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Land use vs. climate as causes of vegetation change: a study in SE Arizona

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Abstract

Research and discussion regarding the causes of historic vegetation change are important to potential policies and prescriptions for addressing problems related to environmental change. This paper examines the case of southeastern Arizona where significant historic vegetation change has occurred. Using repeat aerial photography covering a period of approximately 50 years, the analysis considers the two primary hypotheses for vegetation change in the region: climate, and land use. Subsequent to a brief review of these hypotheses and the methods employed to explore them, the paper looks at two sites in Arizona and analyzes the direction and cause of vegetation change. From both this analysis and a description of historical land uses in the area, evidence is presented that land use and not climate change is the primary driver of historical vegetation in the areas.

Keywords: Historical; Vegetation; Change; Arizona; Aerial photography

1. Introduction

The types and causes of historic vegetation change in southeastern Arizona have been hotly debated for at least 30 years. Debate is arrayed between two polar hypotheses of the causes of change. One pole has focused on climate as the primary agent of change. It is based largely on climate records and the study of repeat ground photography to establish vegetation change (Hastings and Turner, 1965). They have suggested that there has been increasing aridity during the past century, accompanied by a shift toward more intense, shorter-duration summer storms and less winter precipitation. Among other changes, they argue that this has caused an "upward retreat" of oaks to higher, wetter locations in much of the region.

The other hypothesis argues that land use has been the primary agent of vegetation change during the past 150 years. It has relied on historical descriptions, permanent plot studies, land-use histories, historical maps, climate records, contemporary, newspaper reports, and repeat ground and aerial photography (Bahre, 1991; Bahre and Shelton, 1993; Shelton and Bahre, 1993). This argument holds that the impact of historic land uses has been ignored or underestimated and that historical ground photographs typically portray intensely disturbed sites rather than a set of random observations and represent a small fraction of the total area. As a consequence, repeat ground photographs may be misinterpreted as representative of the region at-large and, further, may give an erroneous portrayal of "initial" conditions, Thus, it is possible to come to false conclusions about the existence or direction of change and, ultimately, the causes of change.

Relative to an upward retreat of oaks, the land-use hypothesis argues that there has been no "directional" change in the distribution of oaks within the region in the past 150 years. Rather, it is asserted that there have been both decreases and increases in oak density in response to differential land-use pressure.

Other hypotheses of change are arrayed between these two. Recent organic soil isotope work suggests that the oak woodland has moved downward, rather than

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upward, although this was for only one site (McPherson et al., 1993). In terms of causation, other suggest poly-causality for observed environmental changes that vary across the region (Cooke and Reeves, 1976).

Regardless of hypothesis, a persistent obstacle to the study of vegetation change in the region has been the difficulty of (1) objectively establishing initial conditions, hence (2) determining if the differences observed at two times represent regional change, and, if so (3) establishing its direction and magnitude.

The purpose of this paper is to determine if there has been change in the oak woodlands and, if so, what is its direction and magnitude. This is done through an examination of repeat aerial photography over a 50-year period for two large sites. The results are compared with the two hypotheses of change outlined above to determine which best explains observed differences.

2. Data

One limitation of repeat ground photography is that there is no control over what might have been photographed initially (Rogers et al., 1984). Very few photographs taken over the past century were made by scientists to document conditions at random study plots. More typically, homesteaders, miners, tourists — and even scientists — took photographs to record claims or describe what they had built or seen.

Repeat aerial photography offers several advantages over repeat ground photography for establishing change. First, the US Department of Agriculture during the 1930s launched extensive systematic aerial photography programs. This, when combined with various recent programs undertaken by the US Geological Survey and National Aeronautics and Space Administration, make for a record of some historic depth. Second, because aerial photographic missions are often regional, relatively large areas have coincident coverage. Thus, we have the opportunity to study large areas — rather than points — and we can select random points within them to make them representative. Third, because aerial photographs are essentially planimetric, measurements can be made from them. Finally, aerial photographs offer a rich record that can be reexamined by others to validate findings.

3. Study sites

Criteria for site selection included (1) location along the lower elevation limit of the oak woodland vegetation type in southern Arizona, and (2) coverage by coincident aerial photography from two dates about 50 years apart.

