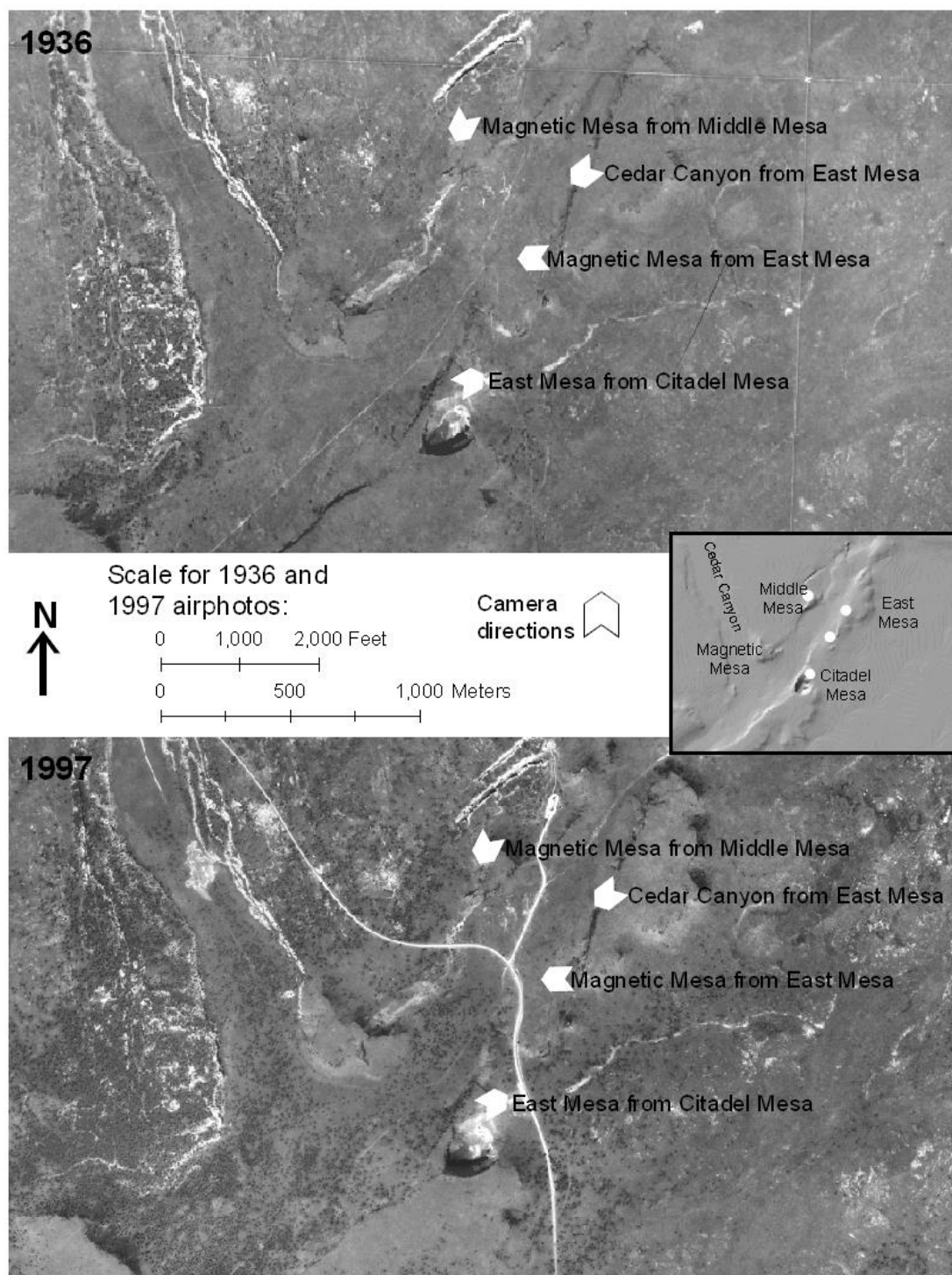


Figure 6.9. Camera positions and directions used in repeat terrestrial photographs.

White arrows placed on these airphotos show the camera positions and directions for the photographs taken by Barrett in 1926, Cinnamon in 1986, and Mlsna in 2005.



