A SPATIAL AND TEMPORAL ANALYSIS OF FOREST AND GRASSLAND CHANGES AT THE TALLGRASS PRAIRIE PRESERVE

By

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CHAPTER 1

INTRODUCTION

1.1. Study Site.

The Tallgrass Prairie Preserve (TPP), owned by the Nature Conservancy of Oklahoma, served as the study area for this research. The preserve consists of approximately 30,000 acres and was purchased by the Nature Conservancy in 1990 in order to preserve a remnant of the tallgrass prairie ecosystem in the United States. Situated in Osage County in northeastern Oklahoma (figure 1.1), the TPP is bounded

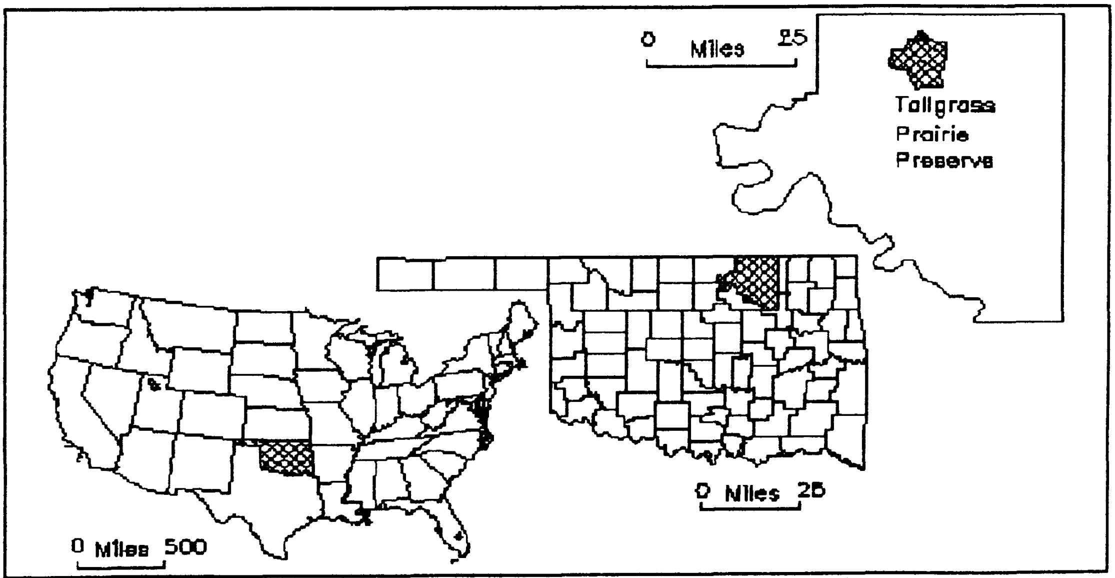


Figure 1.1. Location of the Tallgrass Prairie Preserve.

by deciduous forest to the east and open grassland to the west.

The majority of vegetation at the TPP is dominated by grassland, though bottom land and upland forests form important components of the landscape. The degree to which these forests have expanded or contracted through time relative to grassland is unknown. Historical evidence from the journals of early explorers and settlers suggests that dense upland forests were common in Oklahoma in the 1700s and 1800s (Dyksterhuis, 1948; Wycoff, 1984). However, recent investigations throughout the United States have shown that forests are now encroaching upon grasslands (Nuzzo, 1986; Archer, 1990; Abrams, 1992).

This dilemma poses questions that are interesting both geographically and ecologically. Geographically, the location, patch size, and patch size distribution of forest patches can be studied at different time periods. This type of analysis would raise important ecological questions. For example, should forests be considered as recent invaders which compromise the integrity of the tallgrass prairie ecosystem, or are forests integral parts of this ecosystem which deserve equal preservation?

1.2. Study Objectives.

The purpose of this research is to investigate temporal changes in forests that have occurred within the boundaries of the TPP between 1937 and 1984. Specific objectives are to: 1) determine the areal extent of forests for both time periods; 2) identify forest patches for both time periods; 3) identify forest that has remained unchanged through time and identify forest transitions; 4) ascertain the influence of soil texture on unchanged and changed forest.

CHAPTER 2

LITERATURE REVIEW

2.1. Land Use/Land Cover Change Studies.

Studies involving change in land use or land cover are common themes in geography. Research in this area has also been of interest to range management and wildlife management professionals. More recently, the study of landscape ecology has brought professionals from several disciplines together in order to study spatial and temporal patterns of heterogeneity in landscapes (Cullinam and Thomas, 1992).

The common objective of land use/land cover studies is to compare the spatial distribution of landscape features as they exist at present with their distribution at an earlier date. The time frame under analysis can vary from prehistoric to presettlement to recent. Data sources for delimiting past and present boundaries include fossil pollen records, still photography, aerial photography, survey records, and multispectral scanning. The geographic extent of such studies varies from regional to local.

Fossil pollen spectra analysis has been used to reconstruct movement of the prairie-deciduous forest ecotone in the upper Middle West from 10,000 bp to present (Davis, 1977) and to map shifts in the distribution of eastern deciduous forest taxa over the past 20,000 years (Delcourt and Delcourt, 1987). Long term studies like these are useful in that they provide a perspective in which to view shorter term changes. However, fossil pollen sources are not common and researchers are often more concerned with vegetation changes occurring in the recent past which can be detected with readily available data sources.

Still photography ranging in date from 1892-1976 was used by Bahre and Bradbury (1978) to assess vegetative change along the United States-Mexico border and to evaluate land use policy differences between Arizona and Sonora. Still photographs taken in Yosemite National Park between 1900 and 1985 were used to evaluate the impact of park management programs on vegetation (Vale, 1987). Similarly, Veblen and Lorenz (1988) monitored woody vegetation increase along the forest/steppe ecotone in Southwest Argentina from photographs dating back to 1883. The use of still photography can yield valuable information about vegetation change, yet these studies lend themselves to qualitative descriptions of study sites; little or no quantitative data can be generated to compare between study periods.

Government Land Office survey records have been used by researchers in the United States to investigate vegetation changes occurring after European settlement. Schroeder (1982) has utilized field notes and survey maps to determine the location of prairies in Missouri prior to major settlement in that state. Nuzzo (1986) examined presettlement maps showing oak savanna in eight midwestern states and superimposed these over maps of extant oak savannas. Research utilizing survey records can provide quantitative data to compare vegetation change through time. However, errors can arise because terminology for naming vegetation types and tree species were not standardized among surveyors; there may have been bias in selection of witness trees; and platt maps vary in accuracy and detail (Schroeder, 1982; Nuzzo, 1986).

Remotely sensed images taken from above the earths' surface (multispectral scanning and aerial photography) provide valuable data sources for detecting change in land cover. Multispectral satellite images can be obtained dating back to the early 1970s, Landsat 1 with the multispectral scanner (MSS) was launched in 1972. Present day images can be obtained from either Landsat 5 with the thematic mapper (TM) sensor or any of the three SPOT satellites which have multispectral and panchromatic sensing capabilities. Differences in spatial resolution (80m for MSS, 30m for TM, 20m for SPOT multispectral, and 10m for SPOT panchromatic) and the reduced spectral resolution of MSS make comparisons over long time periods troublesome. Research with multispectral scanning is therefore limited to a few years or a single season. For example, seven different SPOT satellite scenes were utilized to measure change in heterogeneity over a growing season at the Konza Prairie Research Natural Area (Briggs and Nellis, 1991).

Aerial photographs provide a readily available, low cost data source for monitoring change in vegetation over relatively long time periods. The Soil Conservation Service (SCS) began systematically mapping soil units from black and white aerial photography during the 1930s. The SCS has continued to map soil units on approximately 10 year intervals and aerial photography is now available from several other public and private sources. Use of aerial photography has various applications including: detecting differences in forest growth between burned and unburned prairie (Bragg and Hulbert, 1976); monitoring succession (Archer et al., 1988); determining the effects of beaver impoundments on hydrology (Johnston and

Naiman, 1990); assessing rural landscape changes (Turner, 1990); and measuring historical wetland sites (Lyon and Greene, 1992).

2.2. Geographic Information Systems (GIS).

2.2a. Definition of GIS. GIS has become a popular acronym in recent years that has been used to describe a variety of computer software packages and also in reference to research methodology as is evidenced by the phrase 'GIS analysis'. A definition of GIS will be given here because there is some confusion as to the meaning of this term. Star and Estes (1990) define GIS as "an information system that is designed to work with data referenced by spatial or geographic coordinates." An information system has been defined as "a chain of operations that takes us from the observation and collection of data, to storage and analysis of data, to use of the derived information." (Calkins and Tomlinson, 1977). A GIS is not necessarily computer based; in fact, early applications involved simple overlay of transparent sheets each containing different geographic information (McHarg, 1969). Recent advances in digital computer, telecommunication, and aerospace technologies have led to the development of computer software capable of analyzing geographic data much faster and more accurately than manual techniques (Bartolucci and Weber, 1986). GIS packages vary greatly in design and capabilities. For applications in landscape ecology, an ideal GIS should be able to: 1) analyze temporal change; 2) determine spatial coincidence of objects; 3) determine proximity, contiguity, patch size, and patch shape of spatially distributed objects; 4) analyze direction and magnitude of fluxes of energy, organisms or materials; 5) produce graphic output; 6) interface with simulation models to generate new spatial data (Johnson, 1990).

The two most common data formats used to store information in a computer for use in GIS are raster and vector. Raster, or cellular, data structures utilize a series of square grids that overlays the study area. Each cell can be assigned a value that identifies the feature(s) found within. Raster based GISs have been widely used in ecological research because the cellular format is readily compatible with multispectral imagery and because they model 'fuzzy' natural boundaries well (Star and Estes, 1990). Vector based systems store spatial data as points, lines, and polygons. These systems require less memory, provide more information about adjacency and connectivity but have been most widely used for applications with well defined boundaries such as political units (Guptill, 1988).

2.2b. GIS and land use land cover change. Surprisingly few studies have combined GIS with aerial photographs for temporal analysis. Hydrology data from topographic maps in combination with aerial photographs from 1957 and 1987 has been used to model the effect of wetland loss on stream water quality (Johnston et al., 1988). Archer et al. (1988) utilized GIS software to digitize patches of woody vegetation from three sets of aerial photography (1940, 1960, and 1983). Direct comparison between time periods was not possible because of variations in photographic scale and a lack of distinctive control points needed to register the three data sets. Indirect comparison was achieved by visually locating patches and following them through time. Turner (1990) also made indirect comparisons of land use change in rural counties in Georgia from three sets of aerial photography (1950, 1960, 1980). Her methodology involved placing a transparent grid with each cell representing 1-ha over the photography and assigning each cell a class value. The transparent sheets were then digitized into a spatial analysis computer program to compute summary statistics. No attempt was made to assign geographic coordinates to the aerial photographs. LaGro (1991) used GIS to determine patch shape, fractal dimension, and spatial clustering of forests from 1937 and 1987 aerial photographs. Individual patches for each time date were not directly compared (overlay of the time periods was not attempted) because the research objective was not to determine transition of patch types. Johnston and Naiman (1990) used 6 sets of aerial photography ranging in date from 1940-1986 to analyze landscape alteration caused by beaver impoundments. A raster based GIS was used to digitize beaver impoundments from each photo set and allowed direct comparisons between time periods. Overlay and matrix operations performed on the digital data made it possible to monitor changes and compute transition rates for individual impoundments from one study period to the next.

Applications of GIS coupled with aerial photography data represents a relatively untapped method for detecting landscape change. The primary limitation of temporal analysis using GIS has been the lack of historical data (Johnson, 1990). Fortunately, aerial photographs from 1937 are available for the area encompassing the TPP and can be used to document forest locations for that time period. Use of GIS allows direct comparisons to be made with the location of forest in 1984.

CHAPTER 3

NATURAL HISTORY OF THE TPP

3.1 Climate.

The Köppen climatic classification for eastern Oklahoma is humid subtropical (Cfa) being characterized by relatively long, hot summers, mild winters with brief episodes of severe cold, and a short winter dry season (McKnight, 1990). A distinct east-west precipitation gradient exists in Oklahoma with annual totals well above 100 cm in the eastern portions of the state, declining to less than 50 cm westward (figure 3.1). Osage County is located towards the eastern edge of this gradient, receiving an

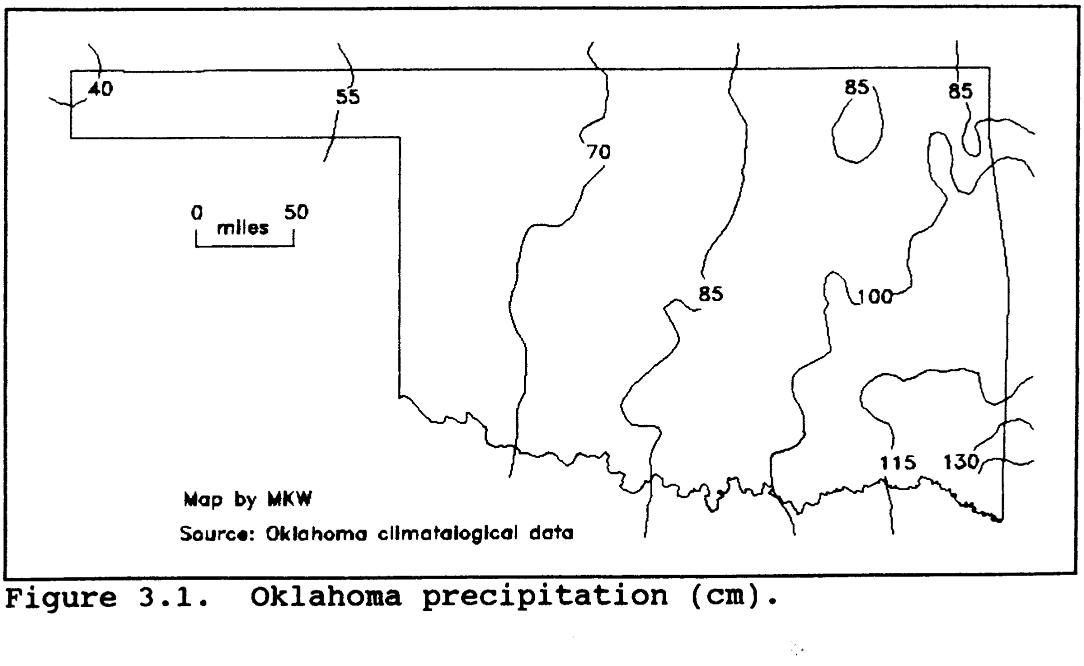


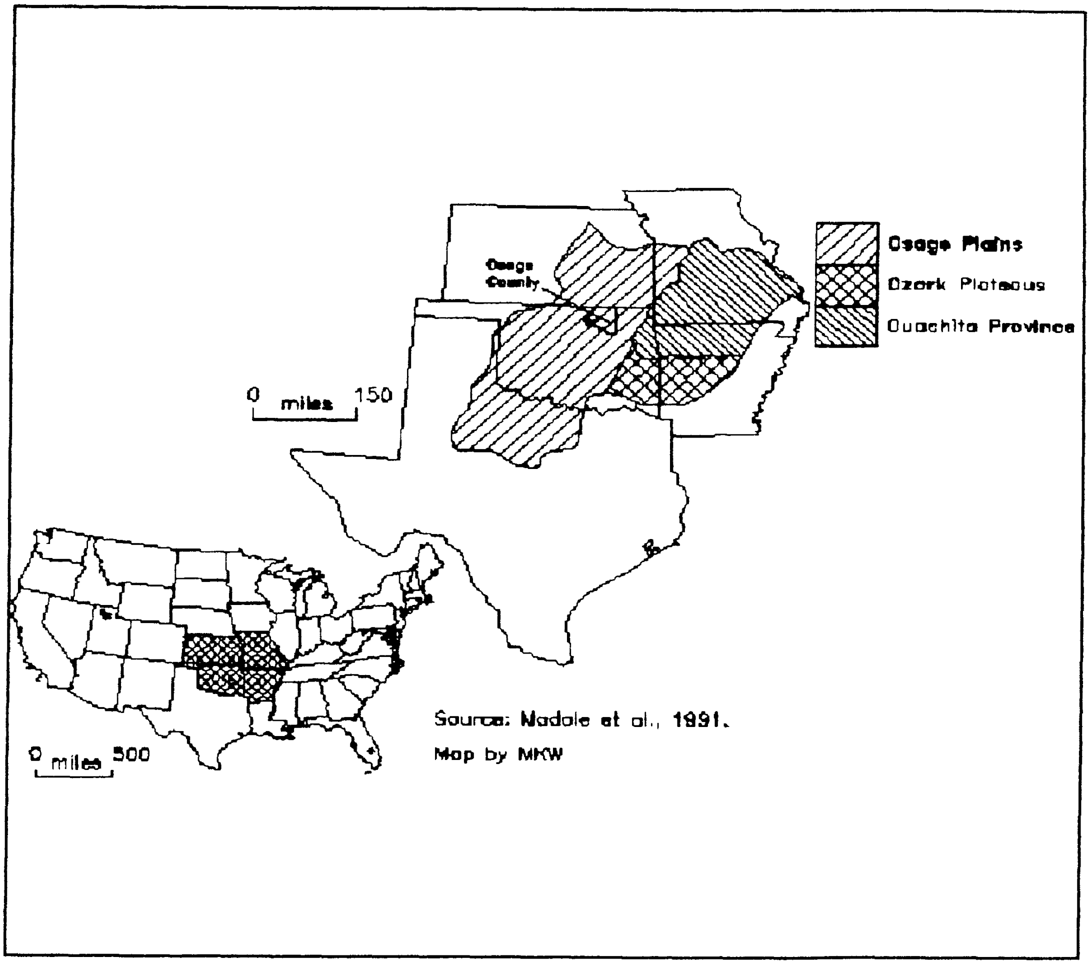
Figure 3.1. Oklahoma precipitation (cm).

average annual precipitation of 94.84cm (table 3.1). During summer months precipitation tends to come from thunder storms followed by periods of drought. These periods of summer moisture stress favors the establishment of grassland rather than woody vegetation.

