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Effects of coppice thinning on growth and yield of Emory oak sprouts in southeastern Arizona

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EFFECTS OF COPPICE THINNING
ON GROWTH AND YIELD
OF EMORY OAK SPROUTS
IN SOUTHEASTERN ARIZONA

by

Ramzi Touchan

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As members of the Final Examination Committee, we certify that we have read the dissertation prepared by Ramzi Touchan

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and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy.

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TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

TABLE OF CONTENTS--Continued

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS--Continued

LIST OF TABLES

ABSTRACT

Emory oak (*Quercus Emoryi*) is a dominant tree species in San Rafael Valley in southeastern Arizona. However, basic information about the effects of coppice thinning on the growth and yield of this species is lacking. Thus, objectives of the study were to measure the effects of coppice thinning on Emory oak survivor growth, ingrowth, and mortality, which are the basic components of a growth budget. This study determined gross growth, net growth, and yield estimates. In addition, this study evaluated the mean annual growth (MAG) values in relation to the biological rotation age of Emory oak in southeastern Arizona.

Coppice thinning treatments were applied to sprouts of different ages. Height and diameter at root collar measurements were taken immediately after thinning and again 5 years later. Sprouts were classified into 5 age groups, 4 stump diameters, and 3 level of coppice thinnings and an unthinned control. The interactions of these treatments and their effect on growth and yield were analyzed.

Stump diameters did not significantly affect the growth components, growth estimates, or yield estimates. The number of residual sprouts significantly affected the growth components, growth estimates, and yield estimates. Survivor growth, gross growth, net growth, and yield were lowest for

1 residual sprout, except for net growth of 8-year-old sprouts. There were no significant differences in net growth between the different coppice thinning treatments. At age 8-year-old sprouts, the mean annual growth of individual sprouts increased as the number of residual sprouts per stump reduced. Based on this relationship, it is recommended that 1 residual sprout be left when thinning sprouts. Age of sprouts significantly affected growth. There was an increase in the mortality of the control sprouts in the 6th year. Based on those results, it is recommended that thinning be conducted in the 5th year of the sprout's growth.

Proper timing of thinning can reduce the rotation age of Emory oak sprouts, if the rotation is based on achievement of a specified diameter. To draw firm conclusions about the effects of thinning on shortening the rotation age, the study measurement needs to be continued into the future.

INTRODUCTION

During the past century, a number of changes have occurred in the vegetation of semi-desert southeastern Arizona. Many natural riparian forests have been eliminated, exotic plants have been introduced, ranges of native species have expanded or contracted, and vast areas of scrub desert have been modified. Changes in vegetation composition have been due largely to grazing, agricultural clearing, woodland cutting, groundwater withdrawal, urban development, and range improvement (Bahre and Hutchinson, 1984).

Wood, which is scarce in the area, has been an important fuel historically in southeastern Arizona. Fuelwood cutting had a substantial effect on the riparian forests, mesquite thickets, and oak-juniper woodland near most of the major cities in southeastern Arizona (Bahre and Hutchinson, 1984). Before the turn of the century, fuelwood cutting on public lands in southeastern Arizona was uncontrolled and had a great impact on the vegetation cover. For example, over 47 million cords (Avery and Burkhart (1983) defined a standard cord as the amount of stacked wood in a pile measuring 4 x 4 x 8 feet or its equivalent. The stacked wood occupies an area of 128 cubic feet) of fuelwood were consumed near Tombstone, Arizona, during the silver boom (1879-1886). Regrowth from these cut areas is again being harvested for firewood.

Mismanagement of land in Arizona and other states was a concern to state and federal agencies, such as the USDA Forest Service, the U.S. Bureau of Land Management, and the forestry Division of the Arizona State Land Department. These agencies realized that continued mismanagement of the area would cause a reduction in the vegetation cover that, in turn, would cause a decline in the supplies of fuelwood.

In recent years, utilization of all fuel types has increased because of the steady increase in the population of southeastern Arizona. For example, the population of Cochise County rose from 74,000 in 1975 to more than 86,000 in 1980. The population of Sierra Vista, Arizona, has risen from 15,000 in 1975 to over 26,000 in 1980 (Bennett 1990). Ffolliott et al. (1979) predicted that fuelwood consumption in the state should increase to over 2 million cords per year in this decade if the current trends continued.

In recent years, the price of fossil fuels has increased rapidly due to several factors including the unstable condition in the Middle East. The situation caused changes in the demand for fuelwood. By 1960, wood was no longer a significant fuel for households or nonforest products industries. Fuelwood consumption in the United States declined from 140 million cords in 1870 to 16 million cords in 1960 (Reynolds and Pierson 1942, USDA 1983). On the Sierra Vista Ranger District of the Coronado National Forest, in southeastern Arizona, the demand for fuelwood harvest was less than 500 cords per year before 1973 (Bennett 1990). The oil embargo of 1973 reversed the trends, with high fossil fuel and electricity prices, and households rapidly increased purchases of wood stoves. On the Sierra Vista Ranger District, the harvest of fuelwood increased greatly between 1973 and 1981. In 1977, over 3000 cords of wood were sold. In 1979, after a cold winter, the volume of fuelwood cut increased to 5,100 cords annually (Bennett 1990). Consumption of fuelwood decreased after 1980, in part, because energy prices were stabilized. It was estimated that in 1984, only 2,700 cords of oak, 2,000 cords of mesquite, and 1,000 cords of juniper were harvested in all of Cochise County (McLain 1988). In 1990, energy prices increased rapidly once again because of the Gulf Crisis. A further energy crisis again could increase the demand for other sources of energy.

Since the mid-twentieth century, land management agencies have been providing better information about vegetation cover and management alternatives. The USDA Forest Service began to conduct fuelwood inventories during the 1950s. According to these inventories, the major fuelwood species in southeastern Arizona are mesquite

(*Prosopis spp.*), oak (*Quercus spp.*), juniper (*Juniperus spp.*), and pinyon (*Pinus spp*) (Bahre and Hutchinson 1984). Most of the fuelwood cut today on the Coronado National Forest is oak and juniper.

In 1980, the USDA Forest Service established a preliminary inventory of the available fuelwood supply by aerial photo interpretation and field measurement on the Sierra Vista Ranger District. The USDA Forest Service identified certain criteria for the areas that could be harvested, including slope constraints, wildlife concerns, visual quality objectives, and area accessibility. These criteria helped to provide better management of the area based on multiple use and sustained yields.

Ffolliott (1988) indicated that the oak woodlands of North America have been exploited by people for fuelwood, fence posts, building materials, and other natural resources. Perhaps of equal importance, these woodlands also have multiple-use values for grazing, watershed, and wildlife conservation. As the demand for these natural resources increases, there is greater recognition of the necessity to implement well conceived management programs in the oak woodlands on a long-term, sustained yield basis and, importantly, in a multiple use context.

The demand for management-oriented research in the oak woodland attracted Touchan (1986), Duenez (1987), Ffolliott

(1988), Ffolliott and Guertin (1988), Tongivichit (1988), Meyer (1988), Al-Hazzouri et al. (1988), Callison (1989), Fowler (1990), Zanga (1990), Borelli et al. (1991), and Nyandiga (1991) to initiate studies to improve management planning. However, Bennett (1990) was the first to study the effects of coppice thinning on the growth and yield of Emory oak sprouts in southeastern Arizona. Coppice thinning by definition is the thinning of the regeneration derived from vegetative sprouting of dormant buds. Daniel et al. (1979) felt that coppice methods of regeneration to be the oldest and, historically, the most widespread method of reproducing a stand that regenerates vegetatively. He also mentioned that coppice methods were described in ancient Egypt and had been used for centuries in Europe, India, Africa, and the Americas.

Wood is scarce in southeastern Arizona and the consumption for fuel is increasing, so coppice thinning could be an important method to maximize volume and shorten the biological rotation age of Emory oak sprouts. The importance of coppice thinning for the oak woodlands encouraged this author to do further investigation on the effect of coppice thinning on survivor growth, ingrowth, mortality, gross growth, net growth, and yield estimate of Emory oak. This study also investigated the effects of coppice thinning on the biological rotation age of Emory oak sprouts in southeastern Arizona. This research has a goal of assisting land managers in preparing management plans which, when implemented, will sustain fuelwood production, as well as maintain the recreational possibilities, watershed protection, and wildlife habitat. This dissertation is the first study thoroughly investigate the effects of coppice thinning on the above components.