We selected two sites, each covering about 24 km^2 (Fig. 1). One is near the settlement of Sonoita (T20S, R16E) on the southeastern flank of the Santa Rita Mountains. It ranges in elevation from 1600 m in the southeast to about the 1800 m in the west. The other site, 23 km almost due south, is near the town of Patagonia (T23S, R15E) on the western flank of the Patagonia Mountains. It has a western aspect with elevations ranging from 1300 m in the west of slightly less than 2000 m in the east. Both sites are in the Sonoita Creek drainage.

Vegetation cover of the Sonoita site is predominantly oak (*Quercus* spp.) grassland punctuated by widely scattered juniper (*Juniperus* spp.). While there are some large mesquites (*Prosopis* spp.) in the swales at the south end of the site near the mouths of Hog and Fort canyons, most of the mesquite on the interfluves are scrub-like and easy to differentiate from oak in the higher-quality aerial photography. Large numbers of oak seedlings are found throughout the site and recent oak recruitment appears high. On the interfluves at the Sonoita site are scattered

Fig. 1. Location of Sonoita and Patagonia study sites in Southern Arizona.

patches of cliffrose (*Cowania mexicana*) and beargrass (*Nolina* spp.).

Unlike the Sonoita site, vegetation cover of the Patagonia site has large mesquite on the interfluves that for the most part are difficult to distinguish from oak in the aerial photography. Also, oak, mesquite, and juniper are fairly evenly dispersed at the Patagonia site. Furthermore, dense stands of yucca and beargrass, especially around the Tres de Mayo Mines, are difficult to separate from stands of oak and mesquite in the imagery. Oak density seems to be greatest on the north-northeast-facing slopes of the Patagonia site.

4. Analysis

The quality of the aerial photography was variable and it was not possible to differentiate among woody species on each image. For this reason, we sought only to identify canopies of trees and shrubs. As described above, these tended to be oaks. It was assumed that there were no major differences in the composition of woody species between dates.

4.1. Total canopy area comparison

The objective was to measure differences in total tree and shrub canopy area at the two sites for two dates. To achieve this, estimates of total cover were made for each data for each site and compared. Differences were attributed to change.

4.1.1. Methods

Images were digitally scanned and geometrically registered (Fig. 2). The ranges of brightness values were enhanced by first eliminating the brightest and darkest (saturated) areas and performing a linear contrast stretch on the remaining values. Because of the contrast between tree and shrub cover against a grass and soil background, it was possible to establish a "threshold" value for tree and shrub cover by examining a histogram of brightness values of each image. The darker (lower) values were associated with tree and shrub canopies and shadows. A binary image was created using the low threshold brightness range for tree and shrub canopy. The result was an image of "canopy" and "no-canopy", and the area proportions of each class were calculated (Fig. 3).

The quality of the 1935 image for Sonoita and the 1936 image for Patagonia are poorer than the later date images due to (a) the late time-of-day the image was acquired and (b) the number of generations (reproductions of reproductions) that preceded the images. Poor quality led to two problems. First, the north-facing slopes were in deep shadow. Unfortunately, these sites are more favorable for trees and shrubs. Second, image reproduction tends to enhance contrast and reduce spatial resolution. By accentuating extreme gray-scale values it is usually easier to distinguish and object from a background. However, this comes at the expense of mid-range values that tend to carry more subtle information about the nature of objects in the image. As a consequence, it is difficult to separate deep shadows on slopes from less dark canopies and the partial shadows they cast. Using a single brightness value decision criterion for an entire image is problematic and yields a canopy estimate that is probably too high.

To partially compensate for image quality, poorly illuminated areas at both sites in both dates were eliminated through use of "mask" which eliminated dark areas. Areas that were clearly illuminated in both dates were selected and tree and shrub canopy area were calculated and compared. Fig. 4 shows the masked image for the early Sonoita photograph.

4.1.2. Results

There is more canopy cover in the recent images for both sites (Table 1). The accuracy of these estimates is open to some question in light of the quality of data and subjective nature of the process used in developing thresholds. However, the direction of change and its comparative magnitude is perhaps less problematic, given that the extreme contrasts of the earlier data would have led to higher rather than lower estimates of canopy.

Aside from problems of shading and the opportunity to underestimate canopy in the 1930s, there is a logical limitation to this approach. A simple comparison of canopy area says very little about the dynamic spatial nature of presumed change. For example, it would be possible to have estimates of canopy cover for two dates that were similar, but were composed of different individual plants. Conversely, estimates that were different might be composed of many of the same individuals. For these reasons it would be worthwhile to consider some of the spatial aspects of canopy cover.