	Precipitation (cm)			Temperature (°C)	
Month	Mean daily minimum	Mean daily maximum	Mean	Mean daily minimum	Mean daily maximum
January	0.00	12.88	3.35	-5	9
February	0.00	18.03	4.19	-3	12
March	0.00	22.61	6.78	2	17
April	0.66	29.77	9.37	9	23
May	1.47	48.56	12.98	13	26
June	0.51	40.67	12.32	19	31
July	0.00	28.68	3.14	21	34
August	0.00	26.52	8.53	20	34
September	0.00	41.10	10.85	16	30
October	0.00	34.65	8.15	9	24
November	0.00	21.92	5.82	2	16
December	0.05	19.08	3.96	-3	10
Year	49.45	161.37	94.84	8	22

Table 3.1. Climatological data based on 93 years of observation at the Pawhuska, Oklahoma weather station.

3.2. Geological Setting.



Source: Madole et al., 1991.
Map by MKW

Figure 3.2. Physiographic Provinces.

The largest part of central and northern Oklahoma has been placed into the Osage Plains physiographic division by Madole et al. (1991) which is a subdivision of the Central Interior Lowlands (figure 3.2). The Ozark Plateaus and the Ouachita Province form distinctive east and southeast boundaries with the Osage Plains. As aridity increases westward, there is a less distinct transition with the Great Plains. North of the Osage Plains the topographic effects of glaciation are apparent, while changes in sea level have produced the coastal plains to the south. The Osage Plains slope eastward with local relief generally between 30 and 100 meters (Madole et al., 1991). Surface rocks are mostly Pennsylvanian in age, consisting of shale interbedded with sandstone, limestone, coal, and conglomerate (Jordon, 1967). The geologic history of the TPP offers an interesting account of past and present processes operating to shape a landscape. Regionally, there have been extreme variations in climate and depositional environment. The resistant sandstone and limestone layers that now form the Osage Hills were deposited during the Pennsylvanian and Permian periods 245-320 mya (Madole et al., 1991) when the regional depositional environment was transitional between shallow, equatorial sea and erodible lowlands (Levin, 1988).

3.3. Paleoecology.

The magnitude of change detected by a temporal analysis of any landscape is dependent upon the time scale being used. Recent conversions of grassland to forest that have occurred throughout North America may appear to be large transitions. However, these conversions are relatively small when compared with changes that have occurred since the Mesozoic era, for example. As with all places on earth, paleoenvironments of the TPP have varied greatly in the geologic past.

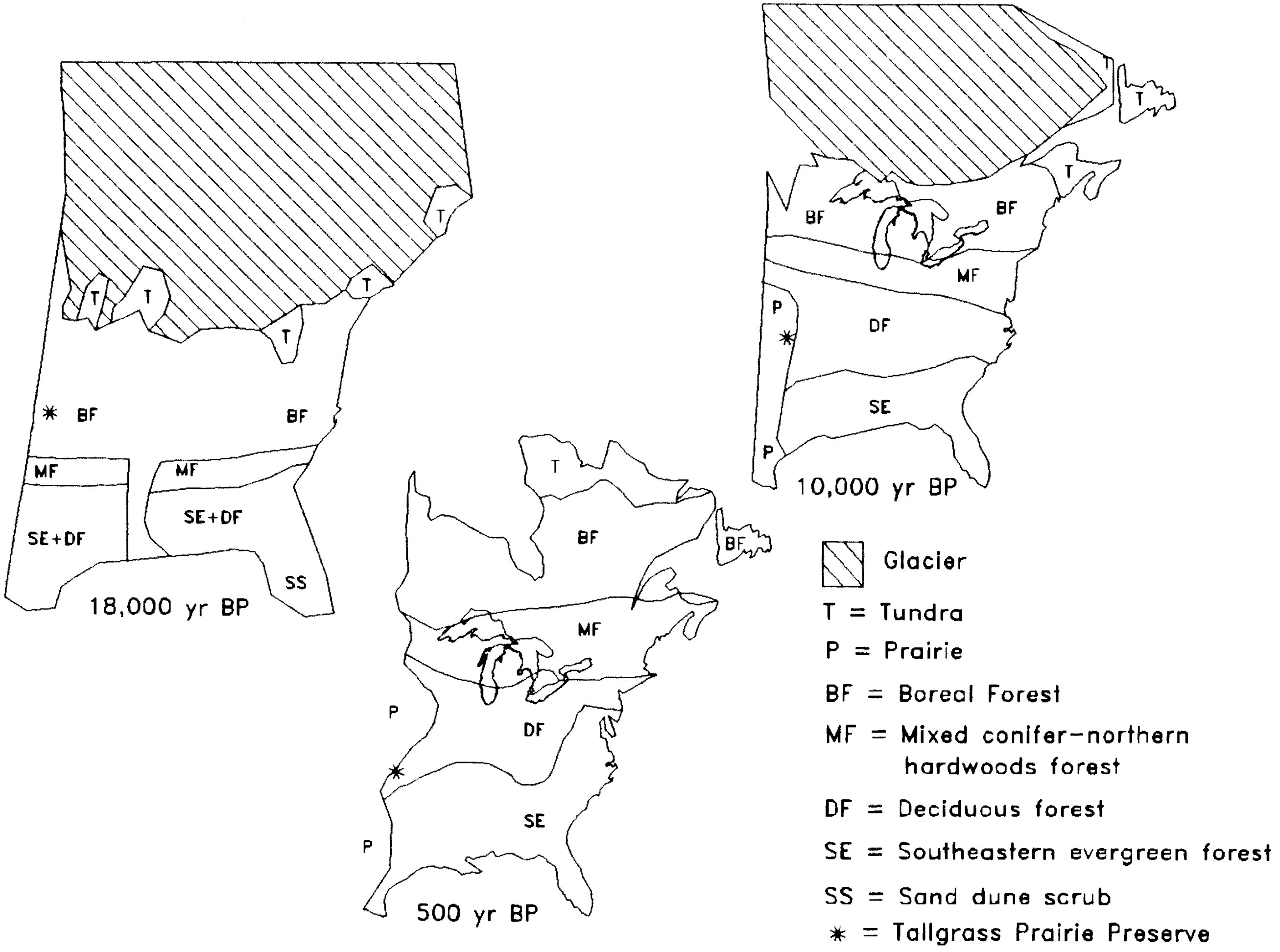
In particular, climatic events operating during the Pleistocene epoch (2 mya) are exceedingly significant in determining the present flora and fauna of the region. Authors agree that through time these communities have experienced large shifts in terms of both species composition and geographic range (see below). It seems reasonable to conclude that present vegetative associations found in Oklahoma and elsewhere along the forest/grassland margin represent one phase of a continually changing assemblage of communities which have resulted from changing environmental conditions. In this sense, current species are abapted by the environments experienced by their predecessors. That is, past environments have acted as screens that allow certain individuals (or groups of like individuals) to pass through but not others. This means that present species composition is controlled more by past environments than present environmental conditions. Since environmental conditions have varied so greatly in the past it seems likely that current communities will be particularly sensitive to environmental changes. Therefore, a discussion of paleoclimates and paleoecology is included as a means of identifying important trends of the past which may reveal information about patterns in the present.

The southern margin of maximum glaciation (18,000 bp) was approximately 5° latitude north of the TPP (Smiley et al., 1991). As the glaciers advanced and retreated there was a corresponding flux in vegetational composition in those regions south of the glacial margin. Reconstructing the parallel movements of ice and vegetation can be an important aid in understanding the current biotic communities that occupy this region.

Unfortunately, the paleoecologic record is meager, making it difficult to extract a complete picture of paleocommunities as they existed in relationship to the glacial margins and to one another. However, it is possible to make inferences using research from the nearest available sources of fossil pollen. For example, evidence from the Kingsdown Formation in western Oklahoma indicates that spruce-pine forest covered much of that region during the mid-Pleistocene (Axelrod, 1985). Fossils found at Kirby Jones Spring in south-central Missouri that dated to the Sangamon glacial period (18,000 bp), included mammoth and bison fossils as well as a dominance of graminoid pollen, suggesting a much drier climate during that time period (Smiley et al., 1991). Other evidence which suggests that precipitation levels in Oklahoma once supported more mesic forests can be inferred from relict populations of sugar maple (*Acer saccharum* Marsh.) presently found in the Wichita Mountains (Dooley and Collins, 1984) and in Canadian County, Oklahoma (Rice, 1960). These localized examples yield important clues to the past but the picture is incomplete unless each site is placed within the context of changes occurring elsewhere on the North American continent.

The work of Delcourt and Delcourt (1987) provides a synopsis of Pleistocene forest migrations throughout the eastern United States (figure 3.3). Their analysis of 162 fossil pollen sites indicates that by about 18,000 bp, boreal forest dominated the latitudes between 41°-34° North but yielded to deciduous forest and grassland in these latitudes as the glaciers retreated northward. By 10,000 bp prairie was estimated to have made major advances into the forests' western margin. At 8,000 bp *Quercus* spp. accounted for over 60% of forest species along the Ozark Plateau but declined in importance to 20%-40% by 500 bp (figure 3.4). This view of fluctuations between boreal forest, deciduous forest, and grassland is supported by the work of Jacobsen and Grim (1986) in Minnesota, as well as Davis (1977), working in the Driftless Region of the upper Middle West.

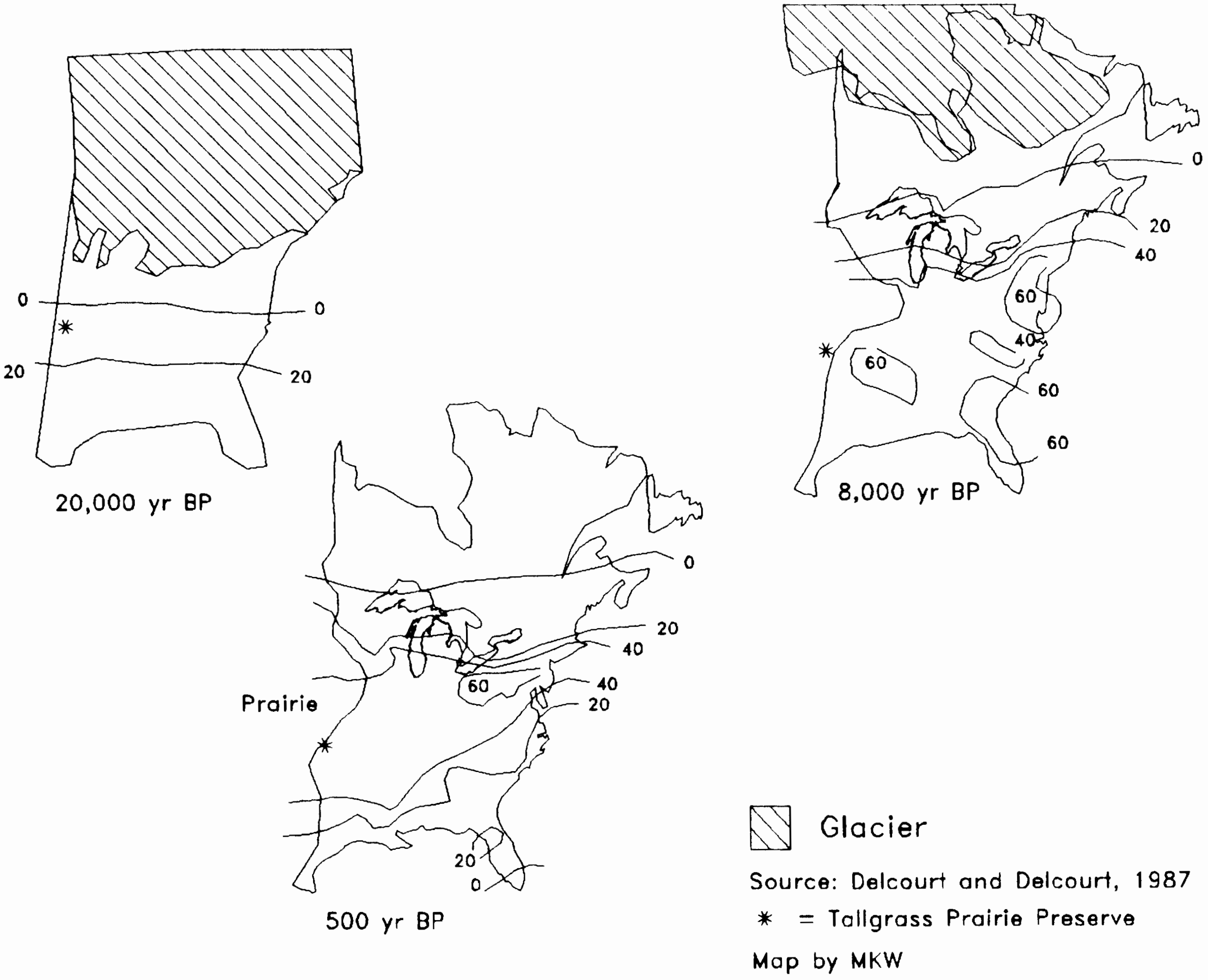
While many specifics regarding past species composition and relative dominance of forest and grassland remains unknown, several conclusions can be drawn from this body of literature: 1) During maximum glaciation, Osage County



Source: Delcourt and Delcourt, 1987

Map by MKW

Figure 3.3 Paleovegetation Maps for the Eastern U.S.



Source: Delcourt and Delcourt, 1987

✳ = Tallgrass Prairie Preserve

Map by MKW

Figure 3.4. Contoured Paleo-dominance Maps for Quercus. (% Trees)

and the surrounding area was probably dominated by a boreal forest which gradually gave way to oak-deciduous forest which was in turn invaded by grassland; 2) The relative dominance of forest and grassland in and around Osage County is likely to have varied greatly in the past 5,000-10,000 years, with forest benefitting from cooler, moister climatic periods and grassland benefitting from warmer, drier periods; 3) In the more recent past grassland has dominated the landscape but stands of oak-dominated forests have survived in many areas; 4) The species which have survived to form grassland and forest communities are likely to be sensitive to environmental changes and are capable of expansion given the right conditions.