LITERATURE REVIEW

This literature review begins with a general introduction to oak taxonomy and a morphological description of Emory oak. Next, the distribution, regeneration, relationship between sprout and stump, management of southeastern Arizona oaks, and specifically, Emory oak are discussed.

Oak Taxonomy

Oaks belong to the family *Fagaceae* and are described as broadleaf trees. Tucker (1980) and Kearney and Peebles (1960), reported that oaks in the United States are divided into three principal subgenera based on leaf, flower, acorn morphology, and time of acorn maturation. Genetic isolation has resulted in the fixation of morphological differences that are used to delimit each group.

Subgenus *Lepidobalanus* (white oak): The acorn shell is glabrous on the inner surface. Within the acorn the abortive ovules are found at the base of the seed, and the cup scales are corky-thickened basally. Maturation is annual. The stigma is short and broad, the leaves are not aristate, and the bark is light gray or brown, with wood light or yellowish brown. White oaks occur throughout the northern hemisphere (Tucker 1980, and Kearney and Peebles

1960).

Subgenus *Erythrobalanus* (black or red oak): Acorns are densely tomentose on the inner surface, the abortive ovules are apical, and the cup scales thin and flat. Maturation is mostly biennial, and the stigma is elongated and narrow. Its leaves are toothed, the bark is usually dark brown or blackish, and the wood reddish-brown. Black oaks occur only in north and central America, and the extreme northern south America. The main distinction between white oaks and black oaks is the character of the inner surface of the acorn shell (Tucker 1980, and Kearney and Peebles 1960).

Subgenus *Protobalanus* (intermediate oaks): The acorn shell is from densely tomentose to almost glabrous, its abortive ovules are lateral, and the cup scales mostly thickened. The maturation is biennial. The stigma is short and broad, the leaves have pointed teeth, and are not bristle-tipped but range from spinose to mucronate. The bark is light grayish-brown, wood light brown. Intermediate oaks are restricted to western North America, and include only 5 species (Tucker 1980, and Kearney and Peebles 1960).

Morphological description of Emory oak

Quercus Emoryi Torr., Emory oak, was named by Lt. Col. W.H.Emory (1811-1887), leader of a military expedition in the Southwest in 1846-1847. He first collected specimens at

Pigeon Creek (Las Palomas), within the present Sierra County, North Mexico (Little 1976). Emory oak is a member of the black oak subgenus, *Erythrobalanus* (Kearney and Peebles 1960). Emory oak also is called black oak, blackjack oak, and bellota. It is a medium-sized evergreen tree, usually 30-40 feet high, with a short trunk 2-3 feet in diameter. Emory oaks have stout, rigid, drooping branches forming a round-topped symmetrical head, and slender rigid branchlets with glabrous dark red-brown or black bark. The leaves are broadly lanced-shaped, 1 to 2.5 inches long, with a short spiny point and a few short spiny teeth that have few hairs on the lower surface.

Emory oak staminate flowers are hoary tomentose aments. The calyx is light yellow, hairy on the outer surface, and is divided into 5-7 ovate acute lobes. It is pistillate sessile or short-stalked, and its involucral scales are covered with hoary tomentum. Acorns mature in one season from June to September. The acorn is 0.5 to 0.75 in. long, is one third or more enclosed by a cup, and is sweetish and edible. The acorns, known in Spanish as <u>bellotas</u>, are nearly free from tannin with its bitter taste. Acorns are an important food for Mexicans and Indians, and are sold in the towns of southern Arizona and northern Mexico.

Emory oak bark, 1-2 inches thick, is dark brown or nearly black, deeply divided into large, oblong, thick plates separating into small, thin, closely appressed scales. The wood is hard and heavy, and is dark brown with thick, lighter sapwood (Sargent 1965, USDA Forest Service, Agriculture Handbook 1976, Elias 1980).

The Emory oak root system has not been described because there are no specific studies on the subject. The root systems of different oak species in California have been investigated, however, Hellmers et al. (1955) reported that the California scrub oak (*Quercus dumosa*) root system was extensive and contained many branches up to 3 inches in diameter. The roots usually were angled downward. In one case, *Q. dumosa* grew through fractured rock to 28 feet. Hellmers et al. (1955) observed that many fine branch roots grew in all directions from the main roots, but few feeder roots were found in the top 6 inches of soil. They also observed root grafting. Hellmers et al. further (1955) reported that the root system of the chaparral species extended laterally much further than the aerial branches, usually 2 or more times as far, irrespective of the type of root system.

Kummerow and Mangan (1981) found that scrub oaks are deep rooting species and they had difficulty in establishing the entire vertical extension of the root system. They also found that 58% of scrub oak roots are between 15.7 to 39.4 inches in depth. A substantial proportion of the root system was still present at 3.3 feet depth and several roots of 0.20-1.2 inches diameter penetrated deeper into the soil. The fine root distribution was uniform with depth from 3.9-15.7 inches. The root R:S ratio was 1.9 for scrub oak.

Research on the rooting habitats of Emory oak is needed. Knowledge of the characteristics of plant root systems is important in the management of vegetation for optimum soil stabilization, flood reduction, and usable water yield. Roots bind the soil and anchor the soil mass. The degree of stabilization achieved depends largely upon the configuration density and strength of the root system.

Oak Distribution

Encinals (literally, "woodland communities") in southeastern Arizona are part of a regional vegetation community called the Madrean evergreen woodlands (Brown 1982). Evergreen (live) oaks are part of western live oak type (Ffolliott 1980). This woodland is centered in the Sierra Madre of Mexico, and extends into southwestern New Mexico, southwestern Texas, and into the mountains of southeastern Arizona. The Madrean evergreen woodlands have 2 components: encinals at lower elevation and Mexican oak-pine woodlands between encinals and montane coniferous forests.

At lower elevations in southeastern Arizona, the encinal is bordered by desert grasslands. Encinals occur between 3,937-5,905 feet. Niering and Lowe (1984) and Walmo (1955) mentioned that oaks are found along wash bottoms on bajadas at elevations lower than 3,937 feet. The elevational boundaries vary in aspect and between adjacent mountain ranges. For example, the Mexican blue oak (*Quercus oblongifolia*) is found at the lowest elevations in the Huachuca Mountains. At increasingly higher altitudes are found Emory oak (*Q. Emoryi*) and Arizona white oak (*Q. Arizonica*). These 3 species often occur together, but Mexican blue oak is seldom found above 5,200 feet. At 5,200 feet, silverleaf oak (*Q. hypoleucoides*) appears. Emory oak, Arizona white oak, and silverleaf oaks are found interspersed in the lower reaches of mountain canyons.

The oak woodlands attain their best growth in canyons and on lower, northerly slopes. They are found in open savannas in many places and in bajadas at the foot of the mountains. Figure 1 illustrates the relative elevations of vegetation types in the Huachuca Mountains and Figure 2 shows the altitudinal relations of tree species of the Huachuca Mountains.

Oak Regeneration

Oak generally regenerates by seedlings, seedling sprouts, stump sprouts, root cuttings, and clones.

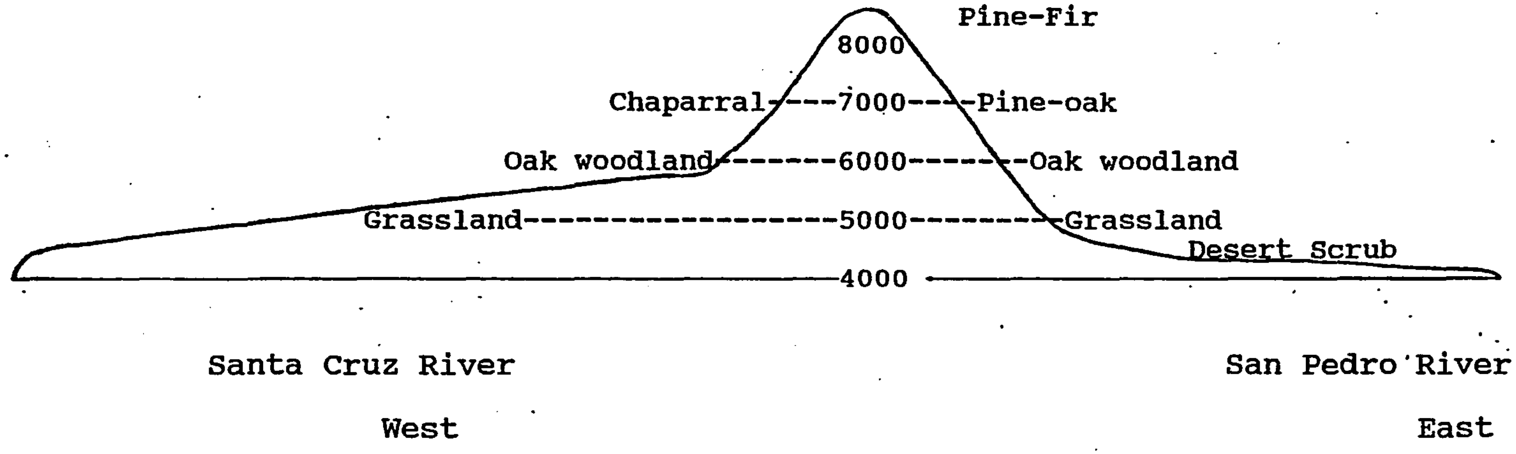

Figure 1. Relative elevation in feet of vegetation types on west (left) and east side of the Huachuca Mountains (Walmo 1955)