**Toward
East Mesa
from Citadel Mesa**

1926 - Barrett



1986 - Cinnamon



2005 - MIsna

Figure 6.10. Repeat terrestrial photographs looking toward East Mesa from Citadel Mesa.



**Toward
Magnetic Mesa
from East Mesa**

1926 - Barrett



1986 - Cinnamon



2005 - Mlsna

Figure 6.11. Repeat terrestrial photographs looking toward Magnetic Mesa from East Mesa.



**Toward
Magnetic Mesa
from Middle Mesa**

1926 - Barrett



1986 - Cinnamon



2005 - MIsna

Figure 6.12. Repeat terrestrial photographs looking toward Magnetic Mesa from Middle Mesa.

Note: The peaks of San Francisco Mountain, clearly visible in the 1986 and 2005 photographs, were apparently obscured by smoke or haze in 1926.



**Toward
Cedar Canyon
from East Mesa**

1926 - Barrett



1986 - Cinnamon



2005 - Misna

Figure 6.13. Repeat terrestrial photographs looking toward Cedar Canyon from East Mesa.

vegetation in the study area and further north. Her results both agree and disagree with Cinnamon's conclusions. The Ironside study agrees with Cinnamon on the abundance of Rocky Mountain juniper in the early-Holocene, but determined that the Colorado pinyon, although present, was rare. Ironside agrees with the late appearance of the one-seed juniper, but places its arrival time considerably later – perhaps as recently as a few hundred years. Both studies agree on the increase in one-seed juniper trees over the last 200 years. The Ironside study additionally suggests that, with the anticipated climate change, one-seed juniper will continue its northward expansion.

Hassler (2006) performed dendrochronology on hundreds of juniper trees in the study area. He dated the one-seed juniper trees on the lower elevation savanna areas at approximately 200 years old. This agrees with the time-line of increasing population suggested by both Cinnamon (1988) and Ironside (2006). This also corresponds to the prevalence of young and middle-aged trees (according to the age classes described in the methods chapter) found in these area during this study. In the more heavily wooded areas in the Coconino National Forest, Hassler (2006) found trees that were approximately 700 years old. This concurs with the frequency of large, gnarled trees found in these areas during this study. None of these findings rule out the possibility of earlier tree populations that might have been removed by prehistoric humans for cooking and warming fires (Cinnamon 1988).

In the late 1990s, Ffolliott and Gottfried (2002) evaluated stand data collected from a pinyon-juniper plot located on Deadman Flats, approximately 6 kilometers (3 miles) southwest of the study area (Figure 1.1). The data had been gathered for the years 1938 and 1991, roughly the same time frame as this study. Ffolliott and Gottfried concluded

that the tree populations had remained essentially stable. They postulated that the notion that this tree population was increasing was a misperception caused by the increasing height and crown diameter of maturing trees. If one takes into account the geographic size and location of their study area (Figure 1.1), their statistical results (if not their conclusion) start to concur with this study. Deadman Flats is located even further south and upslope from my study area. Most of the heavily wooded areas within my study area are at the southern/upslope locations. These areas also contain the highest population of the oldest trees (Hassler 2006). Concurring with the Ffolliott and Gottfried (2002) study, my study found these wooded areas comprised mostly of large mature trees, with some number of young trees continuing to fill in. What was not found in these wooded areas in any study is evidence of senescent trees, snags of trees that appear to have died of old age, or ground litter comprised of old, dead trees. Such evidence would be necessary to conclude that there had been long-term arboreal occupation of these sites (Burkhardt and Tisdale 1969; Young and Evans 1981; West 1984). Perhaps if the Ffolliott and Gottfried study had been conducted further north and downslope as this study was, their conclusions would have been different.

Limitations of the Study

Overall, the results of this study are in strong agreement with other juniper studies conducted around the West in the last several decades. Nevertheless, this study would have been strengthened if resources had allowed both for more field plots to have been sampled, and for more field hands to perform that sampling. During the effort to devise the classification system used, several trips to the field were made to verify and validate the definitions. However, only single subplots were measured at this time. No full hectare

cells with four subplots were measured prior to manual classification. This scale of effort was only made at the conclusion of classification. Additionally, these pilot subplots were all measured in areas of easy access. In retrospect, this, too, was a mistake. The variability across the landscape in spatial arrangement of the trees, as well as in tree density and size, was not adequately appreciated. Additionally, if several teams of two had been available to perform field verification, both the number of field areas measured, as well as the accuracy of the field measurements, would have been improved. If resources had allowed for several cycles of classification/field measurement of four subplots within hectare cells/reclassification to have been had been made, the results of this study would have been improved.