The precise conditions needed for major grassland or forest expansion are not completely understood. A more complete discussion of present forest and grassland communities is included in this study to better understand environmental factors that may favor one vegetation type over another.

3.4. Tallgrass Prairie.

Generally speaking, grassland dominates the western half of Oklahoma while forest dominates the eastern half (figure 3.5). However, a relatively narrow band of grassland extends south from Kansas into northeast Oklahoma. This vegetation has been described as tallgrass or true-grass prairie by Owensby (n.d.) and Buck and Kelting (1962), though Sims (1988) considers this vegetation to be mixed-grass prairie, a transition between the eastern tallgrass and western short-grass prairies. Bailey (1978) has termed this vegetation as parkland trees are locally important. Additionally, Küchler (1964) identified this grassland as the *Andropogon* Prairie. Authors agree that the dominant grassland species found here are Big bluestem

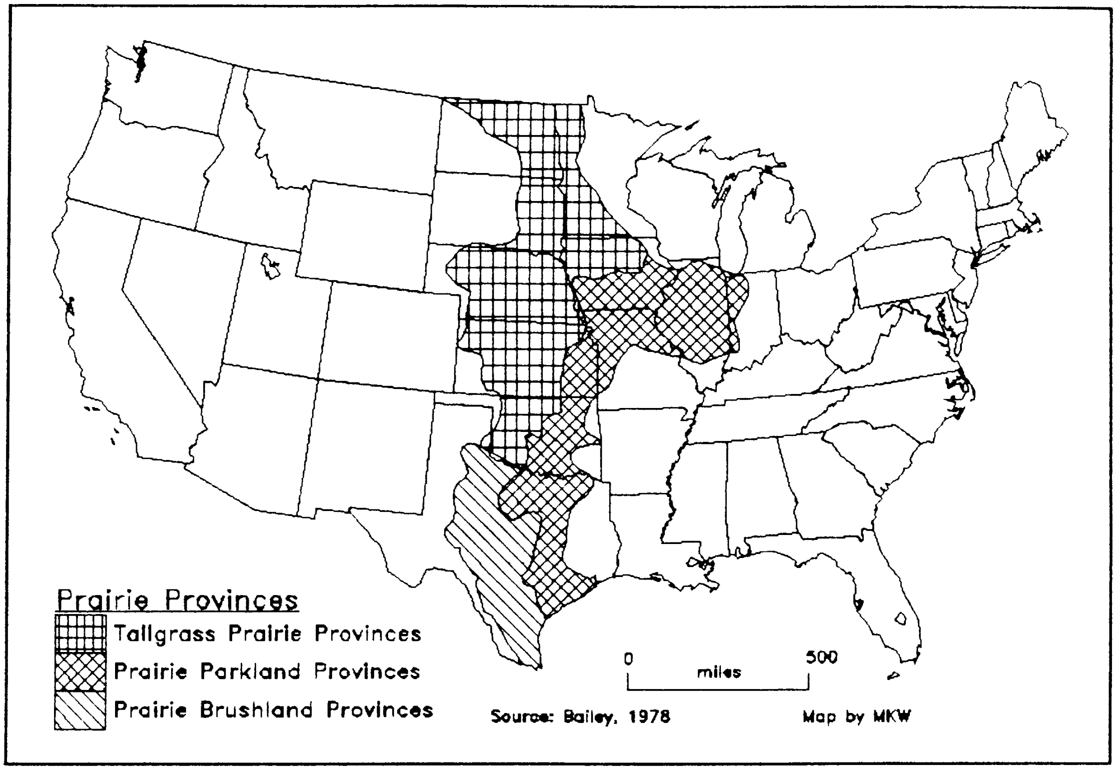


Figure 3.5. Distribution of grasslands in the United States.

(*Andropogon gerardii* Vitman), Indiangrass *(Sorghastrum nutans* (L.) Nash) and Switchgrass (*Panicum virgatum* L.). The type of grassland which occurs in northeastern Oklahoma and in Osage County will be referred to as tallgrass prairie, though some authorities may disagree with this terminology.

Soils underlaying much of the tallgrass prairie are extremely fertile and have been mostly converted to farmland. The thin, rocky soils found in the Flint Hills and Osage Hills discouraged settlers from plowing, saving the tallgrass prairie ecosystem from complete destruction. Although the soil in these areas was not suited to row cropping, native grass pastures were heavily utilized in the late 1800s and early 1900s as summer grazing for beef cattle, which were then shipped by railroad to market (Owensby, n.d.). More recently, changes in grazing management has resulted in pasture utilization being split more or less equally between year-round cow-calf operations and steer grazing (Owensby, n.d.).

In addition to destruction caused by agriculture, grasslands throughout North America have suffered from woody plant invasion. This phenomenon has been reported in northeastern Wisconsin (Dorney and Dorney, 1989), Minnesota (Buell and Canton, 1951), Texas (Dyksterhuis, 1948; Archer, 1989) and Oklahoma (Rice and Penfound, 1959; Johnson and Risser, 1975). In each case the repeating pattern appears to be that changes in the disturbance regime (fire suppression and intensified grazing) caused by European settlers has tended to favor establishment of trees at the expense of grasslands.

Axelrod (1985) argues that the tendency for grassland to be replaced by forest when the disturbance regime is changed attests to the relative youth of grassland ecosystems in North America, which had their genesis 5-7 mya. Paleoecological research conducted in eastern North America (Delcourt and Delcourt, 1987), in Minnesota (Jacobson and Grim, 1986), and in the Driftless Region (Davis, 1977) agree with Axelrod that major grassland ecosystems did not reach their present status until post-glacial times, approximately 10,000 bp. Additional evidence of grassland youthfulness given by Axelrod includes: 1. the presence of most grassland species in neighboring forest communities; 2. paucity of endemic grassland flora and fauna; 3. existence of relict tree populations within grassland ecosystems.

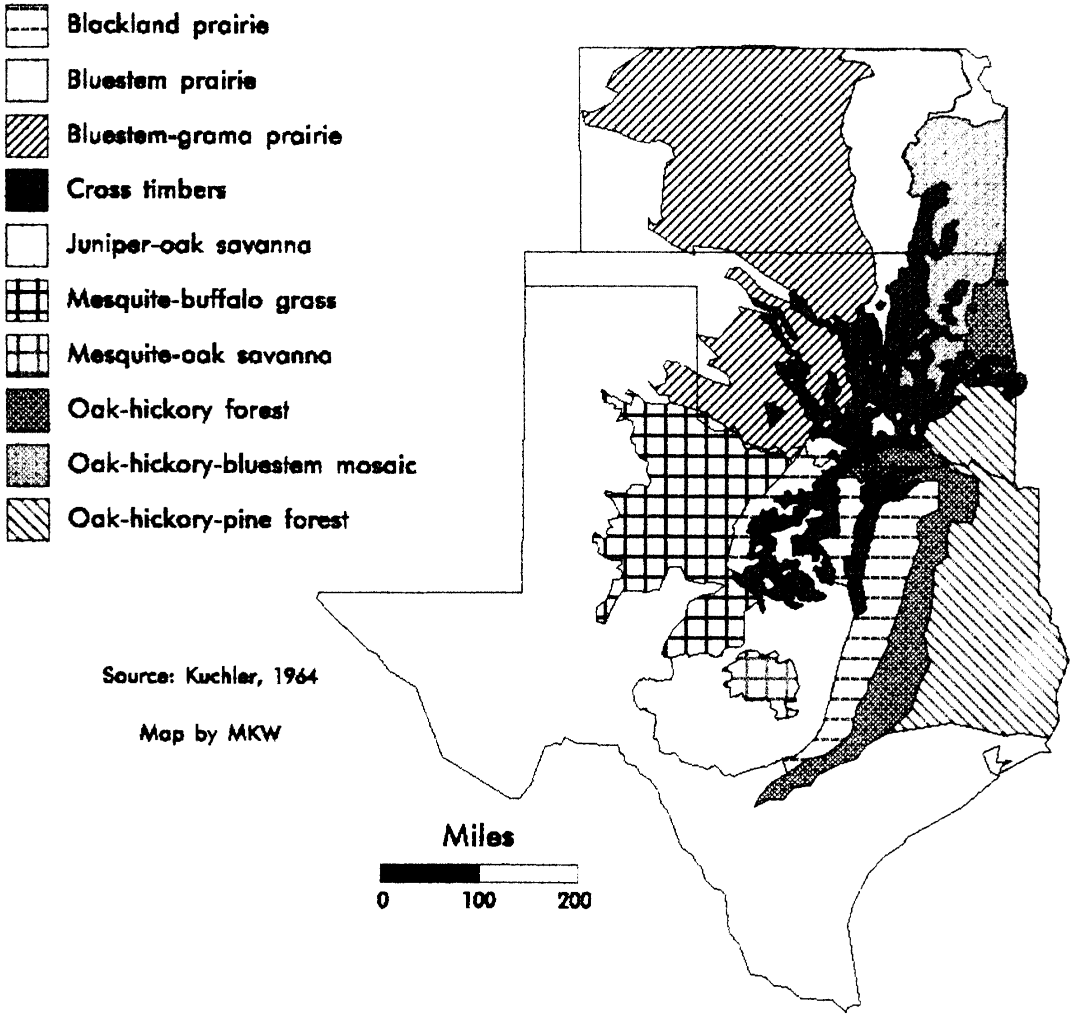
3.5. Cross timbers.

Woody vegetation on the TPP occurs along drainage basins as well as on drier sites. Forests found on mesic sites can be locally diverse in terms of species richness and are quite different from upland forests (Rice, 1965). Upland forests, commonly referred to as 'cross timbers', tend to be dominated by two species: post oak (*Quercus stellata*) and blackjack oak (*Quercus marilandica*). Mesic sites capable of supporting relatively diverse, dense canopied forests are found chiefly along stream valleys, giving these forests a dendritic pattern on the landscape. While *Q. stellata* and *Q. marilandica* can both be found in mesic sites, patches of 'cross timbers' type forest appear to be associated with xeric sites.

Küchler (1964) identified a large part of the vegetation ranging from southern Kansas, through central Oklahoma, and into north Texas as cross timbers (figure 3.6). Osage County is located at the boundary of Küchlers' *Andropogon* Prairie and cross timbers (figure 3.7.).

The origins of the term 'cross timbers' are vague, though two hypotheses which have been offered are: 1) it is a description of the landscape referring to the juxtaposition of east-west flowing streams with the north-south trend of the vegetation; 2) it was used by explorers and settlers in reference to their crossing this vegetation on way to the Great Plains (Dyksterhuis, 1948; Stadler et al., 1992).

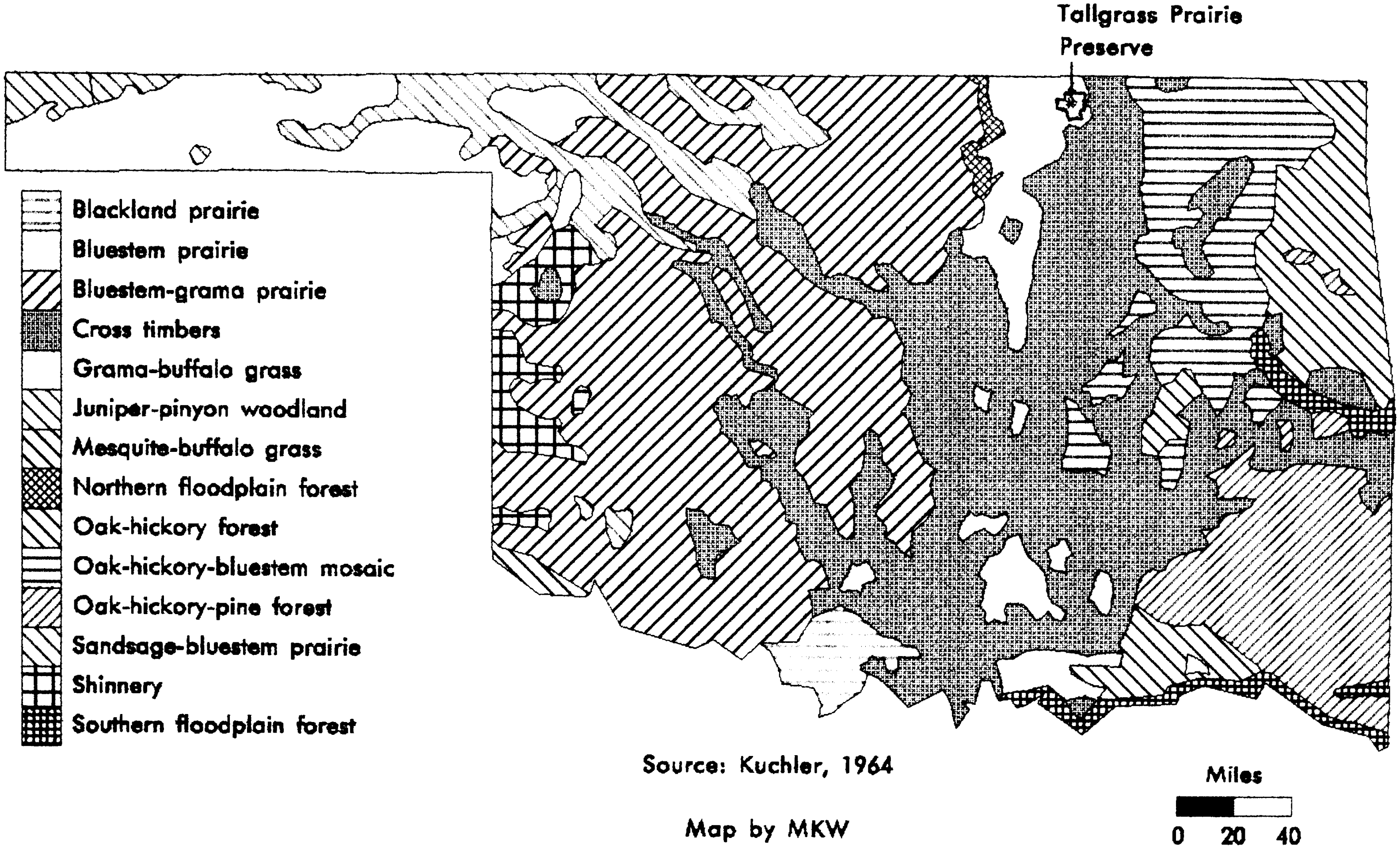
Weaver and Clements (1938) described the forests of this region as post climax eastern deciduous forest surrounded by climax grassland. Bruner (1931), who conducted a state wide survey of Oklahoma, identified this vegetation as an oak savanna which occupied an intermediate position between eastern mesophytic forests and grasslands to the west. Dyksterhuis (1948) accepted Bruners' terminology and equated the cross timbers in north Texas with the oak savanna of Oklahoma. Indeed, Dyksterhuis strongly believed that the pre-settlement forests in Texas were closer to



Source: Kuchler, 1964

Map by MKW

Figure 3.7. Potential Natural Vegetation of Kansas, Oklahoma, and Texas



Source: Kuchler, 1964

Map by MKW

Figure 3.8. Potential Natural Vegetation of Oklahoma

open rangeland than their present appearance suggests.

Rice and Penfound (1959) conducted the first quantitative investigation into the distribution of forest types across Oklahoma. With the data that were collected, they were able to show that: 1) *Q. stellata* and *Q. marilandica* were dominant in all but the eastern most stands, with *Q. stellata* generally being the most common; 2) species richness within stands and basal area of all tree species decreased westward. While no data were collected for the grassland component, Rice and Penfound identified a western oak savanna and a more centrally located oak-hickory savanna. Being heavily influenced by climax theory, Rice and Penfound viewed the westward changes in vegetation as a continuum caused by a precipitation gradient.

Within the TPP, there appears to be relatively discrete patches of forest and grassland with some intermingling of the two. This research addresses the question of whether or not the size and/or location of these forest patches have changed through time.