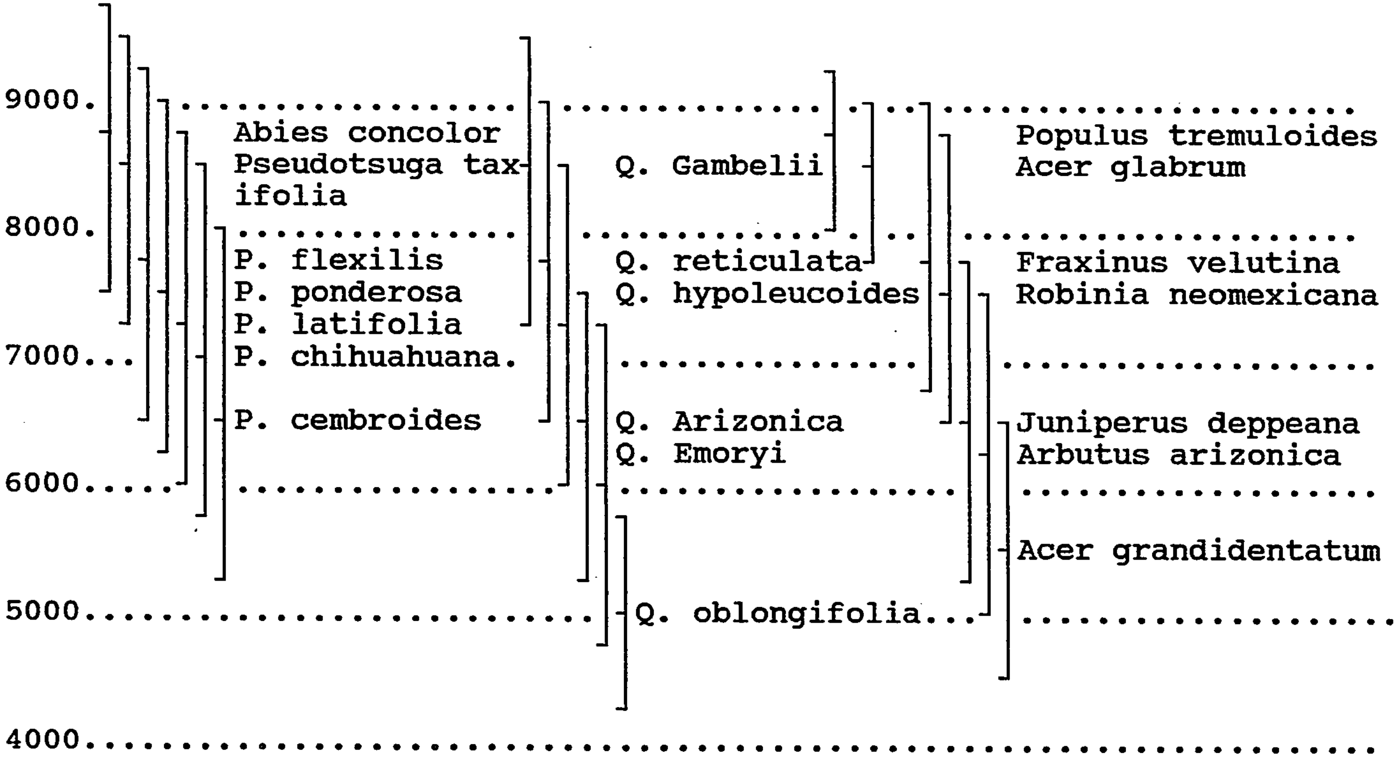

Figure 2. Elevation ranges in feet of major trees of the Huachuca Mountains. The dominant genera are pines and oaks (Walmo 1955).

Regeneration is affected by environmental and silvicultural factors.

McQuilkin (1975) defined seedlings as young plants with stems and roots of the same age. Seedlings take a long time before they become dominant in the stand (Harper et al. 1985). McClaran (1987) mentioned that seedling establishment depends on acorn availability, proper substrate, adequate moisture, protection from herbivores, and limited competition from adjacent plants.

Sanchini (1981) mentioned that seed production per plant is a result of environmental modifications of genetic characteristics which set maximum seed production. The genetic characteristics include general features of the organism's metabolism (assimilation rate and growth rate) and specific reproductive traits (age specific fecundity).

Sanchini (1981) also reported that crown area and stem diameter of both Emory oak and Arizona white oak trees positively correlated to the number of acorns produced by trees. While acorn density is not correlated with crown area or stem diameter, it seems to be a reflection of inherent, genetic differences among trees that affect directly the number of seeds produced on each branch.

The rate of seedling establishment from acorns is low for many species. A large portion of Emory oak and Arizona white oak acorns is lost to predation by insects (weevils), birds, and mammals in southeastern Arizona. It has been estimated that acorn loss for different oak species during mast production year is between 7 to 90% (Cypert and Webster, 1948; Burns et al., 1954; Griffin, 1971; Sanchini, 1981). Furthermore, germination and establishment of remaining seeds is low.

Pase (1969) reported that the survival of *Q. Emoryi* seedlings after 3 years was 27%. It was hypothesized that rainfall is suitable for oak seedling germination and establishment only 1 year in 10. Critical moisture values for seedling establishment are 15 inches or more of October to March precipitation followed by 10 inches or more July to September rainfall.

Al-Hazzouri and Ffolliott (1988) studied the effects of soil salinity and acidity on the germination of Emory oak seeds to provide information on conditions needed for successful germination. The germination of Emory oak seeds was not achieved, but the results were useful in establishing a reference for conditions in which germination will not be successful. Bennett (1988) studied the effectiveness of different soils and soil mixtures as growing media for the survival of Arizona white oak seedlings. He found that the best growing media for survival of Arizona white oak seedlings was loamy sand plus vermiculite, in which 85% of tree seedlings survived. The survival rate in sandy loam soil was 72.5%. The results presented in the two studies are considered a beginning point for future research.

Nyandiga (1991) conducted a study on the germination of Emory oak and Arizona white oak. The objective of this study was to evaluate germinability in two media as influenced by storage and stratification, and to determine effects of oak canopy and depth of burial on acorn viability and germination. Laboratory experiments and field trials were conducted to fulfill these objectives. For both species, germination decreased with increased storage time regardless of storage conditions. Maximum germination of Emory oak was found at 7.5 cm (3 inches) soil depth (29%), with only 5% germination at the soil surface. Germination was higher under trees (20%) than in open grassland (13%).

Presence of oak canopy did not affect germination of Arizona white oak. Germination at 7.5 cm (3 inches) (73%) was not different but exceeded germination at the surface (17%). For both oaks, low germination and viability of acorns at the soil surface was due to desiccation and predation by insects, including the genera *Lepidoptera* and *Curculionidea* (Nyandiga 1991).

Certain species of oak clone vegetatively through spreading rhizomes. Brown (1958) reported that Gambel oak regenerates primarily by this method under dry conditions.

More studies are needed on oak regeneration in southeastern Arizona. It appears that regeneration depends mainly on vegetative processes (Borelli et al. 1991). Pase (1969) studied the survival of Emory oak in south-central Arizona and reported that seedling production usually is prolific after heavy rain, but mortality is over 70% within 3 years. Most mortality is due to drought. Pase (1969) also mentioned that, on the average, there is adequate rainfall to allow the establishment of seedlings every 10 years.