The quantity of volcanic cinders in the study area may render these results less relevant to non-volcanic areas. The one-seed juniper grows in a variety of environmental conditions (Johnsen 1962; West *et al.* 1975; Wright *et al.* 1979). Each set of conditions has impact on the health and growth pattern of the tree. As the fortitude of all juniper species make them successful pioneer species, it is not uncommon to find juniper trees sprouting successfully on various volcanic materials (Burkhardt and Tisdale 1969; Miller *et al.* 1999). In this study area, the presence of cinders varies from negligible to important. On deep, lee-side cinder dunes, the cinders appear to influence both the type of vegetation that can survive there, and the ability to use airphotos to discern the presence of that vegetation. Apparently inhospitable to grasses and forbs, these dunes typically only support juniper trees and deep rooted shrubs, such as Apache plume, saltbush, rabbit bush, and three-leaf sumac. While the reflectance of the shrubs allow

them to show up against the black cinder background, the trees can be completely obscured.

Recommendations for Further Research

Since this study was primarily concerned with quantifying change in canopy cover, none of the findings inspire radically new research directions. There were, however, several tangential findings that merit closer examination.

- As land managers struggle over issues of fire and fire-use, a deeper look into the interaction between prevailing winds, topographic features, and tree density over the study area would be useful. For example, the almost identical southern border of a portion of the Antelope Fire with the pre-existing tree line along a shallow creek bed in the 1936 is likely not coincidental (Figure 6.7). Additionally, in the 1997 airphotos, it can be seen that, while some fairly heavily wooded areas burned, one heavily wooded area in the middle of the fire did not. The wooded areas the fire moved through appear to have had sufficient grasses between the trees to show up as “light” areas on the 1997 airphoto. In the area the fire skipped, the ground between the trees appear to be cinder dominated, and looks dark on the airphoto. This area may have been protected by the lack of fire-carrying fine fuels.
- The interaction between tree density, wind, and cinder depth would be a valuable study, especially in an area where the pronghorn are a species of concern. In this study area, cinders have a profound influence on vegetation cover. Whereas the location of juniper trees on rocky outcroppings is common everywhere, in this study area juniper trees typically dominate the deep cinder slopes as well. In

lightly-cindered areas, a progression from grass matrix between trees to cinder dominated areas as tree density increases was clearly noted. In some areas, even where the trees are fairly well spaced, the presence of grassless cinder rings were evident (Figure 6.14). These cinder rings might be due to the same factors that reduce juniper understory in other locations, such as shading (Schott and Pieper 1984), root competition (Johnsen 1962), interception of precipitation (Johnsen 1962), and allelopathic effects (Arnold *et al.* 1964; Johnsen 1962; Armentrout and Pieper 1987). It is suspected, however, that the aeolian influence on the cinders might also be a factor. The regular occurrence of lee-side cinder dunes attest to the impact of winds on the location and migration of cinders. In the field it was not



Figure 6.14. Cinder rings.

In this view, cinder rings around individual trees can be seen. It is also evident that where trees are growing close together, their cinder rings join and create large areas where grass is entirely excluded.

uncommon to observe cinder mounding around trees (Figure 6.15). These mounds would frequently be deep enough to touch the lower branches of the trees. Wind action on the lower branches would frequently cause them to sweep out grooves in the mounds. It appears that the effect of tree structure on the flow of the wind has a locally important effect.

- A study that examines the relationship between cinder depth and grass growth would provide helpful information. Observations in the field indicate that essentially all the heavily cindered areas are dominated by juniper trees and shrubs, primarily Apache plume, three-leaf sumac, and rabbitbrush. Grasses may be patchy, but are often not present at all. It is suspected that there is a cinder depth beyond which moisture and nutrient requirements for grasses can not be supported. While competition with shrubs and trees likely play a part, observations suggest



Figure 6.15. Cinder mound at the base of a juniper tree.