3.6. Soils.

The distribution of soil types is an important factor determining the distribution of vegetation. In savanna ecosystems around the world, soil moisture and nutrient content are considered vital factors influencing the distribution of grasses and woody growth (Cole, 1986; Skarpe, 1992). Research in Argentina has demonstrated that grasses are able to utilize moisture from upper and lower soil levels while woody shrubs exclusively utilized lower moisture levels (Sala et al., 1989). This indicates that where soil moisture is limited, grasses are superior competitors and dominate over woody growth. However, a reversal of this trend has been reported by Archer (1989) in southern Texas mesquite savannas where intensive grazing by livestock has resulted in woody expansion into grassland. The occurrence of woody growth has been correlated with increased soil nutrient levels in a somewhat circular system described by Vetaas (1992) whereby establishment of woody seedlings initiates a series of micro-site changes which themselves increase nutrient levels. A comparison of forest and grassland soils samples in Oklahoma revealed that soil macro-nutrients (nitrogen, phosphorus, and potassium) and soil moisture exhibited higher levels inside *Rhus coppalina* L. thickets but was considered unimportant in determining the forest/grassland boundary (Pentranka and McPherson, 1979).

Other soil-vegetation research in Oklahoma has tended to focus on the distribution of tree species within a forest stand, excluding grassland (Dwyer and Santlemann, 1964; Johnson and Risser, 1972; Collins and Klahr, 1991). At the Wichita Mountains Wildlife Refuge separate projects were conducted which investigated the influence of soil type on grasslands (Crockett, 1964) and on woody vegetation (Buck, 1964). Regrettably, these studies were not coordinated (e.g., different sampling techniques were used and only three soil types are common to both studies) making it difficult to draw conclusions about the overall distribution of forest and grassland.

While the influence of soil type on vegetation distribution is not well understood, it is clear that there is a close relationship. A total of 39 soil series types are found within the boundary of the TPP (Osage County Soil Survey, 1979). Soils are used in this study to: 1) discriminate between mesic and xeric sites; 2) determine the correlation between soil texture and areas of unchanged and changed forest.

CHAPTER 4

METHODOLOGY

4.1. Data Base Description.

4.1a. Data sources. Four raw data sources were utilized in this research: 1) black and white aerial photographs from 1937 at a scale of 1:20,000; 2) black and white aerial photographs from 1984 at a scale of 1:9,800; 3) U.S.G.S. 7.5 minute 1:24,000 topographic maps (Nanos and Pearsonia quadrangles); 4) the U.S.D.A. Osage County Soil Survey.

4.1b. Raw data conversion. Seven land cover categories were distinguished from both sets of photographs: 1) scattered density forest; 2) intermediate density forest; 3) dense forest; 4) grassland; 5) agricultural; 6) ponds 7) built-up land. Categories are similar to Anderson et al. (1976) except that rangeland was included with grassland and forest was categorized into density classes. Three forest density classes were categorized qualitatively based on a visual estimation of canopy closure in addition to textural and tonal qualities of the photographic prints. Forests were classified as dense if stands were rough textured, dark toned, and if openings within the canopy were smaller than the crown of one mature tree (about five meters). Forests were identified as intermediate if canopy openings were larger than five meters but the stand as a whole still exhibited rough texture and dark tonal qualities. Areas of forest characterized by loosely aggregated trees with large open spaces where it was possible to distinguish individual trees were classified as scattered forest.

The aerial photographs were manually interpreted and a zoom transfer scope was used to change the scale of the photography to that of the topographic maps. Land cover boundaries from the aerial photographs were traced onto mylar sheets that were laid over the topographic maps. The interpreted information was then manually digitized.

Hydrology was digitized directly from the Nanos (U.S.G.S., 1960) and Pearsonia topographic maps (U.S.G.S., 1973). Two categories of streams were delineated: 1) permanently flowing streams (solid blue lines on the topographic maps); 2) intermittently flowing streams (dashed blue lines on the topographic maps).

All 39 soil series occurring within the limits of the study area were digitized and later grouped together based on soil texture. The 1:20,000 soil survey maps were photocopied onto transparent sheets using an 83% reduction to match the 1:24,000 topographic sheets. Transparencies were laid over the topographic maps so that stream and road intersections overlapped and were then digitized. Some adjustment of the transparencies was required from section to section to achieve the best overlap but the process is very similar to zoom transferring.

A raster based GIS (ERDAS) was used to convert raw data into digital format (ERDAS, 1991). All data sets were geo-referenced to a UTM projection because the square grids of this system are more compatible with a raster based GIS than latitude-longitude.

4.2. Creation of GIS Files.

Figure 4.1 illustrates the steps taken to convert each of the four raw data sources into GIS files. Ellipses in the left hand column represent ERDAS modules

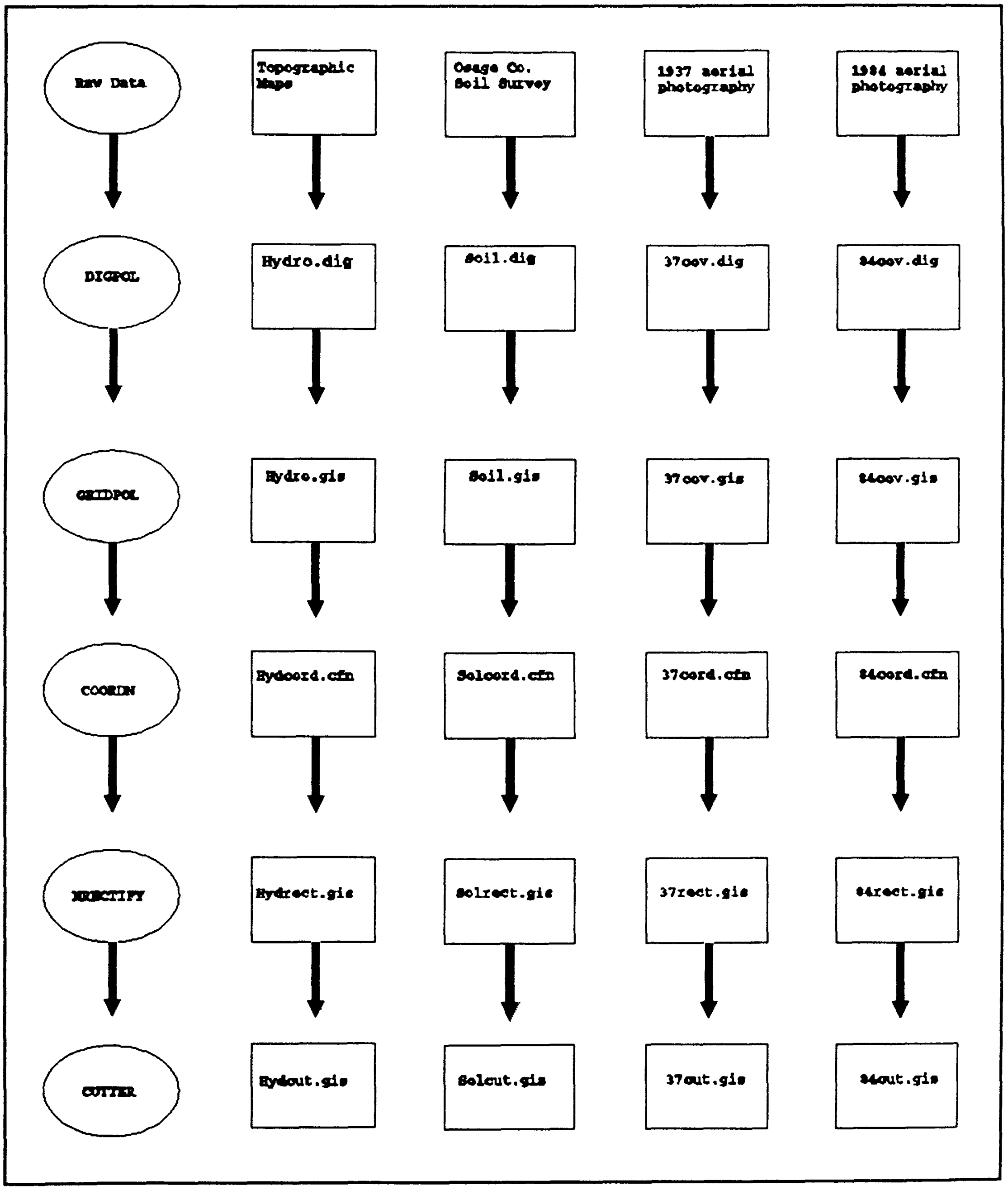


Figure 4.1. Raw Data Conversion.

utilized in the conversion process. The top row of boxes represents each data source and each box down a column represents a file that was created in ERDAS.

4.2a. Digitizing and Rasterization of Raw Data.

Row two of figure 4.1 represents the only vector files generated, each created with DIGPOL, the ERDAS module used for manually digitizing maps. Map set up is the first step in digitizing with DIGPOL. After map scale and projection (UTM) has been specified, an x-axis map coordinate and a y-axis map coordinate are input. The values for these coordinates are entered from the map and three points are digitized with the digitizing puck; left and right reference coordinates which define the y-axis, and a bottom reference coordinate defining the x-axis. DIGPOL also incorporates a 'test accuracy' option in map set up. Using this option it was found that accuracy varied less than 5 meters near the map reference points but could vary 15-30 meters away from the points. This variation is apparently caused by the fact that DIGPOL allows only three map reference coordinates to be entered. The average error from several trial runs was determined to be 22m.

Because ERDAS does not provide other options to improve upon map set up error, a 20m x 20m grid cell size was selected. Rasterization of the vector files was accomplished by using the GRIDPOL module. This process involves entering the desired pixel size, the vector file to be rasterized, and the resulting file name. Individual pixels are automatically assigned x,y file memory values which correspond to row and column position, x,y map coordinates for the pixel center, and a class value.

4.2b. Data registration. Ideally, after the initial gridding process, all data layers should cover the same geographic area. However, spatial error introduced during the interpretation of aerial photographs, differences in photographic scale, inherent geometric distortion in aerial photographs, and human error in the digitizing process can cause data layers to differ from each other. The process of making two or more GIS files conform to one another is referred to as registration and involves three basic steps: 1) selecting ground control points (gcp's) from each image and constructing gcp files; 2) computing a transformation matrix to determine the best fit between files; 3) creating output files with new coordinate systems (ERDAS, 1991).

A gcp is a specific point on the earth for which the x,y map coordinates are known. In a raster file a gcp refers to a specific pixel. In ERDAS, it is necessary to make a gcp file for each GIS file that is to be registered. A gcp file contains information about each gcp pixels, including: 1) source coordinates which give the location of a gcp pixel in the source file; 2) reference coordinates which give the location that the gcp pixel should occupy to conform to another file.

The gcp file is used in the module COORDN to transform the source coordinates to rectified coordinates. Rectified coordinates are the best possible fit between source and reference coordinates. COORDN achieves this fit by constructing a transformation matrix which contains a polynomial equation for each gcp. The exponent used in the polynomial equation determines transformation order. First through tenth order transformations are possible, however, transformations greater than second order achieve a fit by warping cells between gcp pixels. A second order linear transformation was used in this research to avoid problems with pixel warping and to achieve a better fit than a first order transformation.

In addition to specifying transformation order, COORDN requires that an error tolerance be specified to complete the transformation matrix. Error is measured by the root mean square (RMS) method and is given as a distance in pixels between each source coordinate and its corresponding rectified coordinate. All GIS files that were registered for this research had an RMS error of less than one pixel.

The final step in registration utilizes the module NRECTIFY. This module creates a new GIS file with a new grid system with coordinates determined by the transformation matrix generated in COORDN. NRECTIFY transfers class value information from each pixel of the source file to the new grid system. The nearest neighbor method is used when pixel data are qualitative because other methods use averaging techniques for transferring information. After new GIS files have been created, manipulation can begin to extract information.

4.2c. Applying registration techniques. To ensure that each of the four data layers covered the same geographic space, 35 gcp's were included in the digitized versions of the 1937 and 1984 aerial photography, hydrology, and soil files. The gcp's consisted of road intersections and stream intersections which were identifiable in each of the raw data sets. This approach has the advantage of allowing the location of the gcp's to be known before hand, therefore no guesswork is involved in determining coordinates. When the raw data sources were digitized gcp's were entered as points; after these files were rasterized, each gcp occupied one pixel.

The 1937 data set was arbitrarily selected to redigitize first and to register all other files to this one. Gcp files were created for each GIS file; source coordinates were determined by loading the 1937 image on screen, finding each of the 35 gcp pixels, and recording their coordinates. For subsequent images this process was repeated with source coordinates being determined from the image on screen and reference coordinates entered from the 1937 file. As a result, the source coordinates for a particular gcp varied from file to file but had the same reference coordinates in all files.

After gcp files were created for each of the four GIS files, transformation matrices were generated with COORDN, and new GIS files were created with NRECTIFY. A study area boundary was laid over each of the four registered GIS files with the module CUTTER, removing pixels outside the study area. The final row of boxes in figure 4.1 represents four GIS files that have been geo-referenced to a common coordinate system, gridded to a 20m x 20m pixel size, registered to each other using a second order transformation, and delineated by a common boundary.

4.3. GIS Operations.

GIS in this research was used for data manipulation in order to: 1) compute the total area covered by each land cover category for both time periods; 2) separate forests into mesic and xeric categories; 3) identify forest patches; 4) identify areas of forest common to 1937 and 1984; 5) compare the distribution of forests with soil texture.

Area measurements of land cover categories were made from the 37cut.gis and 84cut.gis files by utilizing the DSCASCII module in ERDAS. DSCASCII generates a text file in ascii format which gives the total number of pixels occupied by each of the land cover categories. These data were exported into a spreadsheet program for further analysis. In the spreadsheet, a contingency table was constructed to compare relative percentages of 1937 scattered, intermediate, and dense forests with 1984 scattered, intermediate, and dense forests.

4.3a. Identification of mesic and xeric sites. As discussed previously, floodplain forests on mesic sites are often quite different from upland forests on xeric sites in terms of forest density and species composition. Because of these differences, mesic and xeric sites were distinguished by combining hydrology and soils data; 1937 and 1984 forests were then divided into mesic and xeric categories for separate analysis (figure 4.2; plate 3; plate 11).

To identify mesic sites, RECODE was used to create separate permanent and intermittent stream GIS files; a buffer zone 60m wide was created around permanent streams using the ERDAS module SEARCH, while intermittent stream data were not modified. Previously, the rasterization process transformed streams from linear vectors into a series of connecting 20m x 20m cells. In creating a 60m buffer zone around permanent streams, SEARCH performed a proximity analysis which identified pixels that were one pixel away from permanent streams. The 60m zone is actually a three pixel strip with the stream pixel located in the middle. Intermittent streams were then recombined with the permanent stream buffer zone forming the file, hydbuf.gis.

The choice of creating a buffer zone for permanent streams while leaving intermittent streams unaltered was determined from field experience and partially by software limitations. Undoubtedly some areas falling within an intermittent stream pixel are not truly mesic sites, or only a small percentage of the pixel may be mesic. However, some mesic sites, particularly at the confluence of several intermittent streams, will be overlooked. Similar problems exist with the permanent streams.