Pase (1969) reported that Emory oak plants sprout prolifically when damaged by fire. Johnson et al. (1962) reported that 47% of burned Emory oak in southeastern Arizona had significant basal sprouting, whereas 33% of Arizona white oak plants sprouted after 1 year on the same site. Phillips (1912) found that uncut Emory oak stands lacked trees from seedling origin, and also claimed the poor regeneration of Emory oak is due to livestock grazing. Caprio (1991) showed that Emory oak had better sprouting ability after fire relative to *Q. oblongifolia*. He hypothesized that this was a survivor advantage at sites where fire frequency is low but intensity is high, such as where trees and shrubs form a closed canopies. In contrast, *Q. oblongifolia* had a greater resistance to fire than Emory oak, which may be important to its survival in a dry grassland savanna habitat, where fast moving fires of short duration are frequent.

Relationship Between Sprout and Stump

Wilson (1968) studied the relationship of red maple (*Acer rubrum*) sprouts after the first year of cutting. He mentioned that the inhibited, dormant buds always are present at the base of the stem. These buds remain just beneath the bark by elongating an amount equal to the width of the annual ring. These do not develop further unless the tree is damaged by physical or biotic agents that interrupt vascular connections between the dormant basal buds and the crown. So, when the tree is cut, the external buds start elongating almost immediately and some of the buried buds enlarge, split the bark and then elongate rapidly. The bark can restrict initial elongation and, later, restrict increase in sprout diameter at the point of attachment. The sprouts produces hormones in the growing leaves and acts as a sink for materials moving from the stump. New water conduction vessels and sieve tubes in the stump are oriented towards the growing sprouts, so that each sprout is in direct vascular connection with the stump. Water and dissolved nutrients from the stump and root system move into the sprout mostly through this direct connection and by radial wood rays. Within a few weeks, the growing sprouts produce substances which inhibit development of the remaining buds. These buds continue to grow slowly just as they did before the stem was cut. The part of the stump not connected physiologically with a sprout either through axial vascular tissue or radial wood rays soon dies.

Thimann and Skoog (1933,1934) worked on *Vicia faba* and described a system that may be similar to that found in oak. They mentioned that a basipetal auxin produced in the buds and leaves of the crown inhibits the sprouting of lateral buds. The theory of apical dominance is that a supraoptimal concentration of auxin exists in the inhibited buds. Removal of the tree crown eliminates the major source of auxin; the buds are released for dormancy and sprouts appear. Correlative relationship with the crown are not the only considerations. The root system contributes water, nutrients, and reserve carbohydrates as well as other organic compounds to the stem. Much of the past work on sprouting of the stump related levels of stored carbohydrates in the roots to sprouting vigor (Aldous 1929, Clark and Liming 1953, Eldon and Webster 1959, Woods et al. 1959). Roots of several plants are reported to exude gibberellins (Phillips and Jones 1964, Sitton et al. 1967) and cytokinins (Kendel 1965, Skene and Kerridge 1967, Weiss and Vaadia 1965), groups of hormones shown to participate in apical dominance (Jacobs and Case 1965, Ruddat and Pharis 1966, Scott et al. 1967, and Wickson and Thimann 1958).

Vogt and Cox (1970) studied possible roles of hormones and reserve carbohydrates (Indole-3-acetic acid IAA, Gibberellin acid GA3, Melic hydrozide MH, and sucrose) in controlling sprout vigor of decapitated pin oak (*Quercus palustris* Muench). The term "sprouting vigor" includes the breaking of bud dormancy as well as the subsequent elongation of the sprouts. Vogt and Cox (1970) found out that the inhibition of sprouting by IAA and the antagonism of MH on this effect points to IAA as a potential physiological inhibitor of oak sprouting. Apparently, the concentration of IAA reaching the buds largely determines the intensity of sprouting. Subsequent vigor may be dependent on other factors including endogenous hormones such as gibberellin and cytokinins.

Oak Management Studies

Recently, many studies have been undertaken in oak woodlands. For example, McMurtray (1978) estimated bole wood volume per acre for oak woodland by preparing stock tables. Ffolliott et al. (1979) estimated that oak woodlands contain approximately 236 cubic feet of wood per acre or about 12,000 pounds of standing biomass. Patterson (1980) estimated the total fuelwood volume for oak vegetation types in Arizona was 0.426×10^{10} cubic feet, with individual species contributing varying amounts of volume.

Tolisano (1984) studied the demand and supply of fuelwood in Arizona, estimated that fuelwood demand in Arizona is increasing and is likely to continue to increase to the year 1995 and beyond. In addition, Ffolliott et al. (1979) estimated growth rates for oak woodland communities to be 1.3% of the existing stand volume.

Touchan (1986) found that Emory oak yield varied from 84.8 to 183.4 cubic feet per acre in southeastern Arizona. Growth ranged from 4.9 to 15 cubic feet per acre per year. The biological rotation age of Emory oak sprouts was estimated to be 45 years. Duenez (1987) used regression analysis to develop empirical models for predicting individual tree volume. Chojnacky (1988) developed cubic volume equations for Arizona's juniper, pinyon, oak and mesquite species. Tongvichit (1988) compared the equation forms commonly used in the estimation of individual tree volumes with the measured volumes of Emory oak in southeastern Arizona. Callison (1989) prepared site index curves for Emory oak and found that coarse soil fragments were negatively correlated with site index, while available water holding capacity was positively correlated with site index. Ffolliott and Guertin (1988) developed a computer simulation model to predict the effects of time and land management practices on the growth and yield of oak woodlands in southeastern Arizona. Fowler (1990) developed a volume-growth model for even-aged Emory oak stands. Specifically, variable density yield tables for Emory oak were developed from sample data collected on temporary plots. Zanga (1990) compared plot and point sampling in a forest inventory in the Emory oak woodlands. His results suggested that with plot sampling, a 0.01 acre (1/25th hectare) plot was more efficient than a 0.25 acre (1/10th hectare) plot for all measures of forest densities. With point sampling, a basal area factor of 6 had the highest relative sampling efficiency in terms of estimating trees per hectare.

Few studies have focused on the effects of silvicultural treatments on stump sprouting of Emory oak and Arizona white oak. Both species are characterized by vegetative reproduction which is an important consideration in selecting the most productive type of silvicultural treatment. Consequently, before discussing treatments, it is important to define thinning and, specifically, coppice thinning and its purpose.

Thinning is an important operation in even-aged stands or even-aged groups in uneven-aged stands at any time prior to the beginning of the regeneration period; this is the case when the objective of managing trees is primarily to redistribute growth potential or to benefit the quality of the residual stand. Anderson and Smith (1976) considered thinning as a form of intermediate cutting in immature or young trees which improves the yield of the stand as a whole.

Daniel et al. (1979) described the purposes of thinning in general. First, thinning helps to utilize material that would normally be lost due to natural stand mortality. Secondly, thinning increases merchantable yields by distributing volume growth on fewer larger stems. Thinning allows the forester to select crop trees instead of natures's choice of the biggest dominants. Thinning shortens the rotation if rotation age is determined by the attainment of a certain tree diameter. Finally, thinning provides an early return of invested capital and can increase the rate of return on the investment.

There are few studies on thinning in the oak woodlands, except that conducted by Duenez (1987) and continued by Meyer (1988). Meyer (1988) found that clear cutting greatly increased the proportion of stumps that sprout for Emory oak and increased sprout volume production. Partially-cut, multi-stemmed tree clusters were less likely to sprout and had less sprout volume growth after one year than completely cut clusters.

Only one study focused on the effects of coppice thinning on the growth and yield of Emory oak in southeastern Arizona (Bennett, 1990). He studied the effect of coppice treatment on Emory oak rotation age, and suggested that coppice thinning can reduce the rotation age.

The term coppice describes all regeneration that is derived from vegetative sprouting of dormant or adventitious buds. Most sprouting trees are hardwoods. Coppicing is used often for fuelwood production and was common in Europe until World War II (Daniel et al. 1979). There had been many studies on coppice thinning in the United States. Most studies, however, focused on commercially important species, such as those harvested for lumber, pulp and paper, or veneer. For example, black cottonwood (*Populs trichocarpa*) and red alder (*Alnus rubra*) sprouts were studied during successive coppicing harvests to determine if short rotations would benefit pulp and paper manufacturers (Harrington and DeBell, 1984). The reason that coppice thinning was not used in United States for fuelwood was the abundance of fuelwood available, and there was no necessity for managing stands for maximum volume.

The coppice method depends on vigorous sprouts from small stumps since stumps of larger, older trees sprout too weakly to grow vigorously. Sprouts develop on the top, side, and root collar of stumps. Root-collar sprouts minimize the hazard of rot infection from the parent stump (Daniel et al. 1979). Trees such as Emory oak are cut close to the ground to force the production of root collar sprouts.