In many cases it appears that the cinder depositions found at the base of a juniper tree had accumulated after the establishment of the tree. For example, the grooves in this cinder mound appear to have been formed by wind-swept branches; branches which were likely present before the mound formed.

that the cinder depth, itself, becomes the limiting factor. If this is the case, even the removal of junipers in these areas would not increase grass cover.

- The data set for this study ended in 1997. It is common knowledge that this area of northern Arizona is experiencing a long-term drought. The effects of this drought, and the interaction of boring bark beetles, have been observed on the various pines in this area for the last decade. More recently, the effects of this drought on the juniper trees is becoming evident. While some of the recent mortality of juniper trees was captured by the randomly placed test sites, anecdotal field observations suggest the mortality is becoming quite widespread (Figure 6.16). While the results from this study indicate there has been an expansion in the area occupied by juniper trees, the drought effects could be producing a contraction that may continue for some time. Studying the effects of this drought would be useful.

Implications for the Management of Federal Lands

This study will be useful to local land managers in that it provides statistics on the rate of ecological change occurring over the study area. The Ironside (2006) study supports the hypothesis that the study area is, and will continue to be, climatically favorable to increased tree cover. Barring a major ecological disturbance, it is reasonable to expect the change to continue. Drought, fire (natural, accidental or prescribed), and human harvesting are the three most likely disturbances for the study area.

Conventional wisdom holds that juniper trees are not overly prone to burning (Jameson 1962). The Hassler (2006) study, however, found that under the current drought

conditions, 55% of juniper trees of all ages could be killed, even by a fairly fast moving grass fire like the Antelope Fire. Romme *et al.* (2003) suggested that different fire regimes apply to juniper and pinyon woodlands depending both upon the structure of the woodland (i.e., tree density) and location (i.e., the Great Basin or Colorado). Nothing in this study appears to contradict their findings. What it does suggest, however, is that for this study area no single fire regime would be appropriate. The older, heavily wooded areas in the Coconino National Forest appear to fall into an infrequent, drought/wind driven, high-intensity, stand replacing fire regime. The treeless areas, on the other hand, fall into a frequent, low-intensity surface fire regime. The variously wooded areas in between are in a transitional zone. As the 2002 Antelope Fire demonstrated, under



Figure 6.16 Juniper tree mortality near Arrowhead Sink.

This is an example of an area of considerable juniper mortality – probably drought related.

current conditions, a fast moving grass fire could torch, or scorch-kill, more than half the trees in this zone. However, if the tree populations continue to increase unabated over the next several decades, those areas will start to fall into the high intensity fire regime associated with closed juniper woodland areas. Land managers need to consider the implications of this potential shift in fire regime.

The current drought could change the fire picture considerably (Breshears *et al.* 2005). While stand replacing fire regimes are typically drought driven, the current drought is producing such mortality in some areas that the drought, itself, could almost be considered stand replacing. Climate, climate cycles, and climate change are all hard to predict, but if the current drought continues, it is reasonable to expect more tree mortality. The implications of this mortality on vegetation change, as well as the fire danger posed by an increase in both standing and dead-and-down woody fuels, also need to be taken into account by land managers.

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Appendix A – Results for Accuracy Assessment Field Plots

These tables show the field results for this project by hectare cell. Each test cell is listed by ID number and manual classification class. This table includes the class definition, the percent canopy cover that was actually measured in the field and the class the field measurement would have placed the cell into. The last four columns indicate how the manual classification was evaluated against the field data according to the four criteria defined in Table 16.