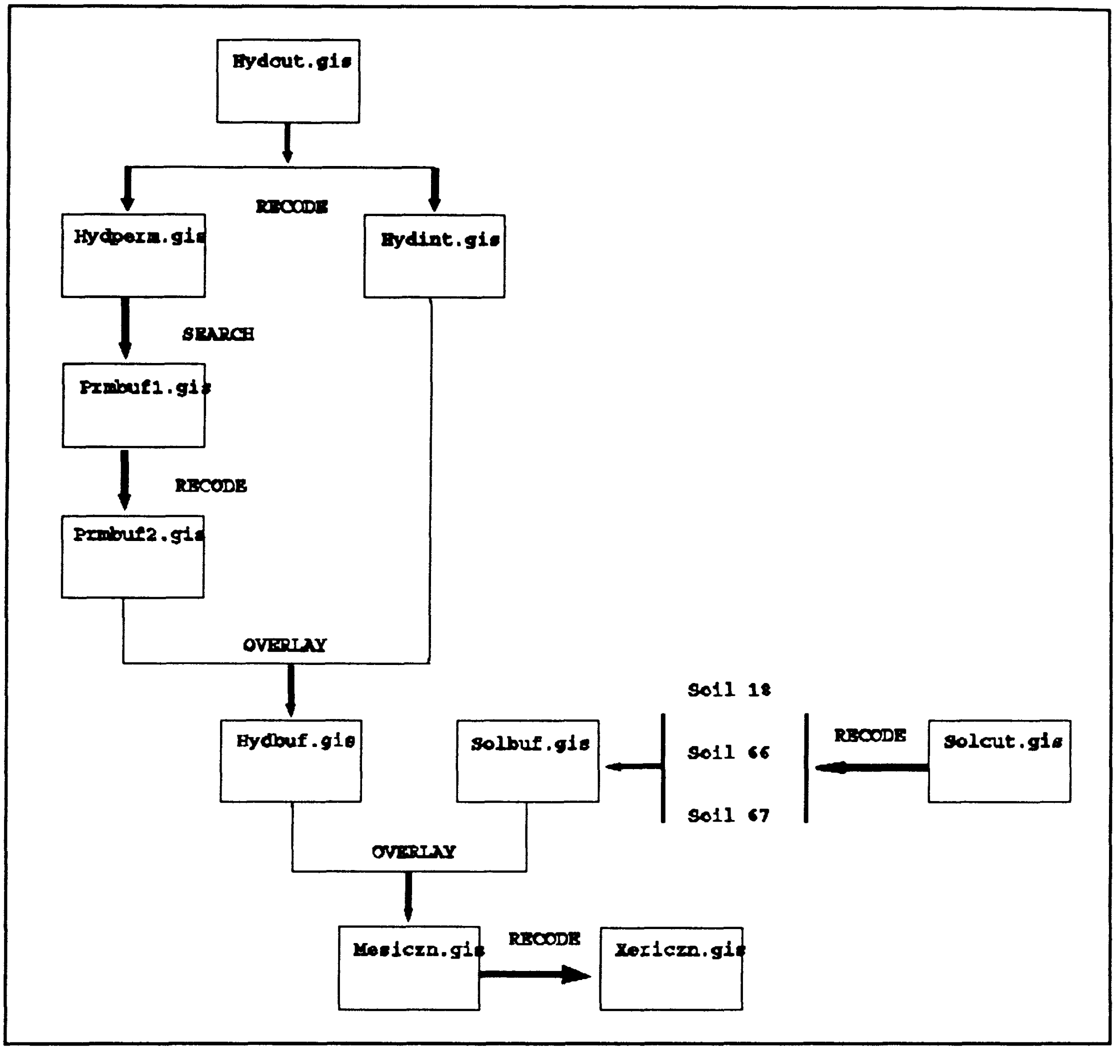


Figure 4.2. Generation of Mesic and Xeric Zones.

Because SEARCH can only analyze complete pixels, a one pixel search results in a 60m zone and a two pixel search results in a 100m zone. A 60m zone for intermittent streams seemed too large and a 100m zone seemed too large for permanent streams. To improve upon mesic site identification, hydrology was combined with soils data.

The soil types shown in figure 4.2 are flood plain soils listed as frequently flooded by the Osage County Soil Survey; flood plain soils listed as rarely or occasionally flooded were not included because it was felt that the mesic portions of these soils would be incorporated under the hydrology buffer zone. At completion, two GIS files were created: 1) mesiczn, in which pixels occurring on mesic sites have values of one and xeric sites have a value of zero; 2) xericzn, which contains the same information except mesic sites have values of zero and xeric sites have values of one.

After identifying mesic and xeric sites, this information was overlayed with the 1937cut and 1984cut files to separate forests into mesic and xeric categories. Ascii files were created with DSCASCII, imported into a spreadsheet and contingency tables were constructed. Contingency tables were used to calculate expected frequencies for each category so that comparisons could be made between mesic and xeric sites within each time period in addition to comparing change in mesic and xeric sites between time periods.

4.3b. Patch analysis. A very useful function of ERDAS software is its ability to identify groups or clumps of pixels that belong to one class. The module CLUMP groups pixels of a selected class value, numbers the groups sequentially, and outputs a new GIS file with sequential numbers replacing class values; pixels not falling within a group are recoded to zero in the output file. To determine contiguous pixels, CLUMP requires that a connectivity radius be specified. A connectivity radius is the maximum distance (in pixels) that pixels can be from each other and still be considered contiguous. A connectivity radius of 1.0 includes four pixels around a center pixel (above, below and to each side); a connectivity radius of 1.5 would include diagonal pixels (eight pixels). CLUMP was used with a connectivity radius of 1.0 to identify forest patches for 1937 and 1984 (figure 4.3). This choice results in more single pixel patches being identified than would a connectivity radius of 1.5, however, there is a more stringent requirement for patch inclusion. Also, using a larger connectivity radius generalizes the data to a greater degree, thus losing information. Figure 4.3 represents the file manipulations employed to identify forest patches.

For brevity, only the manipulation of 1937 files is discussed here, however, 1984 files received identical treatments. Notice that an additional forest category, all-

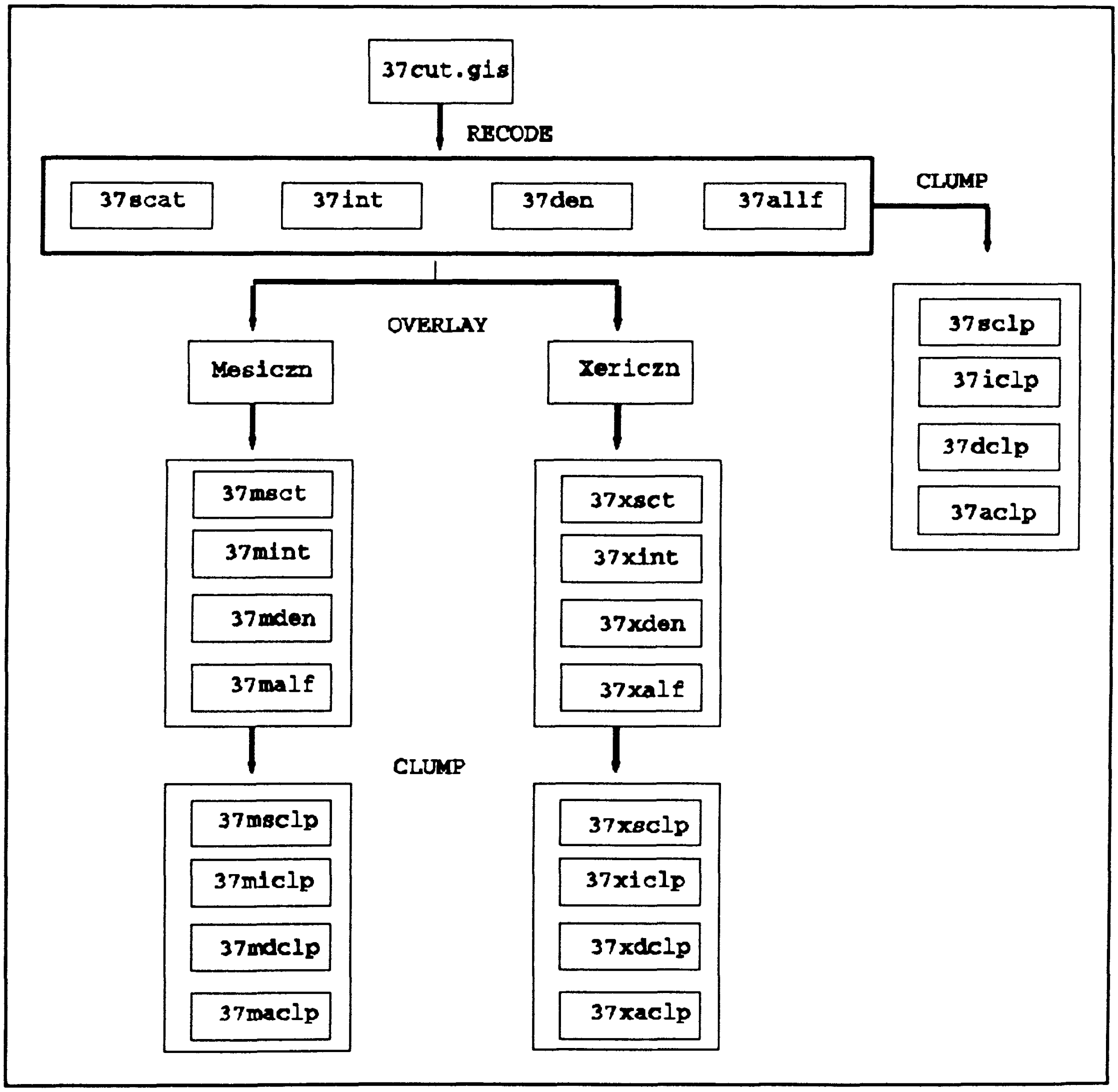


Figure 4.3. Patch Identification.

forest, has been created by combining scattered, intermediate, and dense forest categories. This was done to allow patch analysis of forests as a whole while retaining information about forest density. For each forest category (all, scattered, intermediate, and dense) three types of patches were identified: 1) patches on mesic sites; 2) patches on xeric sites; 3) patches not separated into mesic and xeric categories. Data for all these files were output using DSCASCII and imported into SAS statistical software (SAS Institute, 1985). The Wilcoxon rank sum test was used to compare differences in forest patch size distribution between mesic and xeric sites for each time period as well as comparing forest patches between time periods.

4.3c. Identifying changed and unchanged forest. The 1937 and 1984 land cover files were manipulated so that forested pixels common to both study periods could be identified. To accomplish this, the 1937cut and 1984cut GIS files were analyzed with the module MATRIX. The operation of MATRIX is illustrated in figure 4.4. MATRIX produces a new GIS file containing class values which indicates overlap in class values of the two original GIS files. The new GIS file created, 3784mat, was entered into a second matrix analysis with soil texture (figure 4.5). This procedure produces a GIS file with new class variables based on forest overlap and soil texture. Data were output using DSCASCII and exported into a spreadsheet program.

	1937 Forest		
1984 Forest	Scattered	Intermediate	Dense
Scattered	Class 1	Class 2	Class 3
Intermediate	Class 4	Class 5	Class 6
Dense	Class 7	Class 8	Class 9

Figure 4.4. Operation of Matrix.

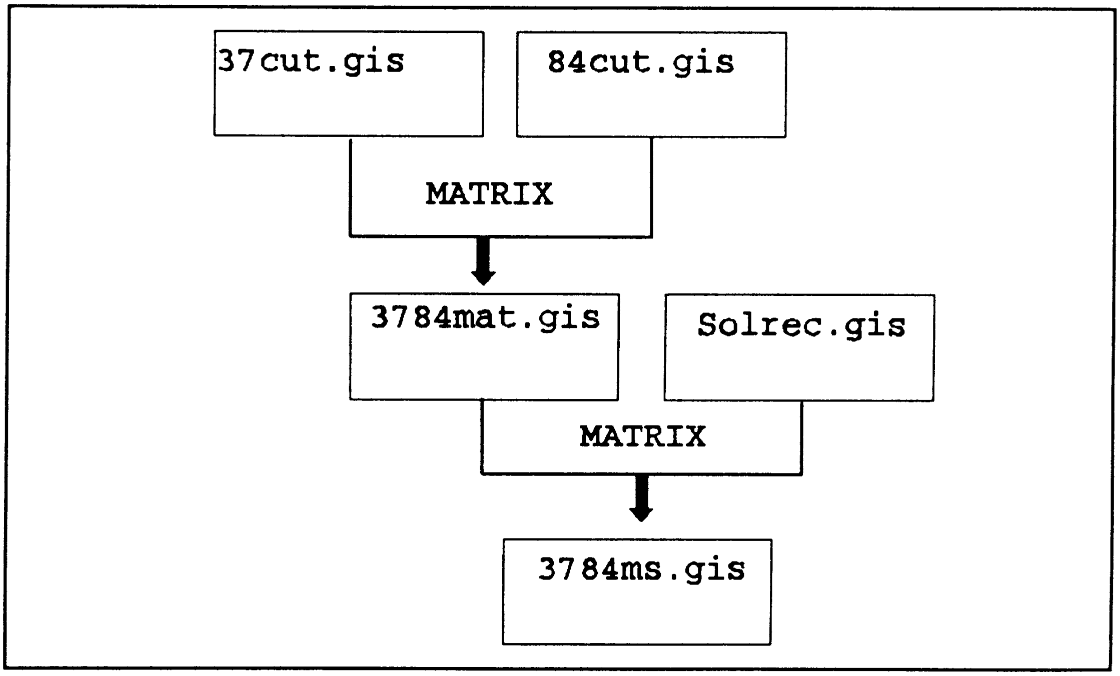


Figure 4.5. Identification of Forest/Soil Overlap.

CHAPTER 5

RESULTS

5.1. Area Measurements.

One of the most basic outputs of a GIS is simple measurement of land cover classes. Total area covered by each forest category and grassland in 1937 and 1984 are listed in table 5.1 (see also plate 1, plate 2). The heading 'All Forest' groups all forest types together, regardless of density or site. The 'Mesic' and 'Xeric' subheadings separate forests by site but not density. The 'Scattered', 'Intermediate', and 'Dense' headings divide forests by density only. Finally, forests are categorized by both density and site under the remaining 'Mesic' and 'Xeric' subheadings.

It was somewhat surprising to find total forest coverage had decreased between 1937 and 1984. An equally interesting aspect of the data is the nearly six fold increase in 1984 dense-xeric forest. While overall changes in area can be determined, the data structure allows change to be analyzed according to site and density.

Beginning with the broadest grouping possible, figure 5.1a shows that the distribution of all 1937 and 1984 forest types by site is practically identical. This indicates that decrease in total forest coverage occurred proportionally on xeric and mesic sites. The distribution of forest density categories independent of site, however, has changed (figure 5.2a and 5.2b). To determine if a pattern exists, further analysis

	Total Coverage (ha)		Total Change (ha) (1984-1937)
	1937	1984	
All Forest	2184.8	1668.9	-515.9
Mesic	469.2	368.1	-101.1
Xeric	1715.6	1300.8	-414.8
Scattered Forest	1515.0	787.4	-727.6
Mesic	194.6	159.8	-34.8
Xeric	1320.4	627.6	-692.8
Intermediate Forest	533.8	409.8	-124.0
Mesic	195.2	120.2	-75.0
Xeric	338.6	289.6	-49.0
Dense Forest	136.0	471.7	335.7
Mesic	79.5	88.0	8.5
Xeric	56.5	383.7	327.2
Grassland	12368.3	13013.9	645.6

Table 5.1. Total coverage (ha) and total change (ha) for 1937 and 1984 forest and grassland.

is needed.

One possible approach is to consider the distribution of the forest density types by the site in which they occur. The distribution of forest density types by site for 1937 and 1984 are shown in figures 5.1b and 5.1c, respectively. The most apparent trend shown here is the increase in percent of dense forest occurring on xeric sites. The relationship between forest density and site can be pursued further by isolating the site.