4.2. Segmented canopy area comparison

The use of a "global" approach in which a single threshold value is applied to an entire image might not be appropriate. "Local" values within small subsets of each image could accommodate better the diversity of terrain and image quality within each image. By accumulating estimates in this manner, both diversity and potential bias are reduced. Moreover, it might reveal some of the spatial aspects of change that would otherwise be hidden in "global" summaries.

4.2.1. Methods

The same digital images created in the methods described above were used. These were subdivided into 25 equally sized image segments. Thresholds were developed independently for each segment (Fig. 5).

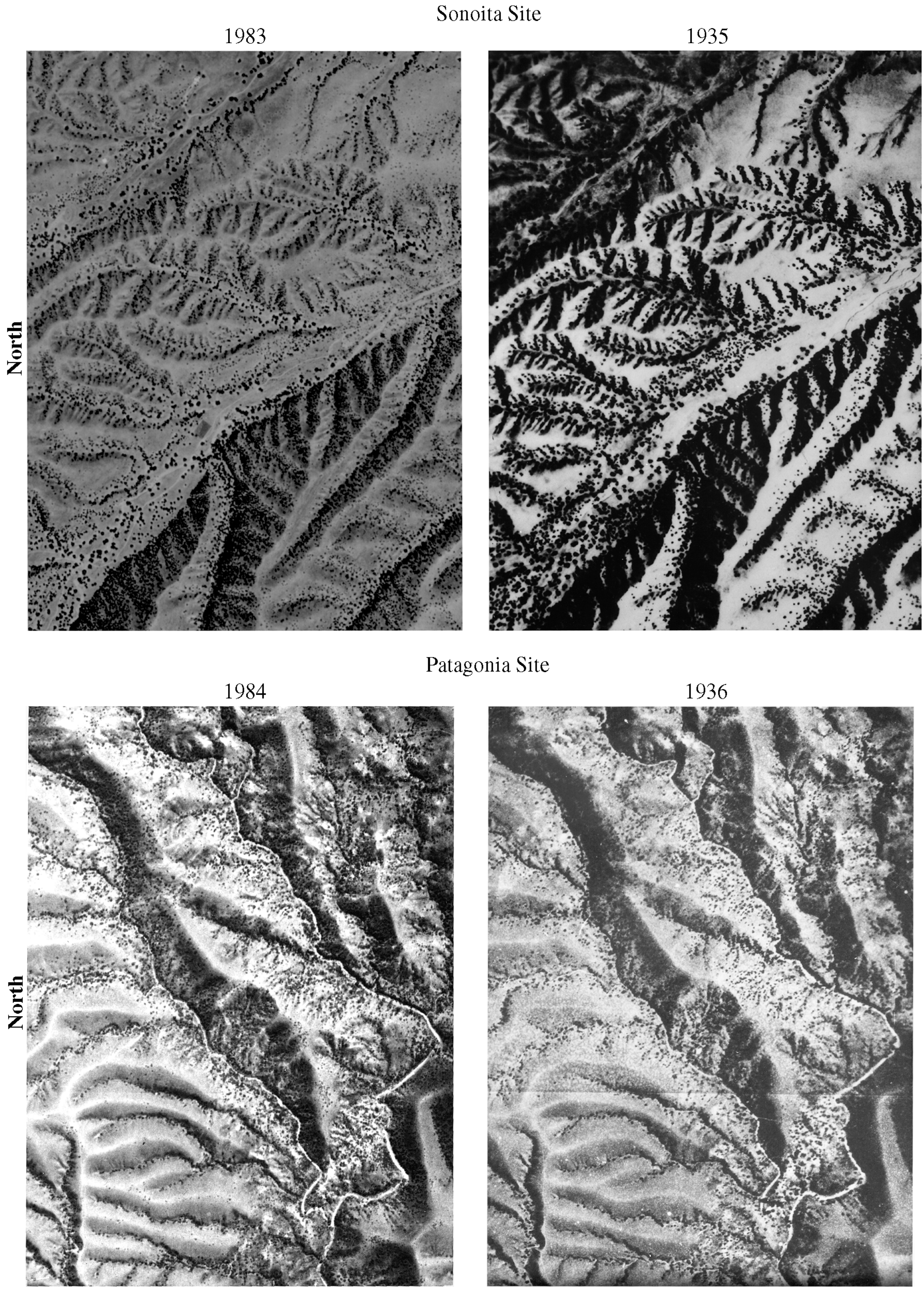

Fig. 2. Scanned images showing the two dates for each site. Images at approximately 1 : 30,000.