Coppice thinning is an important operation for oak silviculture because regeneration from seed is difficult. Pase (1969) mentioned that seedlings have relatively high mortality and slow growth rates, rendering it difficult to restock a stand. On the other hand, stump sprouting is reliable and sprout growth is faster than seedling growth. Smith (1986) reported that coppice silvicultural practices are suited for the oak woodlands. Daniel et al. (1979) described several advantages of coppice reproduction compared to reproduction by seedling. Rapid volume growth occurs in a short rotation, low investment in growing stock produces high return, regeneration is simple, and high vigor reduces hazard from injurious agents. Finally, coppice thinning can be accomplished by mechanical means, often reducing treatment costs.

The study reported upon in this dissertation focuses on the effects of coppice thinning on the growth and yield of Emory oak sprouts five years after coppice thinning in southeastern Arizona. In addition, this study focuses on the effects of coppice thinning on the rotation age of Emory oak sprouts in southeastern Arizona. This study was a continuation, broader, more in depth investigation of the research initiated by Bennett (1990).

DESCRIPTION OF STUDY

Objectives

The general objective of the study was to determine the effects of coppice thinning on the growth and yield of Emory oak. After knowing these effects, a land manager should be able to better supply the people in this area with fuelwood and still manage the oak woodland resources on a sustained-yield basis. This study also was designed to provide further information on the biological rotation age of Emory oak, for example, whether the rotation period is shortened by coppice thinning treatments.

Specific objectives of the study were to:

1. Determine the effects of stump diameter on survivor growth, ingrowth, mortality, gross growth, net growth, and yield during a 5-year interval,
2. Determine the effects of coppice thinning treatments on survivor growth, ingrowth, mortality, gross growth, net growth, and yield during a 5-year interval,
3. Determine the effects of age of the sprouts on survivor growth, ingrowth, mortality, gross growth, net growth, and yield during a 5-year interval,

4. Compare growth after several coppicing alternatives (years after harvesting to coppice) and thinning treatments (number residual sprouts) for the oak woodlands in southeastern Arizona,
5. Determine the effects of coppice thinning on the biological rotation age of Emory oak sprouts, and
6. Determine the effects of coppice thinning on the rotation age based on the achievement of a particular size class.

Study Area

The study area was located at the southeastern end of the Huachuca Mountains, in Cochise County, Arizona (Figure 3). The international border is to the south, and a major drainage in the area, Cave Canyon, is to the west. The area is 10 airmiles south from Sierra Vista and 70 airmiles southeast of Tucson, Arizona. Elevations range from 5,200 feet in the southwest to 6,500 feet in the northeast. Slope is 5-10%. Aspect is south facing slope.

Soils in the San Rafael Valley are dominated by the Castro-Martinez-Canelo association (MH_1) (Hendricks et al. 1985). These soils are deep, moderately fine to very fine textured, gravelly, and on nearly level to steep slopes on

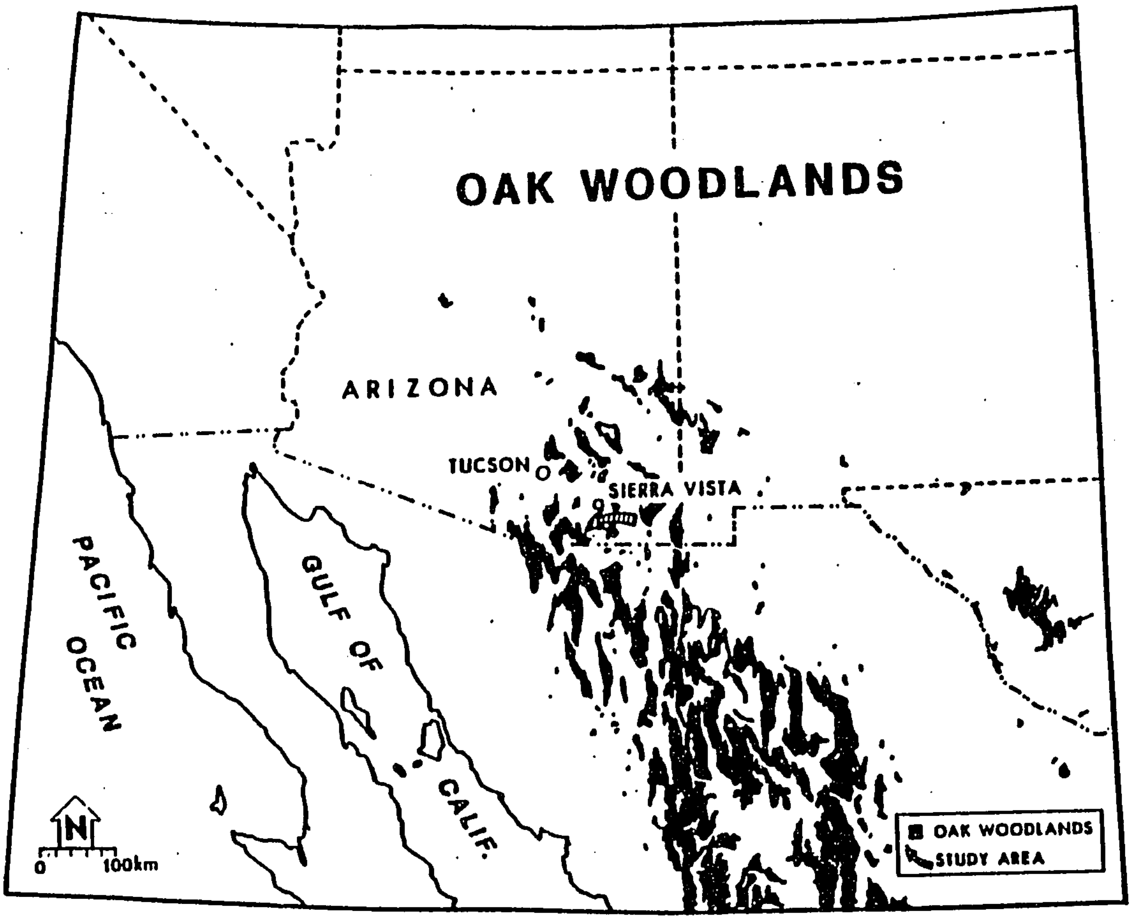

Figure 3. The sample area of the San Rafael Valley.

dissected alluvial fan surfaces and valley slopes. The soils generally are formed in old alluvium from mixed sedimentary and igneous rocks, and are more than 60 inches deep.

The oak woodlands are concentrated on the south and southwest facing slopes of the Huachuca Mountains. The area is characterized by long ridges, old dissected alluvial fans, from southeast to northwest. Denser vegetation in the drainages between the ridges than on the adjacent uplands is due presumably to a greater availability of water.

The study area is found in *Quercus Emoryi/Bouteloua Curtipendula* habitat, and dominated by Emory oak. The area also contains Arizona white oak (*Quercus arizonica*), alligator juniper (*Juniperus deppeana*), and Mexican pinyon (*Pinus cembroides*). There is a wide variety of perennial grass genera on the study area, including *Eragrostis*, *Aristida*, *Avena*, *Bouteloua*, *Bromus*, *Agrostis*, *Festuca*, and *Tridens*.

Southeastern Arizona receives its precipitation primarily during two seasons: winter storm patterns from the Pacific Ocean in the months of November through March, and summer thunderstorms from the Gulf of Mexico. Most rainfall occurs in the summer season of July and August. Records from the nearest weather station, located at Coronado National Monument three miles west of the San Rafael Valley, show that the mean annual precipitation for the area is 20.5 inches (Figure 4).

Mean annual temperature for the area is 60.6 °F (Figure 5). The frost free season ranges from 140 to 200 days (USDA Forest Service, Soil Conservation Service, 1979).