Figure 5.2 c-f illustrates the composition of 1937 and 1984 mesic and xeric

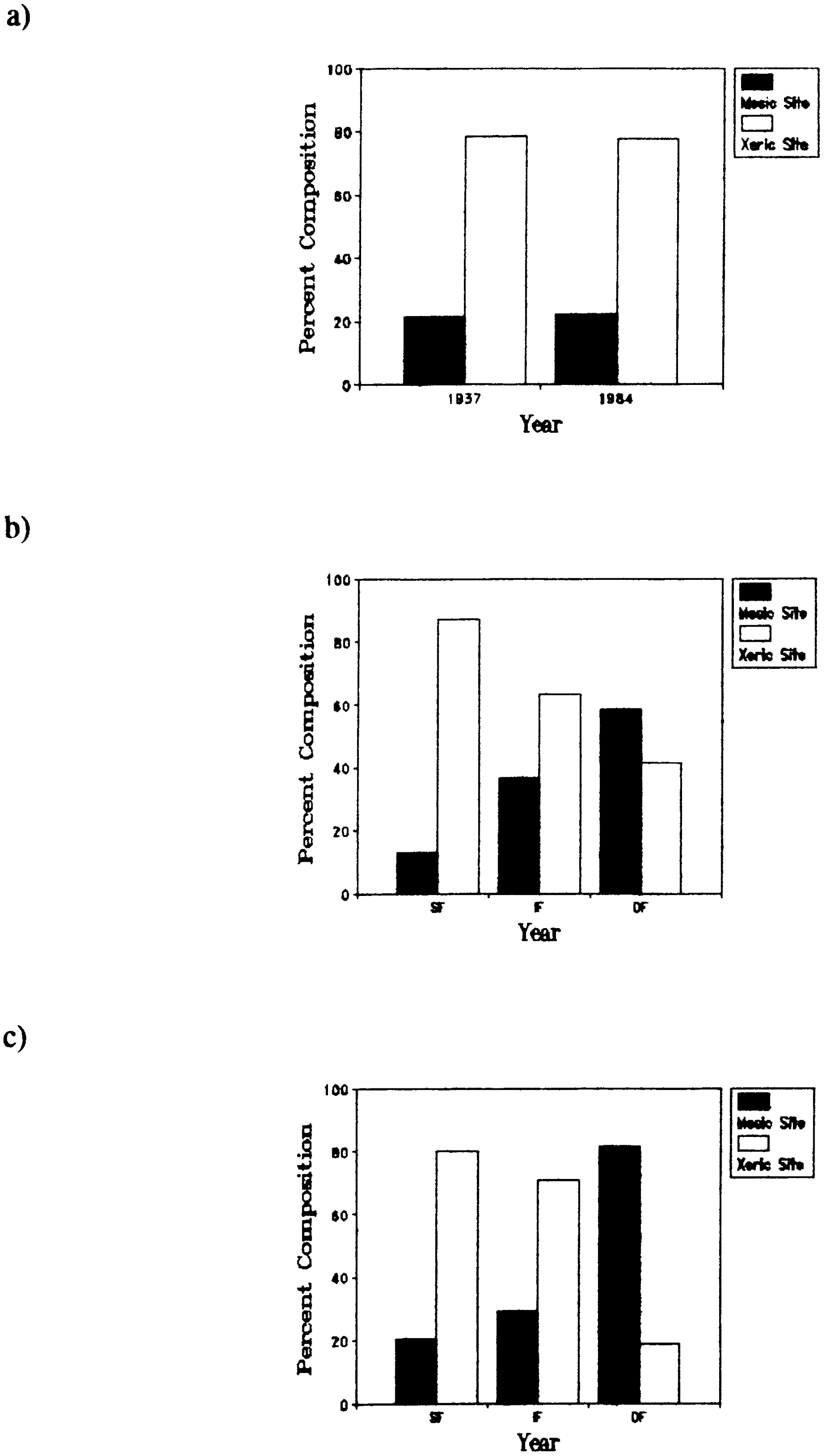


Figure 5.1. Percent mesic and xeric composition of (a) All 1937 and 1984 forests, (b) 1937 forest density classes, (c) 1984 forest density classes.

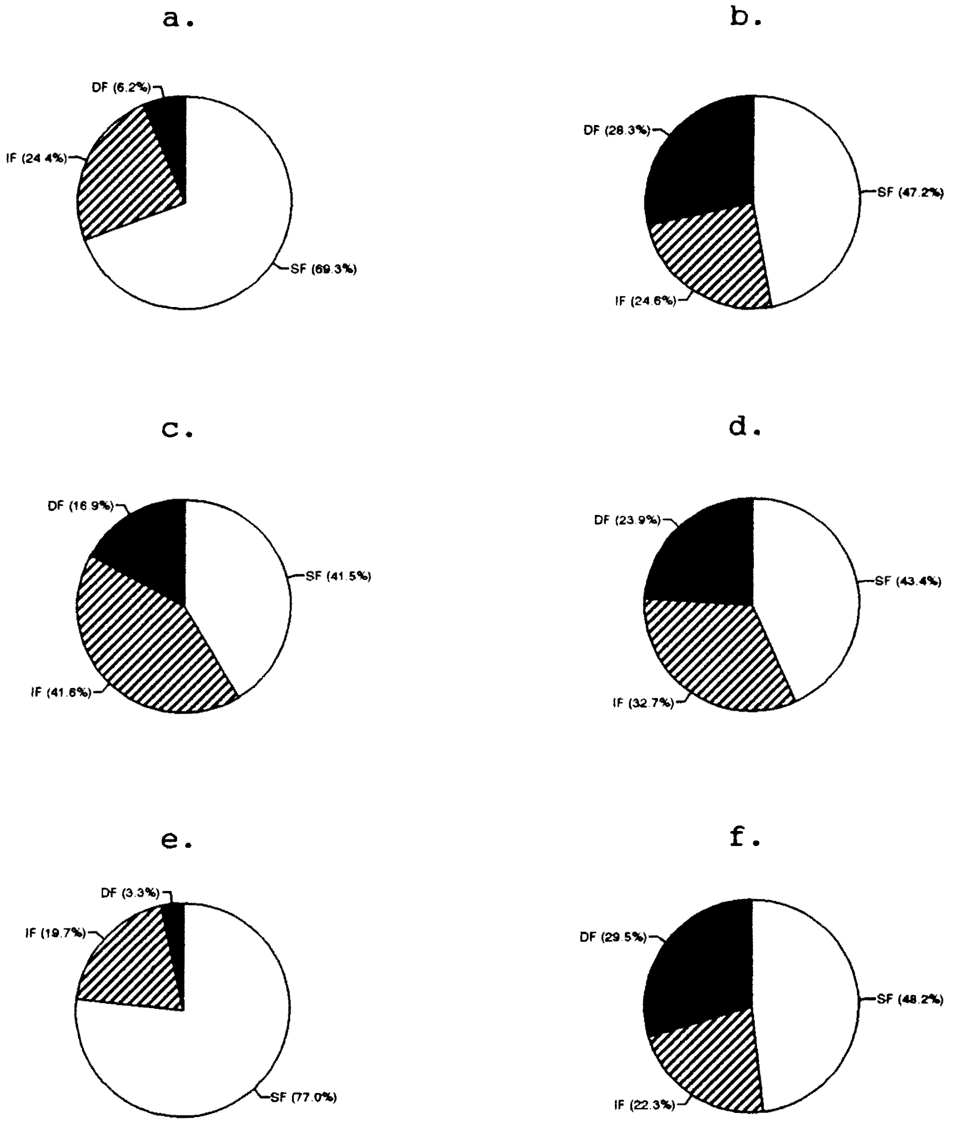


Figure 5.2. Percent scattered forest (SF), intermediate forest (IF), and dense forest (DF) of (a) 1937 all-forest; (b) 1984 all-forest; (c) 1937 mesic sites; (d) 1984 mesic sites; (e) 1937 xeric sites; (f) 1984 xeric sites.

sites according to forest density. Comparing 5.2c with 5.2e reveals that in 1937 mesic sites tended to have higher frequencies of dense and intermediate forests while xeric sites were composed primarily of scattered forest. In 1984 this trend was nearly reversed; figures 5.2d and 5.2f show that dense forest was proportionately more common on xeric sites than mesic sites and scattered forest was only slightly more common on xeric sites. Examining change in site composition between time periods (i.e., 5.2c vs. 5.2d, and 5.2e vs. 5.2f) indicates that both xeric and mesic sites underwent changes in the distribution of forest types between study periods. Additionally, it appears that mesic sites have experienced less change between time periods relative to change occurring on xeric sites.

5.1a. Analysis of area data. Area data were analyzed in a contingency table to evaluate differences in forest coverage between mesic and xeric sites for each study period and also to compare changes between study periods (Table 5.2). A ratio of observed versus expected values was calculated for each cell of the contingency table; a value of 1.0 would indicate no difference. This method allows trends in the data to be described but because there is no distribution to compare ratio values with, no statistical significance can be implied. Therefore, ratio values were used comparatively to determine relative differences between data sets by identifying the ratios that varied most from expected.

Observed values for 1937 xeric versus 1937 mesic and 1937 xeric versus 1984 xeric differed more from expected than did 1937 mesic versus 1984 mesic sites. This indicates that mesic site forests changed little between study periods relative to xeric site forests. Furthermore, 1984 dense forest ratios varied more from expected than

	Scattered Forest	Intermediate Forest	Dense Forest
1937 xeric	1320.4 (1189.6)	338.6 (419.1)	56.5 (106.8)
1937 mesic	194.6 (325.4)	195.2 (114.7)	79.5 (29.2)
$\frac{\text{Obs.}}{\text{Exp.}}$	1.1	0.8	0.5
	0.6	1.7	2.7
1984 xeric	627.6 (613.8)	289.6 (319.4)	383.7 (367.7)
1984 mesic	159.8 (173.6)	120.2 (90.4)	88.0 (104.0)
$\frac{\text{Obs.}}{\text{Exp.}}$	1.02	0.9	1.0
	0.9	1.3	2.7
1937 xeric	1320.4 (1107.9)	338.6 (357.3)	56.5 (250.4)
1984 xeric	627.6 (840.1)	289.6 (270.9)	383.7 (189.8)
$\frac{\text{Obs.}}{\text{Exp.}}$	1.2	1.0	0.2
	0.8	1.1	2.0
1937 mesic	194.6 (198.6)	195.2 (176.8)	79.5 (93.9)
1984 mesic	159.8 (155.8)	120.2 (138.6)	88.0 (73.6)
$\frac{(O-E)^2}{E}$	1.0	1.1	0.9
	1.0	0.9	1.2

Table 5.2. Contingency table analysis of forest area data. Expected values in parentheses.

did the other forest classes. Additionally, the data suggest that in 1937 mesic and xeric sites were very different in terms of forest density composition but have become more similar through time. This change then can be attributed to the increase in dense xeric forest. While total area gained by dense forest was a small percentage of the total forest, it was sufficient to cause a shift in overall forest density composition.

5.2. Patch Analysis.

The results of forest patch (clump) analysis are summarized in table 5.3. Note that the number of patches are not additive; i.e., the sum of 1937 scattered, intermediate, and dense forest patches is not equal to the number of all forest patches. This is caused by the operation of the ERDAS module CLUMP. For example, there may be clumps of scattered, intermediate, and dense forest which border one another; when clumping according to forest density class values these would be counted as three separate patches. However, when clumping all-forest regardless of forest density classification, only one clump is counted. Similarly, mesic and xeric clumps are not additive.

A trend was noted for 1937 forests to have fewer and larger patches. A notable exception to this trend is the dense forest category which has more and larger patches in 1984. Also, in 1937 scattered forests had more patches and a larger mean patch size than intermediate forests, which in turn had more patches and a larger mean patch size than dense forests (i.e., the number of patches and mean patch size decrease with increasing forest density). In 1984 the number of patches also decreased with increasing forest density but average patch size increased with forest density. This suggests that dense forest not only gained in overall area, but individual patches also

	N		Mean (ha)		Std. Dev. (ha)		Median (ha)		Maximum (ha)		Prob> Z (median)
	1937	1984	1937	1984	1937	1984	1937	1984	1937	1984	
All Forest	106	157	20.6	10.6	105.0	59.4	1.1	0.8	680.5	711.0	0.12
Mesic	452	411	1.0	0.9	8.6	5.8	0.1	0.1	147.1	107.5	0.77
Xeric	283	322	6.1	4.0	21.4	14.7	0.3	0.4	202.2	148.3	0.47
Scattered	115	201	13.2	3.9	36.1	10.1	1.0	0.8	217.2	77.4	0.17
Mesic	338	279	0.6	0.6	2.6	1.7	0.1	0.1	40.3	15.9	0.97
Xeric	240	310	5.5	2.0	17.1	4.9	0.4	0.4	189.8	48.0	0.71
Intermediate	98	87	5.4	4.7	20.7	14.9	1.1	1.6	188.2	120.2	0.10
Mesic	204	136	1.0	0.9	2.8	2.7	0.1	0.1	19.3	23.5	0.80
Xeric	197	150	1.7	1.9	5.8	6.5	0.1	0.3	48.6	56.4	0.02
Dense	40	42	3.4	11.2	6.2	56.8	1.3	0.8	32.4	369.9	0.19
Mesic	60	114	1.3	0.8	3.2	4.6	0.1	0.1	17.5	46.8	0.02
Xeric	60	77	0.9	5.0	2.2	18.8	0.2	0.2	14.8	137.1	0.23

Table 5.3. Summary statistics of forest patch data.

consolidated between study periods. Conversely, scattered and intermediate forests lost overall area and individual patches were smaller.

5.2a. Statistical analysis of forest patch data. Because of the large standard deviations present in the data, median values were used in Wilcoxon rank sum tests to determine differences in patch size distribution between study periods (table 5.3). The results of these tests are difficult to interpret because no clear trend emerged. Only intermediate xeric forest and dense mesic forest showed significant differences between study periods with $\alpha = .05$. However, when comparing graphs of forest patch size distribution (figures 5.3 through 5.6) it is not entirely clear why these categories are statistically different and others (esp. dense xeric forest) are not. For instance, intermediate mesic forests (figure 5.5b) appear to have a similar distribution to that of intermediate xeric forests (figure 5.5c), yet p-values for these categories are quite different. Similarly, dense xeric forests (figure 5.6c) exhibits a patch size distribution comparable to that of dense mesic forest (figure 5.5b) but again, p-values are quite different. Overall, it appears that both intermediate and dense forests experienced some changes in patch size distribution between study periods. The trend for intermediate forests was towards fewer, smaller patches in 1984. For dense forest total number of patches only increased by two but mean patch size was much larger in 1984. Dense mesic and xeric categories, showed more patches in 1984 and mean patch size was slightly smaller in 1984 on mesic sites but much larger on xeric sites.