4.2.2. Results

There is more canopy area in the recent images in all but eight of the 50 segments covering both sites. This suggests a general increase in tree and shrub cover for both sites over almost 50 years. Overwhelmingly, there is evidence of a significant increase in tree and shrub

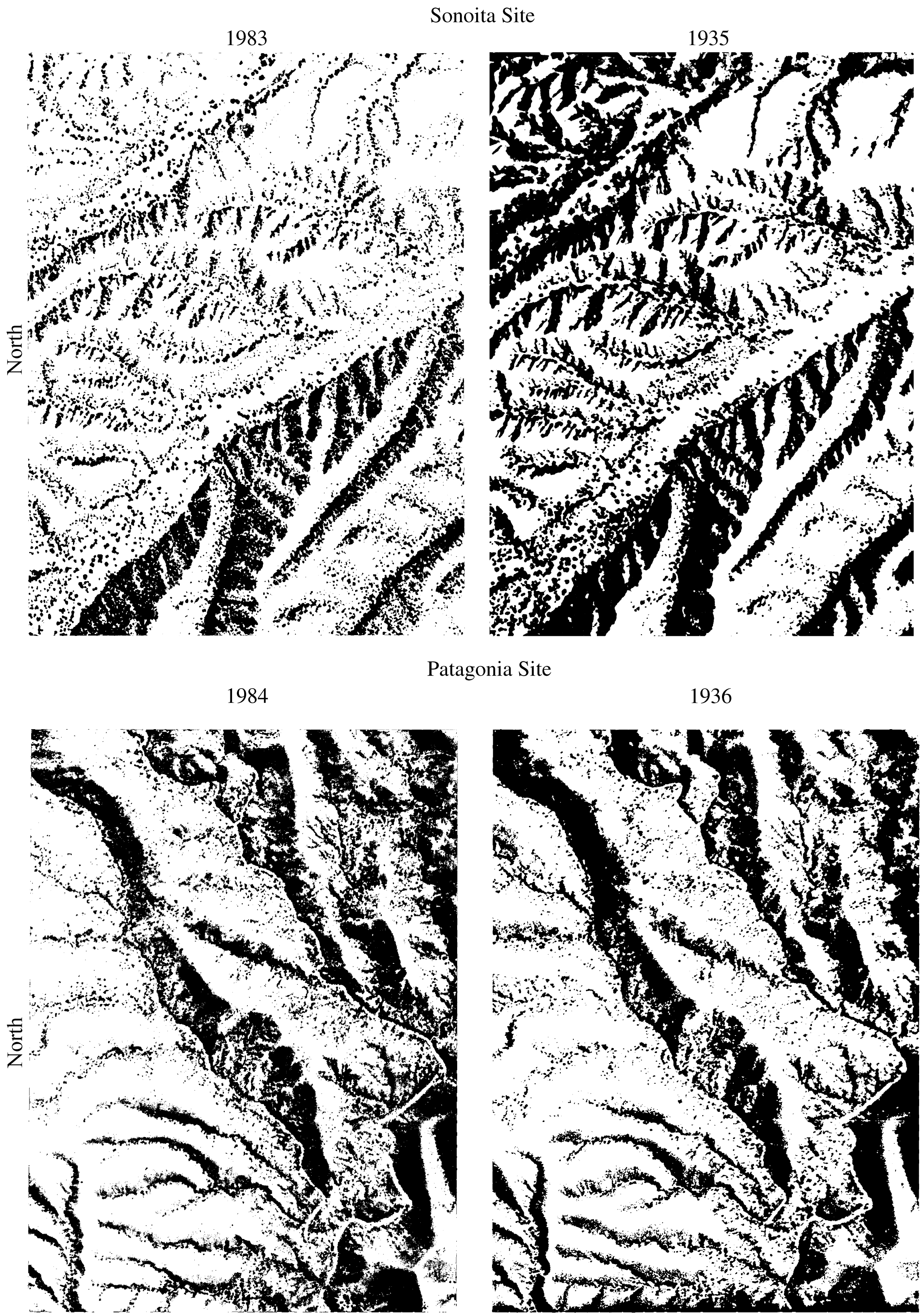

Fig. 3. Binary image for the two dates for each site.

canopy. As noted in the latter analysis, however, three of the 25 image segments showed a decline in tree and shrub canopy. Perhaps most importantly, several segments are adjacent and thus suggest that some part of the observed differences might be related to land use. This canopy decrease is an area of hardpan that was "ripped" and replanted in native grasses in early 1979 in Hog Canyon, near the Hog Canyon Experimental Plot established by the Forest Service in the 1940s (Lockwood, 1996).