Methods

Field Procedure

Five sites in the general study area were delineated, treated by coppice thinning, and initially sampled in 1985 (Bennett, 1990). These sites had been harvested separately over a five-year period, beginning in 1977, with one site harvested each year through 1981. Each site was chosen because of its physiographical (slope, aspect, and elevation) and climatological similarity to the other sites sampled. All 5 areas are located within a 1-mile radius. On each of the 5 sites, stumps from the fuelwood harvestings were selected randomly, classified according to stump diameter (4, 6, 8, and 10 inches), and then assigned a thinning treatment (1, 2, and 3 residual sprouts). Each stump was considered a primary sampling unit. Therefore, each stump had an equal chance of receiving one of the 4 treatments. In December 1984, and January and February 1985, thinning treatments were applied to the residual sprouts (Bennett 1990). These treatments consisted of thinning the

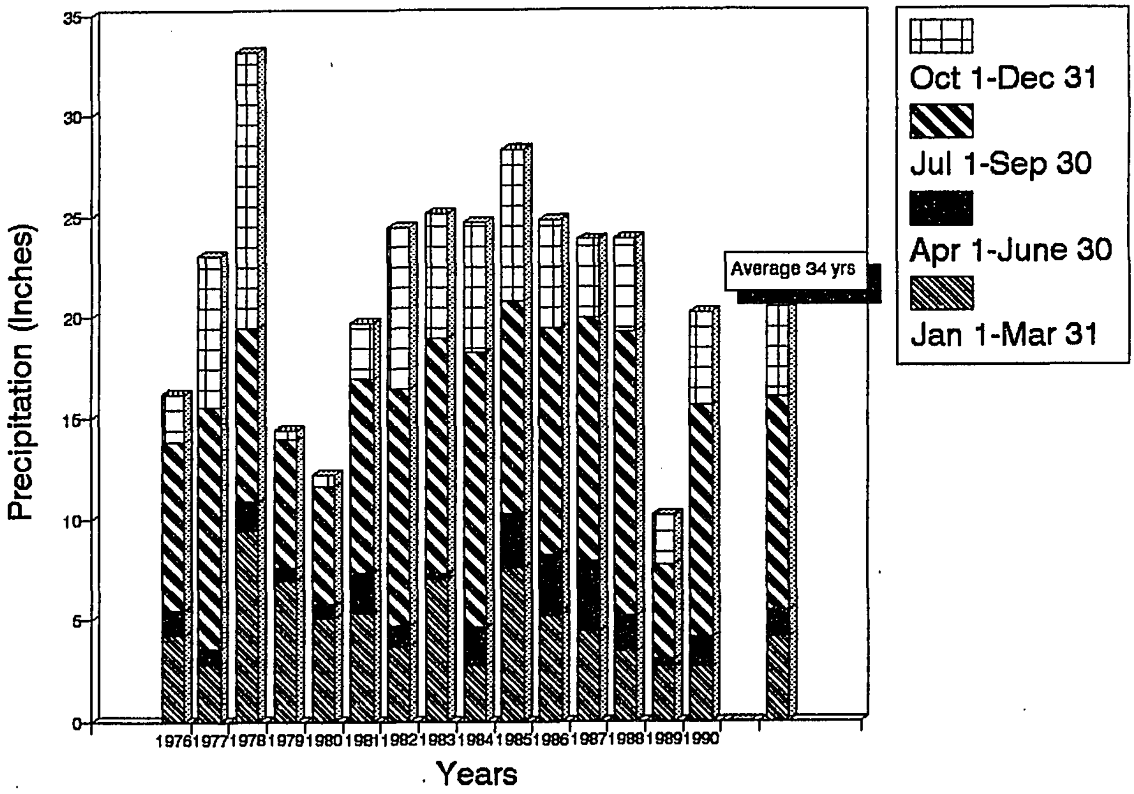

Figure 4. Seasonal precipitation at the Coronado National Monument site, near the study area.

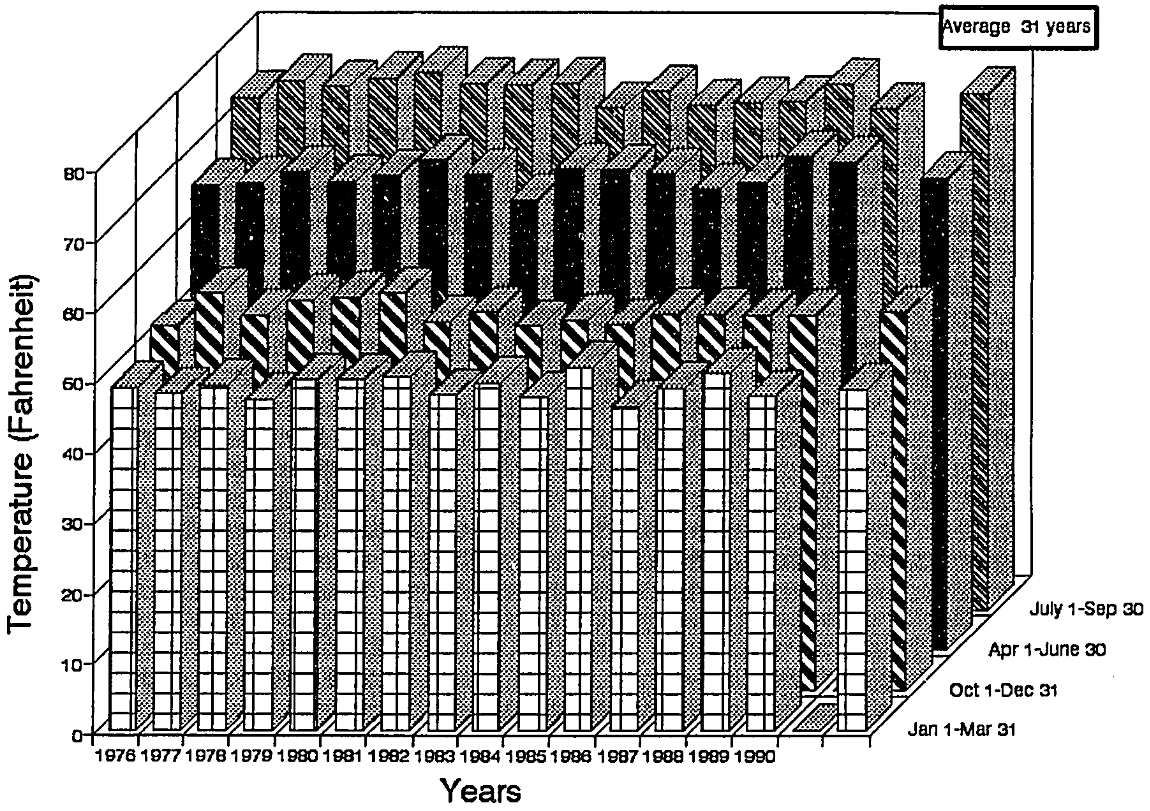

Figure 5. Seasonal temperatures at the Coronado National Monument site, near the study area.

sprouts on the stumps, leaving 1, 2, or 3 of the most vigorous sprouts as residuals (which are sprouts that had been left after thinning). Criteria employed in selecting the residual sprouts were diameter at the base, and height and vigor of the sprouts. A control was included to determine the unthinned sprout growth patterns for the period of the study (1985-1986). Each treatment combination was replicated 10 times.

After the coppice thinning had been applied in 1985, the diameter and total height of the residual sprouts were measured (Bennett 1990). The stumps previously had been labeled with a metallic strip showing the year of harvest, stump diameter, residual sprout number, and replication number. A total of 800 stumps were labeled.

Five years after thinning, in late 1989-early 1990, the diameter of the residual sprouts at stump height and total height of the residual sprouts were re-measured. Diameter at stump height and total height of ingrowth sprouts (the latter being the volume of stems that grew into the lowest inventoried diameter class (4.5 feet or higher) during the growth period) were measured. Ingrowth less than 4.5 feet height was counted only.

Analytical Methods

Analytical methods included estimation of sprout volume, determining growth and yield, and evaluation of mean annual growth values.

Estimation of Sprout Volume. Sprout volume was calculated by a variation of Chojnacky's (1988) oak volume equations for single and multiple stems. For single stems, the original equations presented by Chojnacky were:

$$V= -0.068 + 2.4048(X) + 0.1383(X^2), \text{ for } X \leq 4 \quad (1)$$

$$V= 6.571 + 2.4048(X) - 17.704/(X), \text{ for } X > 4 \quad (2)$$

where: V= volume in cubic feet

$X = (DRC^2)$ (Height in feet)/1,000

DRC= Diameter at root collar in inches

For multiple-stems, the original equations were:

$$V= -0.028 + 1.9545(X^2) + 0.1400(X^2), \text{ for } X \leq 4 \quad (3)$$

$$V= 6.691 + 1.9545(X) - 17.918/(X), \text{ for } X > 4 \quad (4)$$

where: V= volume in cubic feet

$X = (EDRC^2)$ (Height in feet)/1,000

EDRC= Equivalent diameter at root collar in inches

$$EDRC= \sqrt{\Sigma^n{}_1 D_i{}^2} \quad (5)$$

Results of regression goodness-of-fit analyses for Chojnacky equations are summarized in table 1. The coefficient of determination (R^2) was computed using the

Table 1. Regression statistics from volume modeling, various oak species in Arizona (Chojnacky 1988).