5.3. Unchanged Forest and Grassland.

Analysis of 1937 and 1984 mesic and xeric sites revealed differences in the tendencies of forest and grassland to remain unchanged, to be retained, and to persist

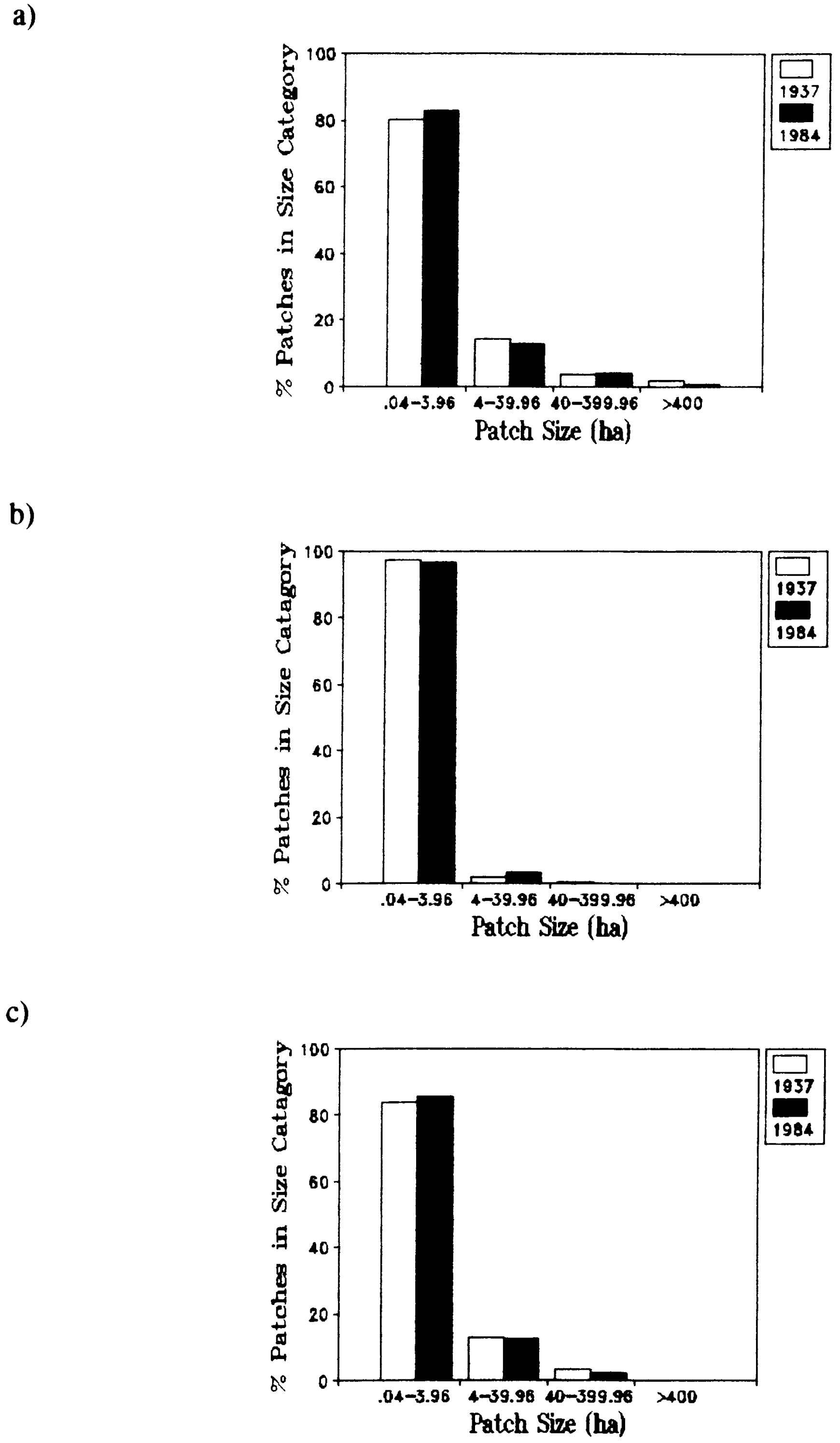


Figure 5.3. Patch size distribution of (a) all 1937 and 1984 forests, (b) all 1937 and 1984 mesic sites, (c) all 1937 and 1984 xeric sites.

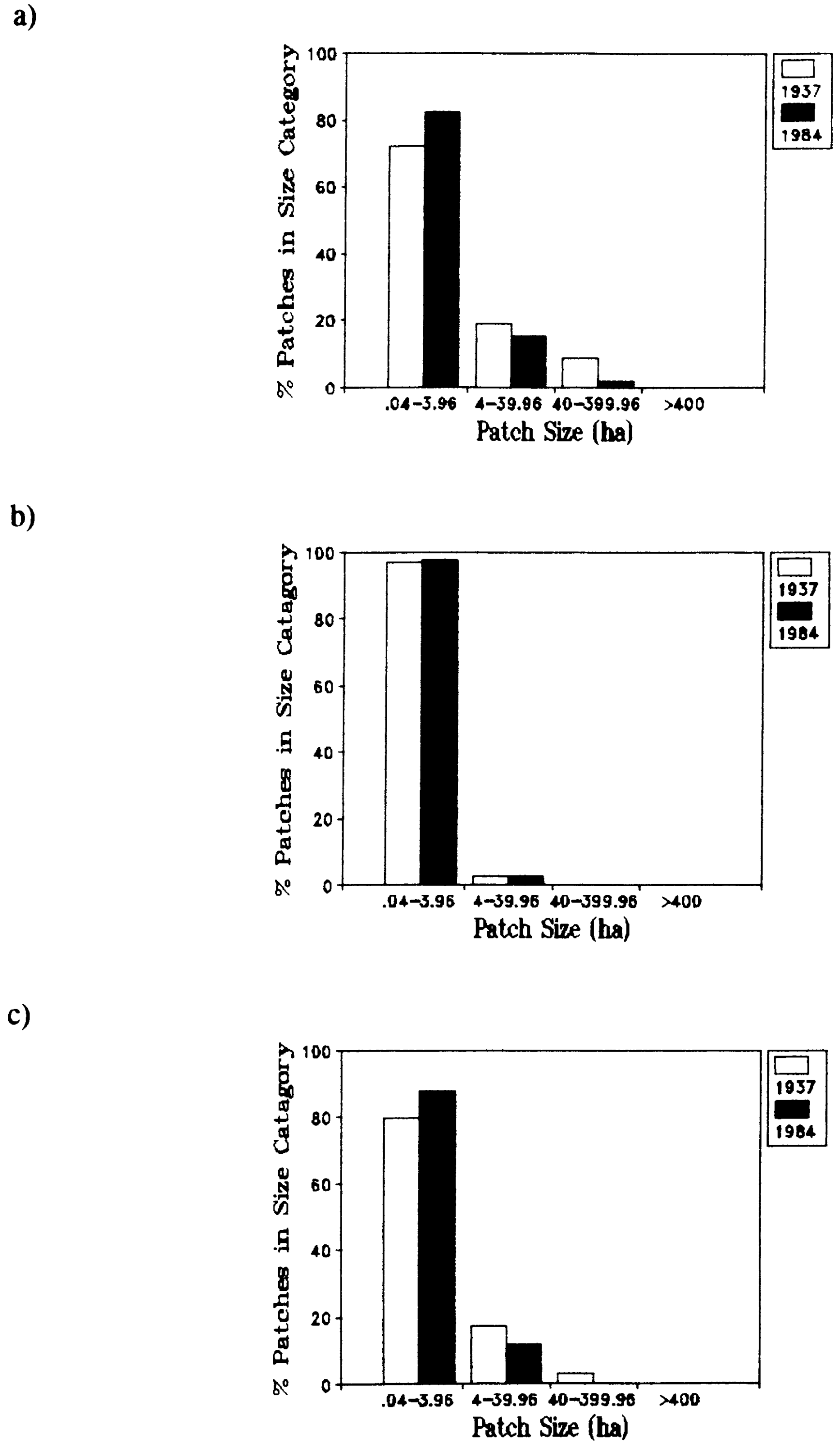


Figure 5.4. Patch size distribution of (a) all 1937 and 1984 scattered forests, (b) all 1937 and 1984 scattered mesic forests, (c) all 1937 and 1984 scattered xeric forests.

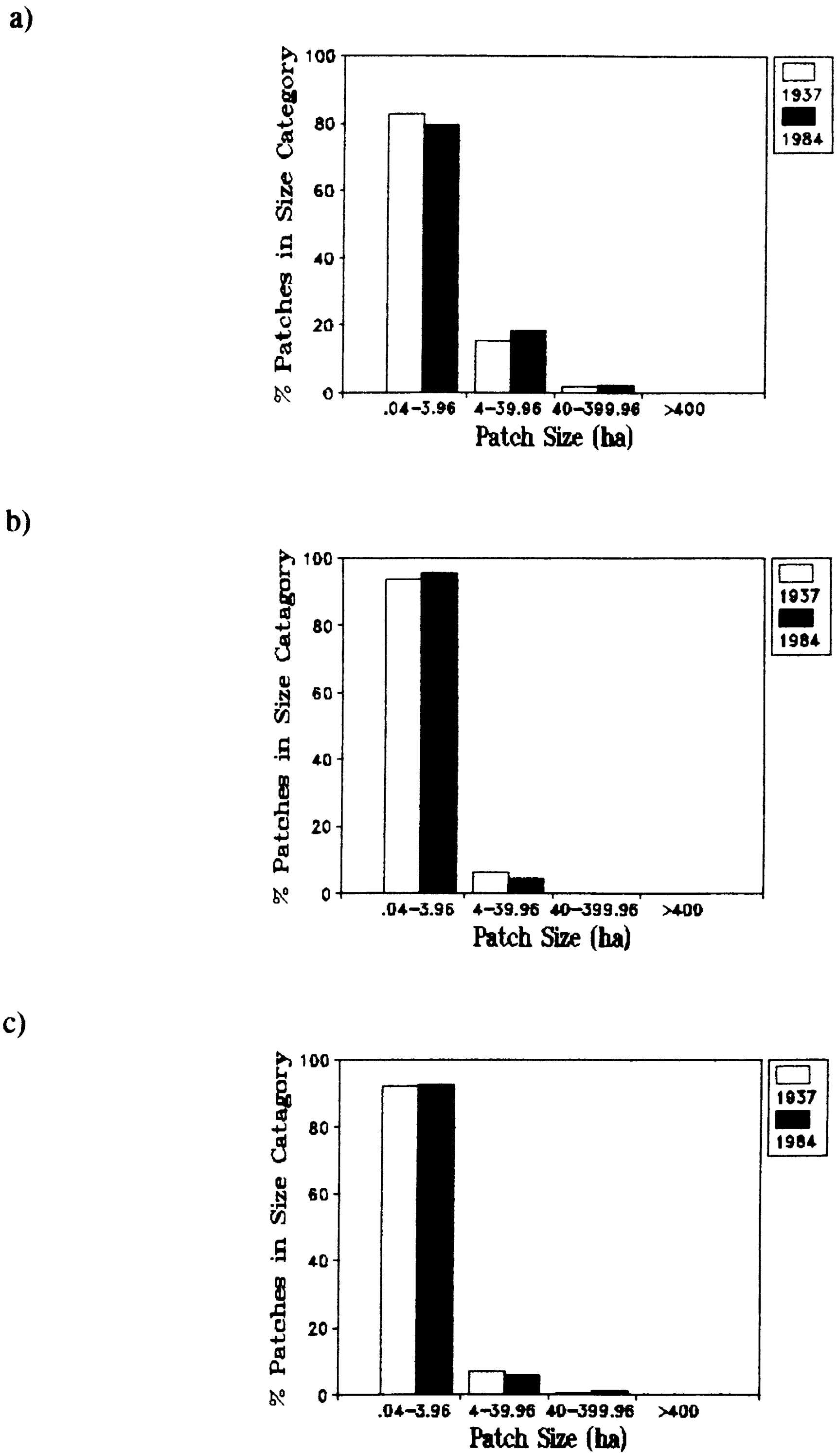


Figure 5.5. Patch size distribution of (a) all 1937 and 1984 intermediate forests, (b) all 1937 and 1984 intermediate mesic forests, (c) all 1937 and 1984 intermediate xeric forests.

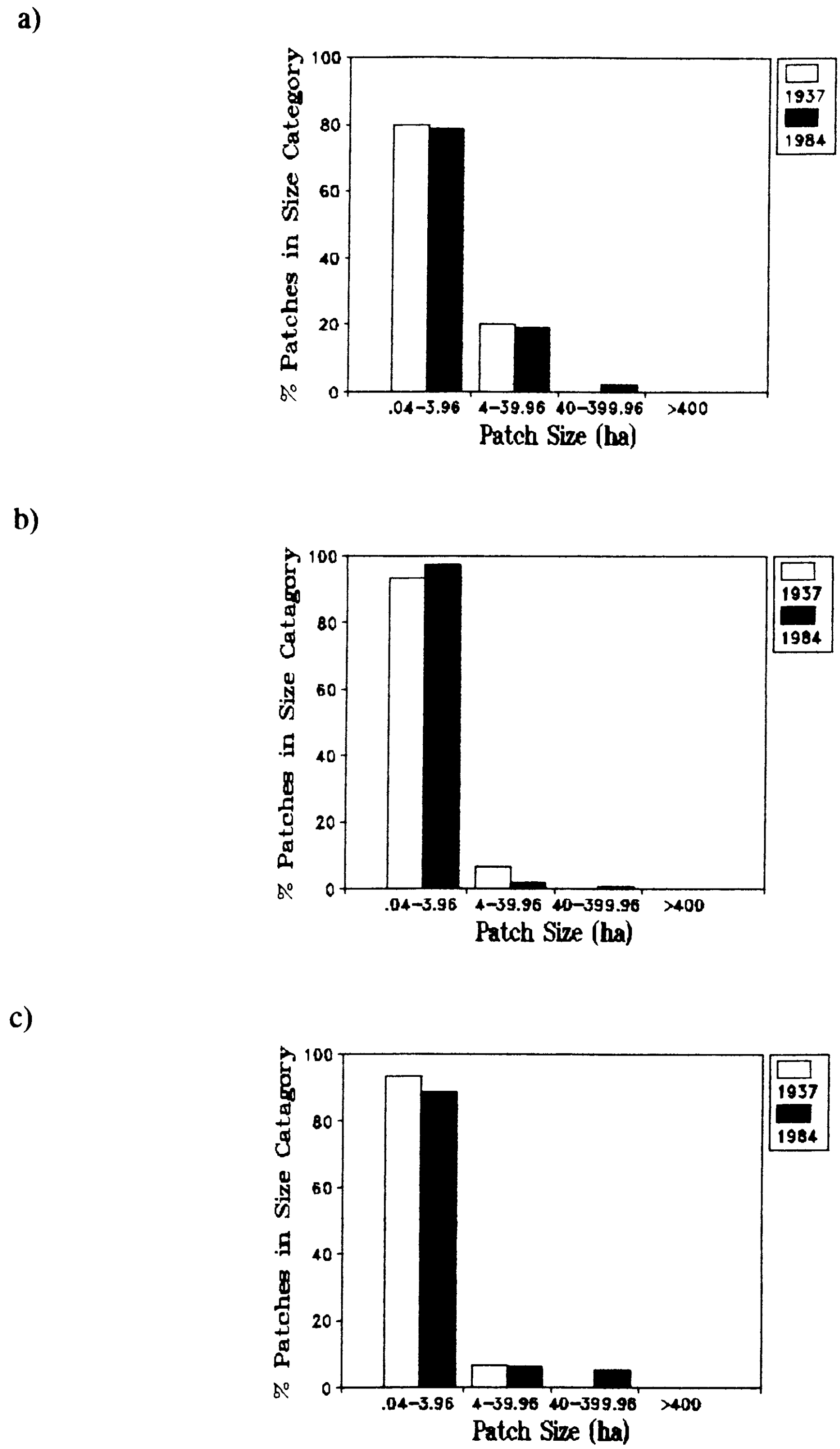


Figure 5.6. Patch size distribution of (a) all 1937 and 1984 dense forests, (b) all 1937 and 1984 dense mesic forests, (c) all 1937 and 1984 dense xeric forests.

(table 5.4, plates 4, 5, and 6). In table 5.4, the unchanged heading represents grid cells that had the same class value in both study periods. Retention values were obtained by dividing the number of unchanged pixels in a particular category by the number of pixels occupied by that category in 1984, thus giving the percentage of that category that was retained from 1937. Persistence values were obtained by dividing the number of unchanged grid cells in a particular category by the number of grid cells occupied by that category in 1937, thus giving the percentage of that category that has persisted into 1984.

Notice that the sum of unchanged scattered, intermediate, and dense forest is not equal to the all-forest category. This is because the all-forest category is independent of forest density; grid cells of 1937 scattered forest, for example, which changed to intermediate or dense forest in 1984 were counted as unchanged all-forest but were not counted under scattered, intermediate or dense. Mesic and xeric subheadings are similarly not additive within groups.

Persistence values were higher than retention values for categories which gained in area (dense forest and grassland). This indicates that dense forest and grassland may have a tendency to remain unchanged while scattered and intermediate forest tended to change to another category. The majority of all forested grid cells in 1984 (81.8%) were forest in 1937. Likewise, most of the 1984 grassland was grassland in 1937 (92.6%). Xeric and mesic sites appeared to follow a similar trend to that of all-forest. Retention and persistence for grassland was higher on xeric sites, as was retention of scattered forest. Other categories had higher retention and persistence values on mesic sites.

a.

	Unchanged (ha)	Retention	Persistence
All forest	1364.6	81.8	62.8
Scattered forest	441.5	56.1	29.2
Intermediate forest	110.1	26.9	20.7
Dense forest	61.2	13.0	45.0
Grassland	12022.2	92.6	97.3

b.

All xeric	1060.3	81.5	61.8
Scattered forest	372.4	59.3	28.6
Intermediate forest	58.5	20.2	17.3
Dense forest	29.7	7.7	52.6
Grassland	10889.3	93.5	97.6

c.