5. Historical land use

The Sonoita Creek drainage was one of the earliest areas of European settlement in Arizona (Bahre, 1991). The San José de Sonoita land grant, established for large-scale livestock raising in 1821, the same year as Mexican independence, once probably included both study sites (Wagoner, 1975). Both sites have been grazed and harvested for fuelwood since the early 19th century (Bahre, 1991). In 1860 nearly 20% of the non-Indian population of Arizona lived along Sonoita Creek and its immediate environs (US Bureau of the Census, 1864).

Fig. 4. Masked image for the early Sonoita site (1935).

5.1. Sonoita site

Immediately south of Sonoita site were the military reservations of Fort Buchanan, established in 1857 and abandoned in 1861 (Serven, 1965), and Fort Crittenden, established in 1867 and abandoned in 1873 (Serven, 1965). The United States government established these forts to protect settlers from Apache depredations in the upper Santa Cruz River valley and along Sonoita Creek. Since the 1870s the Richardson, Gardner, Crown C and Rail X ranches have all run cattle on or near the Sonoita site. Since 1902 when it was included in the Santa Rita Forest Reserve, all of the Sonoita site, except for section 26 and parts of Sections 27 and 28, has been managed first by the US General Land Office and then by the National Forest Service. It was included as part of the Coronado National Forest in 1917. The railroad grade of the New Mexico and Arizona Railroad, established in 1882 and abandoned in 1966, runs along Sonoita Creek (Myrick, 1975).

Rollin Rice Richardson purchased the Monkey Springs Ranch and the former Crittenden Military Reservation in the early 1880s (Kupel, 1995). He named his spread the Pennnsylvania Ranch, and it eventually included nearly 36,000 ha in the Sonoita Valley and most probably both of the study sites. Eventually, he expanded his holdings and renamed his ranch the Crittenden Land and Cattle Company. In 1890, Richardson had about 12,000 cattle on the ranch. The 1891–1893 drought, however, devastated his herd and by August 1893 he had only 4000 cattle.

Theodore F. White did the first United States Public Land Survey of the Sonoita site in 1874 (Surveyors' Field Notes, Book, 1489 and Plat Maps 2381 and 2382). White described the township as covered by oak and grass with heavy oak cover along the southern edge of the township. He also noted that grazing was good.

5.2. Patagonia site

The Patagonia site has been heavily grazed and harvested for fuelwood since at least the end of the mid-19th

Table 1
Comparison of total canopy areas

Site	Date	Canopy pixels (raw image)	Percent change	Canopy pixels (masked image)	Canopy change	Total area
Sonoita	1935	275,927		261,854		11%
	1983	277,753	+ 0.7%	310,428	+ 18.6%	13%
Patagonia	1936	264,002				11%
	1984	405,013	+ 53%		+ 53%	17%