Table A-1: Field Results - Class 1

Test Cell ID	Manual Classification	Class Definition	% Canopy Cover Measured in the Field	Field Measurement Classification	<u>Criteria 4</u> Exact Match	<u>Criteria 3</u> Acceptable	<u>Criteria 2</u> Under-standable	<u>Criteria 1</u> Wrong
51	Class 1	0-0.05%	0.00	Class 1	x			
52	Class 1	0-0.05%	0.00	Class 1	x			
53	Class 1	0-0.05%	0.00	Class 1	x			
54	Class 1	0-0.05%	0.00	Class 1	x			
55	Class 1	0-0.05%	0.00	Class 1	x			
56	Class 1	0-0.05%	0.00	Class 1	x			
57	Class 1	0-0.05%	0.00	Class 1	x			
58	Class 1	0-0.05%	0.00	Class 1	x			
59	Class 1	0-0.05%	0.00	Class 1	x			
60	Class 1	0-0.05%	0.00	Class 1	x			
61	Class 1	0-0.05%	0.00	Class 1	x			
62	Class 1	0-0.05%	0.00	Class 1	x			
63	Class 1	0-0.05%	0.00	Class 1	x			
64	Class 1	0-0.05%	0.00	Class 1	x			
65	Class 1	0-0.05%	0.00	Class 1	x			
66	Class 1	0-0.05%	0.00	Class 1	x			
67	Class 1	0-0.05%	0.00	Class 1	x			
68	Class 1	0-0.05%	0.00	Class 1	x			
69	Class 1	0-0.05%	0.00	Class 1	x			
70	Class 1	0-0.05%	0.04	Class 1	x			

Table A-2: Field Results - Class 2

Test Cell ID	Manual Classification	Class Definition	% Canopy Cover Measured in the Field	Field Measurement Classification	<u>Criteria 4</u> Exact Match	<u>Criteria 3</u> Acceptable	<u>Criteria 2</u> Under-standable	<u>Criteria 1</u> Wrong
1	Class 2	0.06 -0.5%	0.54	Class 3	x			
2	Class 2	0.06 -0.5%	0.00	Class 1			x	
3	Class 2	0.06 -0.5%	0.50	Class 2	x			
4	Class 2	0.06 -0.5%	0.24	Class 2	x			
5	Class 2	0.06 -0.5%	0.24	Class 2	x			
6	Class 2	0.06 -0.5%	0.00	Class 1			x	
7	Class 2	0.06 -0.5%	0.55	Class 3		x		
8	Class 2	0.06 -0.5%	0.25	Class 2	x			
9	Class 2	0.06 -0.5%	0.00	Class 1			x	
10	Class 2	0.06 -0.5%	0.29	Class 2	x			
11	Class 2	0.06 -0.5%	0.00	Class 1				x
12	Class 2	0.06 -0.5%	0.00	Class 1		x		
13	Class 2	0.06 -0.5%	0.53	Class 3				x
14	Class 2	0.06 -0.5%	0.08	Class 2	x			
15	Class 2	0.06 -0.5%	0.61	Class 3		x		
16	Class 2	0.06 -0.5%	0.00	Class 1				x
17	Class 2	0.06 -0.5%	0.50	Class 2	x			
18	Class 2	0.06 -0.5%	0.00	Class 1		x		
19	Class 2	0.06 -0.5%	0.50	Class 2	x			
20	Class 2	0.06 -0.5%	0.00	Class 1			x	

Table A-3: Field Results - Class 3

Test Cell ID	Manual Classification	Class Definition	% Canopy Cover Measured in the Field	Field Measurement Classification	<u>Criteria 4</u> Exact Match	<u>Criteria 3</u> Acceptable	<u>Criteria 2</u> Under-standable	<u>Criteria 1</u> Wrong
101	Class 3	0.51 – 5%	0.53	Class 3	x	x		
102	Class 3	0.51 – 5%	1.82	Class 3	x			
103	Class 3	0.51 – 5%	0.43	Class 2				
104	Class 3	0.51 – 5%	0.72	Class 3	x			
105	Class 3	0.51 – 5%	1.25	Class 3	x			
107	Class 3	0.51 – 5%	0.51	Class 3	x			
108	Class 3	0.51 – 5%	0.66	Class 3	x			
109	Class 3	0.51 – 5%	0.41	Class 2				
110	Class 3	0.51 – 5%	2.63	Class 3	x			
111	Class 3	0.51 – 5%	0.74	Class 3	x	x		x
112	Class 3	0.51 – 5%	1.53	Class 3	x			
113	Class 3	0.51 – 5%	0.64	Class 3	x			
114	Class 3	0.51 – 5%	0.00	Class 1				
115	Class 3	0.51 – 5%	0.70	Class 3	x			
116	Class 3	0.51 – 5%	4.83	Class 3	x			
117	Class 3	0.51 – 5%	1.72	Class 3	x			
118	Class 3	0.51 – 5%	0.58	Class 3	x			
119	Class 3	0.51 – 5%	3.14	Class 3	x			
120	Class 3	0.51 – 5%	2.87	Class 3	x			
121	Class 3	0.51 – 5%	1.56	Class 3	x			