All mesic	304.3	82.7	64.9
Scattered forest	69.0	43.2	35.5
Intermediate forest	51.6	42.9	26.4
Dense forest	31.6	35.9	39.7
Grassland	1132.9	84.8	94.8

Table 5.4. Total area unchanged, retention, and persistence of forest and grassland on (a) all sites, (b) xeric sites, (c) mesic sites.

Individual forest density categories exhibited much less of a tendency to remain unchanged within a class than when all were grouped together. This suggests a trading off between forest types rather than forests changing to grassland or other land cover classes.

5.4. Changed forest and grassland.

The relative amount of 'trading' between land cover categories is given in table 5.5 in which the values listed are total area and percent contribution of 1937 categories to the composition of 1984 categories. Retention for individual forest density categories can be expanded upon by considering the amount of each category that was previously forested. For example, only 13.0% of all 1984 dense forest was retained from 1937 but nearly one half was scattered forest and one third was intermediate forest resulting in a total of 92.4% having been forested (plate 9). 1984 scattered and intermediate forests had higher percentages of unchanged grid cells but lower overall contributions from other forest categories. 74.9% of 1984 scattered forest and 82.9% of intermediate forest was previously forested. Grassland had the greatest percentage of unchanged grid cells and a high persistence.

Differences between xeric and mesic sites were noted for 1984 dense forest which had a relatively high contribution from scattered forest on xeric sites, while dense mesic sites received less from scattered forest. Most 1984 dense xeric forest was previously forested (93.5%) and only 24.9 ha was grassland or other categories. No xeric or mesic forest was composed of less than 70% previously forested areas.

Persistence of 1937 forests can also be expanded upon by considering how much of each category remained forest. By examining table 5.5 column-wise it can be seen that 90.4% of 1937 dense xeric forest and 74.8% of dense mesic forest was forested in 1984. Scattered and intermediate forests had higher overall persistence on mesic sites, though both experienced more transitions with grassland than did dense

a.

1984	1937			
	SF	IF	DF	GL & O
Scattered forest	441.5 (56.1)	126.3 (16.0)	22.1 (2.8)	197.6 (25.1)
Intermediate forest	202.4 (49.4)	110.1 (26.9)	26.84 (6.6)	70.5 (17.1)
Dense forest	220.6 (46.8)	153.6 (32.6)	61.2 (13.0)	36.2 (7.6)
Grassland & other	643.8 (5.0)	130.0 (1.0)	25.4 (0.2)	12207.0 (92.6)

b.

Scattered forest	372.4 (59.3)	81.5 (13.0)	10.9 (1.7)	162.8 (25.9)
Intermediate forest	167.9 (58.0)	58.5 (21.0)	10.3 (3.6)	52.9 (18.3)
Dense forest	210.0 (54.7)	119.2 (31.1)	29.7 (7.7)	24.9 (6.5)
Grassland & other	566.6 (4.8)	155.7 (1.3)	5.4 (0.1)	11031.9 (93.8)

c.

Scattered forest	69.0 (43.2)	44.8 (28.1)	11.2 (7.0)	34.8 (21.8)
Intermediate forest	34.8 (28.9)	51.6 (42.8)	16.5 (13.7)	17.6 (14.6)
Dense forest	10.7 (12.1)	34.4 (39.1)	31.6 (35.9)	11.32 (12.9)
Grassland & other	79.1 (5.8)	60.4 (4.4)	20.0 (1.5)	121.0 (88.3)

Table 5.5. Total area and percent contribution (in parentheses) of 1937 forest and grassland to 1984 (a) all sites, (b) xeric sites, (c) mesic sites.

forest. Significant amounts of 1937 grassland was converted to 1984 forest but even more 1937 forest was lost to grassland resulting in a net loss of forest.

5.5. Forest/Soil Relationships.

Recoding of the original 39 soil series resulted in five soil texture classes (table 5.6, plate 3). Analysis of 1937 and 1984 forests revealed differences in the occurrence of forest types according to soil texture (table 5.7). However, this is to be expected because the identification of soil types by soil survey scientists is heavily influenced by the presence or absence of forest cover. In general, forests in both study periods were most common on stony silt loam soils and least common on loam and silt clay loam soils. Little variation between study periods was detected in the distribution of forest according to soil texture. The relative percentage of all-forest

Soil Texture	Total area (ha)	Percent Coverage
Stony silt loam	3880.6	26.2
Silt loam	4620.1	31.2
Silt clay loam	2621.8	17.7
Loam	2916.0	19.7
Fine sand loam	750.1	5.1

Table 5.6. Total area and percent coverage of soil texture classes.

a)	1937	1984	Change (ha)
Stony silt loam	52.1	55.1	-217.48
Silt loam	16.0	15.6	-87.4
Silt clay loam	4.9	4.5	-30.4
Loam	4.2	3.4	-34.0
Fine sand loam	22.9	21.4	-141.2

b)	1937	1984	Change (ha)
Stony silt loam	56.9	54.4	-431.4
Silt loam	8.1	12.7	-31.1
Silt clay loam	5.2	6.0	-2.6
Loam	5.2	4.0	-47.5
Fine sand loam	24.6	22.9	-191.4

c)	1937	1984	Change (ha)
Stony silt loam	41.9	42.9	-47.0
Silt loam	29.6	22.0	-67.4
Silt clay loam	4.4	5.1	-2.6
Loam	2.2	5.5	10.9
Fine sand loam	21.9	24.5	-16.2

d)	1937	1984	Change (ha)
Stony silt loam	39.0	66.7	260.9
Silt loam	49.8	14.8	2.1
Silt clay loam	3.1	1.6	3.3
Loam	0.3	0.6	2.6
Fine sand loam	7.8	16.3	19.8

Table 5.7. Percent distribution of a) all forest, b) scattered forest, c) intermediate forest, d) dense forest by soil texture classes.

occurring on soil texture types was practically identical for 1937 and 1984. The distribution of scattered and intermediate forest types has likewise changed little between study periods. The exception was dense forest which shifted from being concentrated on silt loam soils in 1937 to stony silt loam soils in 1984. Additionally, most of the dense forest increase occurred on stony silt loam soils.

5.6. Soil and unchanged forest.

The percentage of unchanged forest (retention) comprising 1984 all-forest was shown to be quite large on stony silt loam, silt loam, and fine sandy loam soils (table 5.8). 1984 forests on silt clay loam and loam soils retained smaller percentages of 1937 forest but still retained over 50%. Retention within forest density types tended to be much lower, again suggesting forest-forest trading and/or forest-grassland transitions. Of the individual forest density categories, scattered forest on stony silt loam retained the greatest percentage of 1937 forest while dense forest on silt clay loam and loam soils retained no grid cells from 1937. Retention was greatest for intermediate and dense forests on silt loam soils.

Persistence of 1937 all-forest, scattered, and intermediate forests was much lower than retention but tended to follow a similar pattern, i.e., soil textures with the highest retention tended to have the highest persistence. This trend did not hold for dense forest which had persistence values greater than retention. Persistence of dense forest on fine sandy loam soils was greater than any other category. The anomalous pattern of dense forest can be linked to the fact that dense forest gained area between study periods while all other forest classes decreased. Dense forest exhibited lower retention values because new areas were added in 1984; other forest types had higher

a)	Retention	Persistance	No Change (ha)
Stony silt loam	85.2	68.9	780.7
Silt loam	81.9	61.3	212.5
Silt clay loam	64.4	45.8	48.4
Loam	52.0	32.6	29.7
Fine sand loam	81.2	58.3	289.7

b)	Retention	Persistance	No Change (ha)
Stony silt loam	61.8	30.7	263.6
Silt loam	35.3	28.9	35.2
Silt clay loam	51.0	30.7	24.0
Loam	44.9	17.9	14.1
Fine sand loam	57.4	27.7	102.7

c)	Retention	Persistance	No Change (ha)
Stony silt loam	18.9	14.9	33.2
Silt loam	49.5	28.3	44.5
Silt clay loam	10.8	9.6	2.2
Loam	5.1	9.8	2.2
Fine sand loam	28.9	24.9	29.0

d)	Retention	Persistance	No Change (ha)
Stony silt loam	8.6	51.1	27.0
Silt loam	37.6	38.8	26.2
Silt clay loam	0.0	0.0	0.0
Loam	0.0	0.0	0.0
Fine sand loam	10.4	76.1	8.0

Table 5.8. Percent distribution, retention, and persistance of a) all forest, b) scattered forest, c) intermediate forest, d) dense forest by soil texture classes.

retention values because area was lost. The higher persistence values of dense forest on fine sandy loam and stony silt loam soils indicates that 1937 dense forest on these soils tended to remain forested while some scattered and intermediate forests on these same soils became grassland.

5.7. Soil influence on forest and grassland transitions.

Soil texture appeared to exert at least some influence on forest and grassland transitions (table 5.9). Forest density changes were most common on stony silt loam soils, silt loam, and fine sand loam soils. Conversion of grassland to forest was also most common on the same three soils. Changes occurred proportionately between mesic and xeric sites; 20.3% of forest-forest, 24.0% of grassland to forest, and 20.2% of forest to grassland transitions were on mesic sites. Higher soil moisture levels favoring woody growth may explain the slightly larger percentage of grass to forest conversions on mesic sites.

Forest loss was consistency higher on all soils than forest gain but soils with large forest losses also tended to have large forest gains and large forest density transitions. Trading between forest density classes and between forest and grassland may be evidence of natural shifts in vegetational boundaries caused by factors such as herbivory or climate. Also, transitions may be data artifacts caused by coding or spatial errors, i.e., a pixel actually did not change forest density but was interpreted incorrectly from the aerial photographs, or data layers were not registered properly and transitions are shown which did not occur.

Plate 6 shows that grassland to forest transitions rarely occur in distinct patches but are usually associated with other changes. Large distinct patches of forest to

a.

	Forest to Forest	Forest to Grass	Grass to Forest
Stony silt loam	456.9	135.2	352.8
Silt loam	106.6	47.0	134.3
Silt clay loam	22.1	26.8	57.2
Loam	14.4	29.0	61.7
Fine sand loam	150.0	66.3	207.1

b.

Stony silt loam	430.0	129.0	329.7
Silt loam	8.2	5.1	21.9
Silt clay loam	16.7	22.3	42.2
Loam	9.7	26.4	52.8
Fine sand loam	133.3	57.8	202.1

c.

Stony silt loam	26.9	6.2	23.1
Silt loam	98.4	41.9	112.4
Silt clay loam	5.4	4.5	15.0
Loam	4.7	2.6	8.9
Fine sand loam	16.7	8.5	5.0

Table 5.9. Forest and grassland transitions by soil texture type.

forest transitions are found towards the southeast corner of the study area and distinct patches of forest loss can be found in many places, particularly towards the northwest. In several areas forest loss, forest gain, and forest density transitions are found side by side. A region in the south-central portion of the study area where this occurs is known to have been herbicided in the past (Bob Hamilton, pers. comm.).

Differences in herbicide application and/or effectiveness coupled with cattle grazing may be responsible for shifts in vegetational boundaries in some areas. Transitions were wide-spread across the landscape and do not appear to posses any particular pattern.

5.8. Conclusions.

Analysis of change in forest coverage between 1937 and 1984 within the TPP identified differences in total area, percent distribution of forest density categories, and differences between mesic and xeric sites. Differences were also detected in patch size distribution between study periods, though results were somewhat ambiguous. It was determined that soil texture does influence the retention and persistence of forests through time. Transitions between forest density classes and forest and grassland also seemed to be influenced by soil texture.

Total forest area decreased between 1937 and 1984 but the proportion of dense forest on xeric sites increased dramatically. This gain in dense xeric forest resulted in mesic and xeric sites becoming more similar in terms of forest density composition in 1984. Forest density composition of mesic sites appear to have changed little. Analysis of forest patches revealed that there were more, larger dense forest patches on xeric sites in 1984 but patch size distribution was not significantly different from 1937. Matrix analysis showed that over 90% of 1984 dense forest was forest in 1937 with nearly 80% being scattered and intermediate forest. The increase in dense forest may be attributable to conversion of previously forested areas rather than expansion into grassland. Most (90.4%) 1937 dense xeric forest remained forested in 1984. Retention and persistence of forests were relatively high on stony silt loam, silt loam, and fine sand loam soils. These soils were also associated with forest and grassland transitions. Persistence of dense forest was particularly high on fine sand loam soils.

Forest loss was consistently greater than forest gain. Forest to forest and forest/grassland transitions were found to be relatively common across the landscape. Increase in dense forest appeared to be concentrated in a few isolated areas rather than occurring randomly. Forest loss and density transitions were found to be more distinct than was forest gain.

Overall loss of forest coverage coupled with an increase in dense xeric forest has altered landscape structure within the TPP. In 1937 forests on uplands were predominantly scattered forests while dense forest was relatively rare. The boundary between forest and grassland was relatively indistinct in many places with an intermingling of the two vegetation types. In 1984, however, the boundary has become more distinct. Ecological implications of this shift in landscape structure for plant and animal species will vary according to the environmental requirements of each species. Those requiring an interspersion of forest and grassland will have lost habitat while those species requiring larger tracts of dense forest stand to benefit.

This research does not provide any evidence that the landscape structure of the TPP in 1937 was more similar to presettlement than 1984. There was sufficient time after original settlement for forests to have experienced major changes by 1937. This study has shown that in 1937 forests were an important part of the ecosystem but have changed in their characteristics.

5.7. Potential causes of forest density change.

This research did not attempt to identify the mechanisms responsible for changes in forest density. Research in other grassland ecosystems suggest that fire suppression can lead to increased density of woody vegetation. For example, Archer (1988; 1989; 1990) has suggested that intensified grazing by livestock and fire suppression are responsible for the steady decrease in grassland at the expense of woody vegetation in south Texas over the past 50 years. Bragg and Hulbert (1976) have also implicated fire suppression as the cause for increased coverage of woody vegetation in Kansas. Similarly, Abrams (1992) has linked fire suppression with the conversion of oak savannas to oak forests throughout the Upper Midwest. At the TPP, increase in dense xeric forest is most pronounced in the southeast corner of the study area (see plate 2). Comparing 1937 and 1984 photographs of this area reveals that the forest/grassland boundary is more linear in 1984, suggesting that fence lines and/or roads have been constructed. It is possible that differences in fire regime across these man-made boundaries are responsible for increased forest density. Fence lines and roads may have been utilized as fire breaks for controlled burning; the side of the boundary not burned would favor forest canopy closure.

Fire suppression in some areas of the TPP may explain increased forest density but overall loss of forest coverage requires some other explanation. It is possible that frequent controlled burns in areas of forest loss could have removed woody vegetation and prevented its regrowth. Other techniques for removing woody growth such as herbicide application, bulldozing, or chaining may have been utilized in order to allow grasses to become established for livestock grazing. All these techniques have been used by previous land owners; some areas have received a combination of treatments (Bob Hamilton, pers. comm.). Unfortunately, written ranch records were not kept in the past so it is not possible to correlate land management practices with forest/grassland changes. Field surveys of areas with forest loss revealed a variety of conditions. Many areas now have short, dense woody regrowth while other areas appear to have well established grassland with little woody regrowth. These differing conditions may reflect the length of time since forests were cleared. Areas with little woody growth may have been cleared relatively recently, while areas with dense regrowth have been untreated for longer periods of time. Transitions between forest and grassland may result from naturally occurring boundary movements, past land use practices, or may be data artifacts. Relatively large parcels of forest were lost after 1937 and a large percentage of forests remained unchanged or only changed forest density classes.

At present there is insufficient evidence to identify specific mechanism(s) responsible for overall forest loss or forest density gain. However, it seems likely that these changes are related to past land use practices rather than naturally occurring phenomena. Forest density gain appears particularly concentrated in a few areas where land management may have differed in the past. While it is impossible to determine what conditions existed at the TPP prior to settlement, forests appear to be well established components of the landscape and not invaders that cause deterioration of the grassland ecosystem.

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