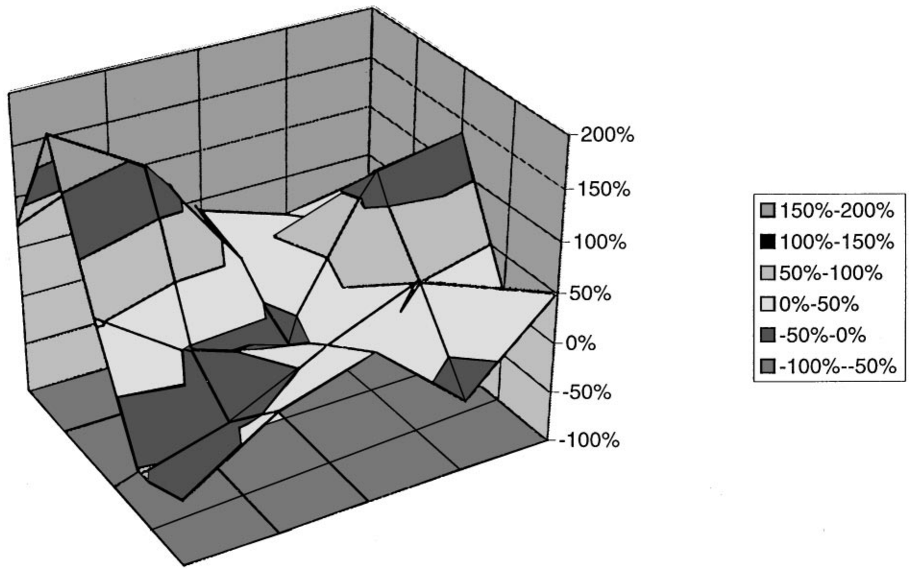

Fig. 5. Sonoita cover change 1936–1983.

century. Even today, it shows evidence of livestock overgrazing on the privately owned (patent) lands. Unlike the Sonoita site, however, it is dotted with small mines and prospects (at least 16). Copper, lead, and silver were the major products of the mines. Although some of the mines are still worked on small scale, the last major operations were during the Great Depression (Schrader, 1915; Keith, 1975). The site is within the Palmetto Mining District and has been mined since at least 1850 (Keith, 1975); one smelter near the Jarilla Mine on the southern edge of the site was built in 1850 (Keith, 1975). The trees on the site, especially the oaks, show greater evidence of past cutting than those at the Sonoita Site. Major mines on the site or immediately adjacent to it are: Jarilla Mine (est. 1850), Three R mining group (est. 1913), Domino or Old Chief Mine (est. 1881), and Sonoita Mine (est. 1879) (Schrader, 1915).

The first survey of the Patagonia site (T235, R15E) was done by Theodore F. White in 1876 (Surveyors' Field Notes, Book 1486) when he surveyed the northern and western boundaries of the township. He recorded oaks there and described the area as having good grazing. The section lines were not surveyed until 1913 when J.B. Wright and W.H. Elliott described the vegetation cover of the township as "… oaks, greasewood, cacti, coarse beargrass, scrub oak, few oak trees, some mesquite, willow, some cedars … fair growth of native grasses" (Surveyors' Field Notes, Book 2497). Only a few of the westernmost sections of the Patagonia site are patent lands; the remaining sections are Coronado National Forest and mining claims. Pumpelly, who worked in the mines near here in the mid-19th century, pointed out that the Salero Mines, located about 25 km northwest of the Patagonia Site, have been worked since the 1750s (Wallace, 1965).

The two areas along the northern edge of the study site in which decreases in vegetation cover are noted are on private, rather than Forest Service land, adjacent to roads, and show evidence of recent disturbance.

6. Conclusions

6.1. Human agency and woody vegetation increase

Given the distance between the sites and the almost uniform direction of change, we might attribute changes to a force with regional expression, such as climate. However, research on climate variability over this same general period (the last century, or so), comes to two conclusions that are not necessarily contradictory. One group of researchers found a modest drying and a shift in seasonality of precipitation. They used this to explain a presumed upslope "retreat" of oaks (Hastings and Turner, 1965). We found no retreat of oaks but, instead, an increase in woody vegetation including oaks. The other group has found no significant individual events or significant cyclic changes (Cooke and Reeves, 1976; Bahre and Shelton, 1993; Shelton and Bahre, 1993). These findings suggest that the cause for any observed directional regional change in the oak woodlands, at least in the past 50 years, cannot be attributed solely to climate.

The history of land use at both sites since the 1850s argues strongly for human agency to explain the increase in woody vegetation across the region. Prior to the 1930s and 1940s, local populations were mainly reliant on local supplies of wood for fencing and domestic heating and cooking; livestock grazed open ranges, and fences were usually only found along railroad rights-of-way, around croplands, or in certain sections of the National Forest. Moreover, the woodland wildfire regime had been affected by lifestock overgrazing and Forest Service policies of fire exclusion. In addition, until the early 1900s, local wood was used for mine shoring and to fuel the steam engines for all manner of uses such as lifting, crushing, and even ice-making. While the use of wood for domestic heating and cooking declined after the early 1900s, in 1940 44% of the occupied dwellings in Arizona still relied on wood for heating and cooking (US Bureau of the Census, 1943, pp. 110–114). Bahre and Hutchinson (1985) estimated that as much as 486,000 cords of wood were consumed over a 120-year period around the town of Tombstone, about 60 km to the east of the study sites. They found the most significant impact there, including the documented selective removal of juniper, and the harvesting of oaks as evidenced by ax-scarred stumps surrounded by multiple-stem crown sprouts, in the oak woodlands of the mountains surrounding Tombstone (the Dragoons, Huachucas, and Whetstones). Similar evidences of wood harvest are apparent at the Sonoita site, especially along roads.