Table A-4: Field Results - Class 4

Test Cell ID	Manual Classification	Class Definition	% Canopy Cover Measured in the Field	Field Measurement Classification	<u>Criteria 4</u> Exact Match	<u>Criteria 3</u> Acceptable	<u>Criteria 2</u> Under-standable	<u>Criteria 1</u> Wrong
151	Class 4	5.01 - 15%	9.09	Class 4	x		x	x
152	Class 4	5.01 - 15%	2.14	Class 3				
153	Class 4	5.01 - 15%	17.86	Class 5				
154	Class 4	5.01 - 15%	3.95	Class 3				
155	Class 4	5.01 - 15%	8.31	Class 4	x			
156	Class 4	5.01 - 15%	0.91	Class 3				
157	Class 4	5.01 - 15%	5.59	Class 4	x			
159	Class 4	5.01 - 15%	9.27	Class 4	x			
160	Class 4	5.01 - 15%	7.70	Class 4	x			
161	Class 4	5.01 - 15%	8.32	Class 4	x			
162	Class 4	5.01 - 15%	3.72	Class 3		x		x
163	Class 4	5.01 - 15%	2.80	Class 3				
164	Class 4	5.01 - 15%	2.72	Class 3				
165	Class 4	5.01 - 15%	1.91	Class 3				
166	Class 4	5.01 - 15%	7.59	Class 4	x			
167	Class 4	5.01 - 15%	2.74	Class 3				
168	Class 4	5.01 - 15%	5.08	Class 4	x			
169	Class 4	5.01 - 15%	7.21	Class 4	x			
170	Class 4	5.01 - 15%	8.55	Class 4	x			
171	Class 4	5.01 - 15%	7.62	Class 4	x			

Table A-5: Field Results - Class 5

Test Cell ID	Manual Classification	Class Definition	% Canopy Cover Measured in the Field	Field Measurement Classification	<u>Criteria 4</u> Exact Match	<u>Criteria 3</u> Acceptable	<u>Criteria 2</u> Under-standable	<u>Criteria 1</u> Wrong
201	Class 5	15.01 – 30%	8.78	Class 4				x
202	Class 5	15.01 – 30%	17.18	Class 5	x			
203	Class 5	15.01 – 30%	3.59	Class 3				x
204	Class 5	15.01 – 30%	25.99	Class 5	x			
205	Class 5	15.01 – 30%	13.77	Class 4				x
206	Class 5	15.01 – 30%	25.94	Class 5	x			
207	Class 5	15.01 – 30%	29.78	Class 5	x			
208	Class 5	15.01 – 30%	22.15	Class 5	x			
209	Class 5	15.01 – 30%	17.44	Class 5	x			
210	Class 5	15.01 – 30%	18.69	Class 5	x			
211	Class 5	15.01 – 30%	26.03	Class 5	x			
212	Class 5	15.01 – 30%	17.95	Class 5	x			
213	Class 5	15.01 – 30%	9.85	Class 4				x
214	Class 5	15.01 – 30%	9.26	Class 4		x		
215	Class 5	15.01 – 30%	26.32	Class 5	x			
216	Class 5	15.01 – 30%	11.47	Class 4				x
217	Class 5	15.01 – 30%	10.50	Class 4				x
218	Class 5	15.01 – 30%	26.29	Class 5	x			
219	Class 5	15.01 – 30%	25.49	Class 5	x			
220	Class 5	15.01 – 30%	21.05	Class 5	x			