					Median statistics					
DRC	Basal	R^2		Predicted	Median	95% mean CI				
class	stems	Wt.	Unwt.	volume	DRC	n=5	n=10	n=20	n=50	n=100
Inches				(Ft^3)	Inches	-------Percent---------				
<16	Multiple	.91	.87	2.3	10	27	20	15	11	9
>16	Multiple	.91	.77	11.9	18	15	11	8	6	4
<16	Single	.90	.82	1.4	7	35	26	20	15	13
>16	Single	.90	.89	21.7	19	14	10	7	5	4

WT = Computed from weighted regression sum of squares with all tree sizes combined.
Unwt = Recomputed from data without consideration of regression weights.

regression weights, and computed again without regression weights. Confidence intervals (CI) for each volume equation were computed for two DRC classes corresponding to trees above and below the point of change (X). The median size tree was selected in each DRC class for actual computation. Then 95% CI were computed for predicting mean tree volume from varying number of sample trees.

Two of the equations, (1) and (2), were modified to avoid negative volume values resulting from small sprout measurements (height and diameter) and then used in the study. The intercept and the slope of the regression line between the vertical axis and the horizontal axis were adjusted so that the line passed through the origin (Bennett 1990). The smallest volume estimated by Chojnacky was 0.16-cubic foot for a tree in the 4-inch DRC and 6-foot height class. The smallest DRC in this study was 0.5 inches and the shortest height was 4.5-foot, resulting in a tree volume of -0.065 cubic feet using Chojnacky's original volume equation for single-stemmed sprouts.

For single-stemmed stumps, the modified equation used in this study was:

$$\text{Volume} = 1.708(X) \tag{6}$$

where $X = (DRC^2)$ (height in feet)/1,000

For multi-stemmed stumps, the equation was:

$$\text{Volume} = 1.677(X) \tag{7}$$

where $X = (EDRC^2)$ (height in feet)/1,000

<u>Estimation of Growth</u>. The basic components of a growth budget are <u>survivor growth</u>, <u>ingrowth</u>, and <u>mortality</u>. These components define <u>gross growth</u> and <u>net growth</u> as follow:

Gross growth = Survivor growth + Ingrowth (8)

Net growth = Gross growth - Mortality (9)

Survivor growth is the volume increment on trees present at both inventories (Marquis and Beers 1969, Husch et al. 1971). The formula for survivor growth is:

$$G_g=V_{s2}-V_{s1} \quad (10)$$

where:

G_g= gross growth of initial volume

V_{s1}= Initial volume of survivor trees, that is, live trees measured at both inventories

V_{s2}= Final volume of survivor trees, that is, live trees measured at both inventories

The term <u>survivor growth</u> was used instead of <u>accretion</u> in this study because accretion represents gross growth of initial volume when mortality represents the volume of trees at the time of their death (Husch, et al. 1971). In this study, it was difficult to determine accretion because the time of death of a sprout at each sample unit could not be detected, and most of the apparent dead sprouts were missing, particularly in the control.

Ingrowth is the volume of those sprouts that grew into the lowest inventoried DRC class during the growth period (Avery and Burkhart 1983). The smallest DRC class measured in this study was 0.5 inches.

Mortality is the volume of sprouts that were measured in first inventory and died in the subsequent 5-year growth period. Sprouts died because of decadence, competition, insects, diseases, and windthrow.

Net growth represents the volume increment based on the initial tree volume plus ingrowth after mortality has been deducted. When ingrowth is added to net growth, the result is volume production (Avery and Burkhart 1983).

Determination of Yield. Yield is the total volume of each sample unit, including the volume of original sprouts and ingrowth. It is a measure of the standing volume that is available for harvesting at a specific point in time. Yield was determined by summation of volume for all individual sprouts. In this study, yield was evaluated at two periods in time, in 1985 and 1990.

Evaluation of Mean Annual Growth. Mean annual growth (MAG), the average annual increase of a tree in reference to its age, is derived by dividing tree volume by its age (Avery and Burkhart 1983, and Daniel et al. 1979). Based upon 80 cross-sections taken by Touchan (1986), MAG was calculated for each tree at diameter dbh. DBH is measuring the diameter of the tree at breast height (4.5 feet height. The dbh measurement was converted to DRC by using Chojnacky's (1988) equation:

$$DRC= 0.41 + 1.3552(dbh) - 0.0122(dbh^2) \quad (11)$$

$$R^2 = 0.92$$

For each sprout volume was calculated by using equation (6). The relationship between MAG and age was analyzed to estimate the biological rotation age, following the procedure outlined by Avery and Burkhart (1983). The points were plotted on a scatter diagram and a curve was fitted to the points. An equation describing this curve was derived by using the model:

$$Y = bx - cx^2 \quad (12)$$

where: Y = mean annual growth

x = sprout age

b and c = constants.

In the present study, MAG was calculated for each coppice thinning treatment. Then, the points were plotted on the same curve as defined from the data collected in the earlier study (Touchan 1986) to determine if the coppice thinning shortened the biological rotation age of Emory oak sprouts. A figure showing the plotted points was considered unnecessary because the sprouts were too young to show any meaningful pattern.

<u>Statistical Analysis</u>. Analysis of variance was used to determine if there were statistically significant differences among the coppice thinning treatments in terms of survivor growth, ingrowth, mortality, gross growth, net growth, and yield. The level of significance for the tests was 0.10. The analysis of variance model used (SAS 1985) was:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \epsilon_{ijk} \tag{13}$$

Y_{ijk}= the k th observed value of survivor growth, yield, etc. for the (ij)th cell

α_i= the effect of the ith level of factor A

β_j equals the effect of the jth level of factor B

$\alpha\beta_{ij}$= the interaction effect for the ith level of factor A and the jth level of factor B

A = the effect of number of residual sprouts

B = the effect of stump diameters

ϵ_{ijk}= the random error associated with individual observations

It was not always possible to have an equal number of sampling units for all treatment combinations in this study. Many of the original sample units (stumps) were lost because the metallic tags were buried by litter, or eaten by wildlife, etc. The number of sampling units lost was 67, distributed randomly among the treatments evaluated.

Because the source data were unbalanced (unequal number of sample units), a general linear model procedure available in SAS (PROC GLM) was used to estimate the mean and the sums of squares. This procedure eliminated the problem of unbalanced data in the analysis, that is, the contamination of differences between means of the factors by effects of other factors; for example, the estimate of the effect of stump diameters can be contaminated by the effect of number of residual sprouts. PROC GLM in SAS solved this problem by adjusting the means to remove the contaminating effects (least square means) (SAS 1985).

Least square means are the estimates of the treatment means. If the data are balanced, the least squares means will be equal to the observed means. For unbalanced data, least square means adjust for unequal class size, producing estimates of means that would be expected from a balanced design. Least square means and their standard errors for each growth and yield estimation were given as an appendix.

Before conducting the analysis of variance, a test for homogeneity of variance was made. The test showed that the variances of different samples were not equal. Different types of transformations were made, but they did not eliminate heterogeneity among variances. Therefore, weighted least squares (WLS) (Draper and Smith 1981) was used to estimate the analysis of variance model. In cases where there is heterogeneity among variances, WLS estimation provides minimum variance linear unbiased estimates, when $1/ij$ is used as the weight for each observation and ij is the variance of the observation in (ij)th cell.

Pairs of least square means were compared with a t-test. The test was used because it is appropriate in cases where data are unbalanced and differences between least square means must be tested. To protect against inflation of the type I error rate, α, α will be divided by the number of differences tested. If the probability of observing a t value under H_0 is less than α/number of comparison, the difference between the means were considered significant statistically (Kuehl and Axelson, 1990).

RESULTS AND DISCUSSION

Results presented include the effects of coppice thinning on survivor growth, ingrowth, and mortality, the basic components of a growth budget. Gross growth and net growth will be derived from the growth budget components and used to obtain growth estimate. Other results are yield estimates and evaluation of MAG values in relation to the biological rotation age in the Emory oak woodland. Effects of stump diameter, number of residual, and age of sprouts on growth in each period between initial fuelwood harvesting and coppice thinning treatment also are discussed.

Growth Components

Survivor Growth

In general, stump diameters significantly affected survivor growth at sprout ages 4 and 7 years, and not at ages 5, 6, and 8 years. The number of residual sprouts for each sprout age group significantly affected survivor growth. For all sprout age groups, the interaction among stump diameter and number of residual sprouts was not significant.