Mining operations were comparatively small at the Patagonia site and there is no evidence of mining at the Sonoita site, and the population densities near the sites did not match those of historic Tombstone. However, in light of the energy economy of the period, demands placed on local wood resources likely differed only in intensity, not in kind. The energy and building resources trapped by the local population were almost totally locally derived until relatively recently.

The increase in woody vegetation cover observed between the 1930s and 1980s at our two sites is consistent with the hypothesis of human agency for at least three reasons. First, over this period there was a decline in demand for woody vegetation for fuel and fencing as other more economic alternatives became available. Second, in parallel with declining demand, access to forest resources became increasingly controlled and restricted by the Forest Service during this period. Third, policies of fire suppression pursued for most of the past 90 years by the Forest Service have tended to favor the establishment of woody species at the expense of grasses. Given the combined weight of these factors, it is reasonable to assume that human activities have had selective impact on woody vegetation over the past century.

Repeat aerial photography is an especially appropriate tool for the study of change. Coverage is continuous and the area covered is far more extensive than any other set of observations in many parts of the world, permitting a wider sample for study. Similarly, the period of record now permits the study of change over a period of time that spans several generations It is also part of the public record and thus available for reexamination by any number of researchers. The use of digital techniques for image comparison of aerial photography offers results that are more quantitative and perhaps less subject to bias.

6.2. Policy implications

The direction and causes of woody vegetation changes, especially in tropical and temperate savanna and grassland landscapes, are the subject of considerable policy discussion and debate in the context of global environmental change. Much about this discussion and debate has to do with identifying the directions of landscape change, such as decreases in total woody phytomass, increases in xerophytes, and the purported upward displacement of woody vegetation along a xeric-to-mesic gradient. The use of repeat aerial photography is the most foolproof means to identify and assess the direction of vegetation changes over large areas and offers empirical data that invites re-examination of earlier evidence regarding the direction of vegetation change in some areas.

In this context, our study contributes to the small number of growing studies that have similarly produced evidence for the need of a more thorough and integrated comprehension of human agency in landscape development. Fairhead and Leach (1996) in an exhaustive study of a forest savanna mosaic in Guinea, West Africa, also employ repeat aerial photography to demonstrate that the direction of landscape development was not one of progressive deforestation leaving forest remnants, but rather of human-derived islands of woody vegetation surrounding long-established villages in grassland savanna — despite ground studies since the colonial period providing evidence for the opposite. Unruh (1994) provides numerous examples from different parts of the tropics, of the expansion in range and abundance of valuable tree species due to particular land uses occurring at specific locations and periods in time. In addition, Leach and Mearns (1996) discuss several cases of human occupied landscapes from Africa where the direction of landscape change was misinterpreted.

The specific implications for policy, following re-interpretation of examples of land cover change, fall into three categories: (1) cases where there is clear evidence that woody vegetation has increased due to land use could not then be used to provide evidence for policies that attempt to respond to deforestation, climate change, etc., and as such existing policies regarding deforestation and conservation for such areas would need to be reformulated; (2) a more comprehensive understanding of land-use and land-cover change can provide the basis for policies that allow for or embrace different directions of land-use and land-cover change; and (3) occurrences of increasing woody vegetation at the landscape scale, such as that described by our Arizona study, has the potential to influence future policy formulation for areas where there is definite decrease in woody phytomass over time — in other words, what potential policy options may be learned about from land-use ecologies where the direction of landscape change has not been away from wooded landscapes, but rather towards it?

The existence of cases where the use of repeat aerial photography has resulted in a reinterpretation of landscape direction with regard to presence of woody phytomass, raises the question as to how many, and which other landscapes, covering what total area, may have likewise been misinterpreted. While this may have regional (largely national) policy repercussions, it may also have international treaty obligation implications as specific obligations can depend on the land area in a particular country that is changing; and foreign aid to developing countries can be tied to such participation and similar environmental programs.

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