Table A-6: Field Results – Class 6

Test Cell ID	Manual Classification	Class Definition	% Canopy Cover Measured in the Field	Field Measurement Classification	<u>Criteria 4</u> Exact Match	<u>Criteria 3</u> Acceptable	<u>Criteria 2</u> Under-standable	<u>Criteria 1</u> Wrong
251	Class 6	> 30%	24.32	Class 5				x
252	Class 6	> 30%	27.36	Class 5				x
253	Class 6	> 30%	30.22	Class 6	x			
254	Class 6	> 30%	39.36	Class 6	x			
255	Class 6	> 30%	26.74	Class 5				x
256	Class 6	> 30%	34.25	Class 6	x			
257	Class 6	> 30%	31.31	Class 6	x			
258	Class 6	> 30%	34.63	Class 6	x			
259	Class 6	> 30%	34.56	Class 6	x			
261	Class 6	> 30%	32.18	Class 6	x			
261	Class 6	> 30%	41.06	Class 6	x			
262	Class 6	> 30%	33.69	Class 6	x			
263	Class 6	> 30%	30.17	Class 6	x			
264	Class 6	> 30%	31.68	Class 6	x			
265	Class 6	> 30%	36.27	Class 6	x			
266	Class 6	> 30%	28.17	Class 5		x		
267	Class 6	> 30%	41.74	Class 6	x			
268	Class 6	> 30%	35.28	Class 6	x			
270	Class 6	> 30%	41.59	Class 6	x			
271	Class 6	> 30%	39.18	Class 6	x			

Appendix B – Results for Accuracy Assessment Field Sub-Plots

These tables show the field results for this project on the subplot level. Each test cell is listed by ID number. The measured canopy cover for each of the four subplots is listed, as is the average cover of the four subplots. This average is the final field result value given to the hectare test cell.

Table B-1: Class 1 – Subplot Field Results

Class 1					
Plot ID	% Cover per Subplot	Average Cover of Subplots	Plot ID	% Cover per Subplot	Average Cover of Subplots
51	0.00	0.00	58	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
53	0.00	0.00	69	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
55	0.00	0.00	56	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
57	0.00	0.00	63	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
59	0.00	0.00	52	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
60	0.00	0.00	67	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
64	0.00	0.00	68	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
61	0.00	0.00	54	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
62	0.00	0.00	65	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
70	0.14	0.04	66	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	

Table B-2: Class 2 – Subplot Field Results

Class 2					
Plot ID	% Cover per Subplot	Average Cover of Subplots	Plot ID	% Cover per Subplot	Average Cover of Subplots
4	0.61	0.24	9	0.00	0.00
	0.37			0.00	
	0.00			0.00	
	0.00			0.00	
8	1.00	0.25	3	0.81	0.50
	0.00			1.20	
	0.00			0.00	
	0.00			0.00	
16	0.00	0.00	1	0.57	0.54
	0.00			1.58	
	0.00			0.00	
	0.00			0.00	
20	0.00	0.00	7	1.57	0.55
	0.00			0.06	
	0.00			0.58	
	0.00			0.00	
5	0.96	0.24	10	1.16	0.29
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
12	0.00	0.00	6	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
18	0.00	0.00	11	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
13	2.12	0.53	15	2.46	0.61
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
14	0.30	0.08	19	1.99	0.50
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
2	0.00	0.00	17	1.99	0.50
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	

Table B-3: Class 3 – Subplot Field Results

Class 3					
Plot ID	% Cover per Subplot	Average Cover of Subplots	Plot ID	% Cover per Subplot	Average Cover of Subplots
103	1.20	0.43	112	2.26	1.53
	0.52			2.33	
	0.01			1.51	
	0.00			0.00	
108	1.46	0.66	117	1.33	1.72
	0.30			1.46	
	0.87			4.09	
	0.00			0.00	
111	0.85	0.74	109	1.65	0.41
	1.44			0.00	
	0.69			0.00	
	0.00			0.00	
115	0.03	0.70	102	4.34	1.82
	2.78			2.96	
	0.00			0.00	
	0.00			0.00	
120	1.07	2.87	113	2.30	0.64
	5.86			0.28	
	4.55			0.00	
	0.00			0.00	
105	1.16	1.25	110	2.69	2.63
	2.55			0.42	
	1.30			7.40	
	0.00			0.00	
118	2.31	0.58	116	4.18	4.83
	0.00			8.38	
	0.00			6.75	
	0.00			0.00	
104	2.88	0.72	119	5.04	3.14
	0.00			7.51	
	0.00			0.00	
	0.00			0.00	
107	2.04	0.51	114	0.00	0.00
	0.00			0.00	
	0.00			0.00	
	0.00			0.00	
101	2.13	0.53	121	3.13	1.56
	0.00			3.10	
	0.00			0.00	
	0.00			0.00	

Table B-4: Class 4 – Subplot Field Results

Class 4					
Plot ID	% Cover per Subplot	Average Cover of Subplots	Plot ID	% Cover per Subplot	Average Cover of Subplots
161	8.00	8.32	168	8.47	5.08
	13.00			7.41	
	8.92			0.07	
	3.36			4.36	
157	22.38	5.59	155	12.14	8.31
	0.00			9.25	
	0.00			5.52	
	0.00			6.33	
163	6.52	2.80	154	2.69	3.95
	0.57			1.50	
	4.10			5.29	
	0.00			6.32	
156	1.25	0.91	166	2.40	7.59
	2.32			3.46	
	0.08			7.09	
	0.00			17.40	
169	11.51	7.21	162	8.35	3.72
	4.36			1.43	
	2.58			5.10	
	10.41			0.00	
167	2.53	2.74	153	34.20	17.86
	1.36			17.94	
	7.08			19.28	
	0.00			0.00	
152	0.61	2.14	170	26.35	8.55
	1.18			7.86	
	2.88			0.00	
	3.87			0.00	
160	0.86	7.70	171	6.30	7.62
	11.15			5.44	
	6.93			3.35	
	11.87			15.38	
165	3.17	1.91	159	19.97	9.27
	1.69			9.62	
	2.78			4.25	
	0.00			3.25	
164	7.87	2.72	151	3.57	9.09
	3.01			32.77	
	0.00			0.00	
	0.00			0.00	

Table B-5: Class 5 – Subplot Field Results

Class 5					
Plot ID	% Cover per Subplot	Average Cover of Subplots	Plot ID	% Cover per Subplot	Average Cover of Subplots
214	16.74	9.26	218	39.05	26.29
	7.71			23.43	
	5.96			25.44	
	6.63			17.24	
213	12.83	9.85	212	27.45	17.95
	7.41			17.02	
	3.09			16.86	
	16.06			10.47	
217	14.41	10.50	215	31.44	26.32
	2.62			23.17	
	3.55			18.43	
	21.42			32.23	
203	2.91	3.59	208	23.83	22.15
	2.79			27.62	
	1.85			12.80	
	6.82			24.34	
210	13.09	18.69	220	16.83	21.05
	9.47			27.14	
	34.73			25.02	
	17.49			15.20	
202	4.85	17.18	204	21.50	25.99
	24.11			25.95	
	25.31			30.81	
	14.44			25.71	
205	11.61	13.77	211	41.99	26.03
	12.28			35.17	
	12.19			7.91	
	18.99			19.06	
201	9.64	8.78	207	20.17	29.78
	10.44			46.39	
	15.04			30.01	
	0.00			22.57	
209	25.22	17.44	206	27.52	25.94
	21.01			32.59	
	11.39			26.03	
	12.13			17.60	
216	6.34	11.47	219	31.55	25.49
	13.49			23.27	
	23.22			16.86	
	2.83			30.29	

Table B-6: Class 6 – Subplot Field Results

Class 6					
Plot ID	% Cover per Subplot	Average Cover of Subplots	Plot ID	% Cover per Subplot	Average Cover of Subplots
269	13.10	24.32	262	63.55	41.06
	23.79			19.50	
	20.32			39.63	
	40.07			41.57	
251	22.61	26.74	261	37.39	32.18
	28.31			26.43	
	29.24			34.38	
	26.79			30.52	
255	33.61	30.22	271	38.70	39.18
	17.47			42.24	
	21.36			45.52	
	48.46			30.24	
253	45.94	31.68	268	47.60	35.28
	21.00			14.94	
	28.27			45.78	
	31.51			32.80	
264	32.43	34.25	254	41.51	39.36
	41.18			24.78	
	30.21			45.59	
	33.19			45.57	
256	31.70	34.56	267	44.00	41.74
	40.52			33.29	
	34.22			32.89	
	31.79			56.80	
259	16.02	30.17	258	54.68	34.63
	29.60			46.48	
	44.77			19.47	
	30.28			17.90	
263	16.17	27.36	266	35.15	28.17
	36.04			26.90	
	19.55			33.84	
	37.68			16.77	
252	55.79	36.27	270	23.37	41.59
	28.90			49.30	
	36.87			47.00	
	23.52			46.69	
265	29.07	33.69	257	29.79	31.31
	31.52			36.07	
	40.31			30.50	
	33.85			28.90	