Stump Diameter. Stump diameter at time of thinning generally did not consistently affect survivor growth (Figure 6). For 4-year-old sprouts, survivor growth for a

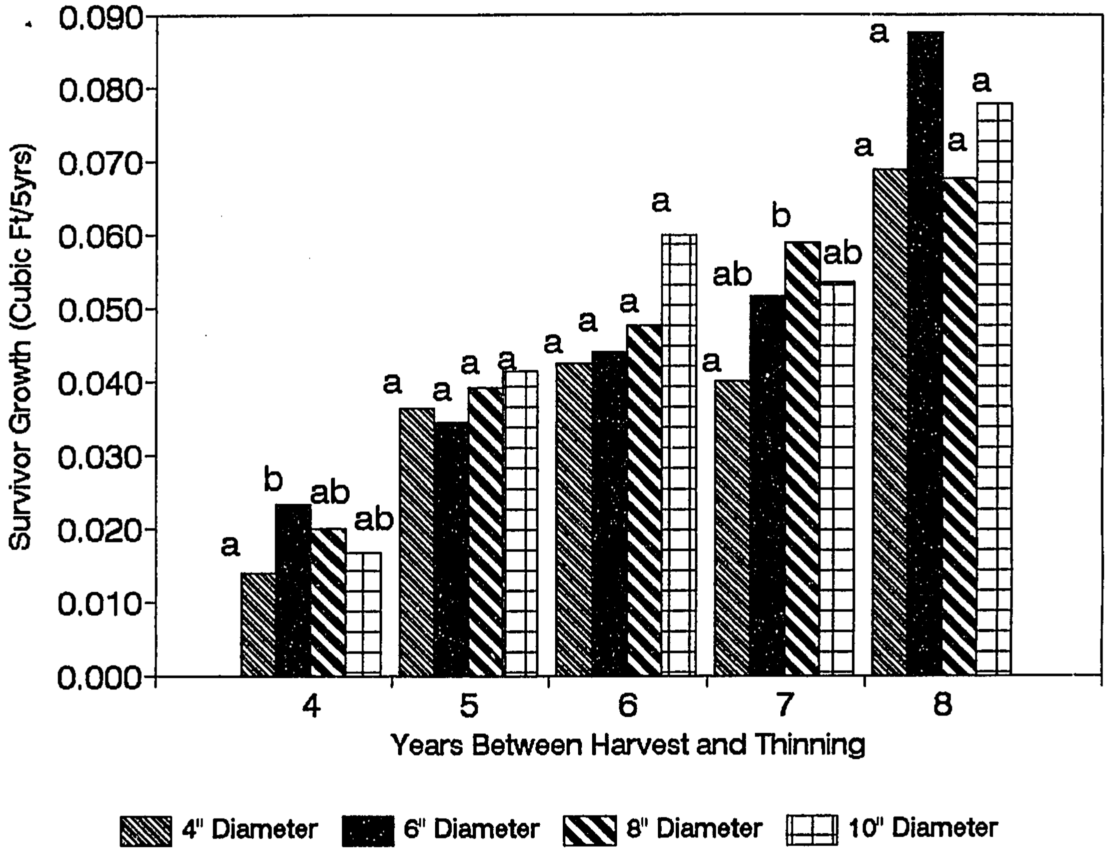

Figure 6. Effects of stump diameter on survival growth. Bars in group with different letters differ significantly (p<0.1).

4-inch diameter stump was lower than survivor growth from a 6-inch diameter stump. At sprout age 7 years, survivor growth for a 4-inch diameter stump was lower than that for an 8-inch diameter stump.

Bennett (1990) found stump diameters of Emory oak had no significant impact on sprout growth in the initial year after the coppice thinning treatments; this could be due to the root grafting phenomenon common to the oaks. Root grafting helps the sprout to support itself by absorbing food, nutrient, and water from other trees.

In studies conducted elsewhere, Wendel (1975) found that the proportion of stumps sprouting, number of sprouts per stump, and dominant sprout height were not correlated with parent tree vigor or dbh for red oak (*Quercus rubra*), yellow poplar (*Liriodendron tulipifera*), and black cherry (*Prunus serotina*) in West Virginia. Roth and Hepting (1943) and Church (1960) found that the ability of oaks (*Quercus spp.*) and sugar maple (*Acer saccharum*) to sprout was related inversely to tree age and stump size in western Virginia. The age of the stump also could play an important factor in the sprouting of Emory oak. Touchan (1986) found that most Emory oak sprouts past the biological rotation age were infected by heart rot which might affect sprout growth.

<u>Number of Residual Sprouts</u>. The unthinned sprouts (control) showed the highest survivor growth at age 4-year-

old sprouts (Figure 7). Survivor growth for 1 residual sprout was lower than the other thinning levels

Survivor growth for 2 and 3 residual sprouts at sprout age 7 and 8 years was not different significantly from the unthinned residual sprouts. Growth of thinned trees concentrated on fewer sprouts; this likely represents an advantage to fuelwood cutters who would expend less labor during harvesting. In the younger sprout age groups, such as 4 and 5 years, the effects of coppice thinning were not clear. The residual sprouts probably needed more time to express consistent growth differences. It could be that 2 and 3 sprouts will have the same growth of unthinned control sprouts when the sprouts of age classes 4 and 5 reach age 7 and 8 years.

<u>Age of Sprouts</u>. The age of sprouts significantly affected survivor growth (Figure 8). The interaction among age of sprouts and number of residual sprouts was significant, although the interaction between age of sprouts and stump diameter was not. The interaction among age of sprouts, stump diameters, and number of residual sprouts was not significant.

Eight-year-old sprouts had the highest survivor growth. Four-year-old sprouts had the least survivor growth.

In addition to age of sprouts, site quality could affect sprout growth. In general, the higher the site

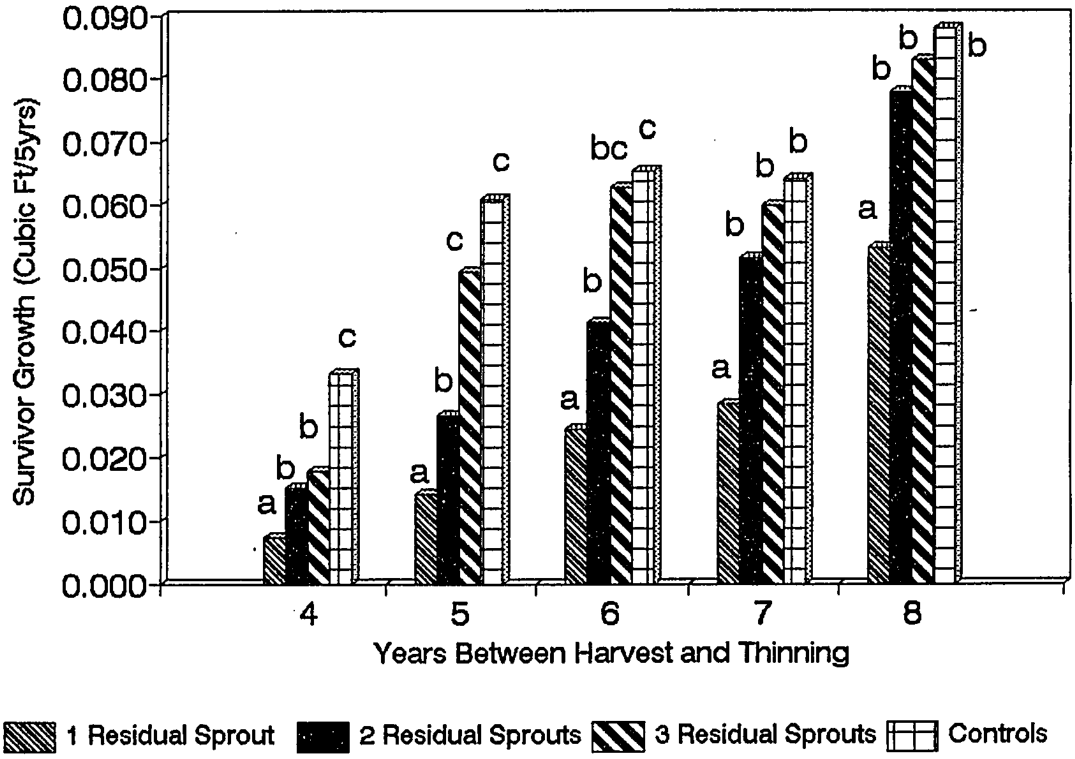

Figure 7. Effects of number of residual sprouts on survival growth. Bars in group with different letters differ significantly (p<0.1).

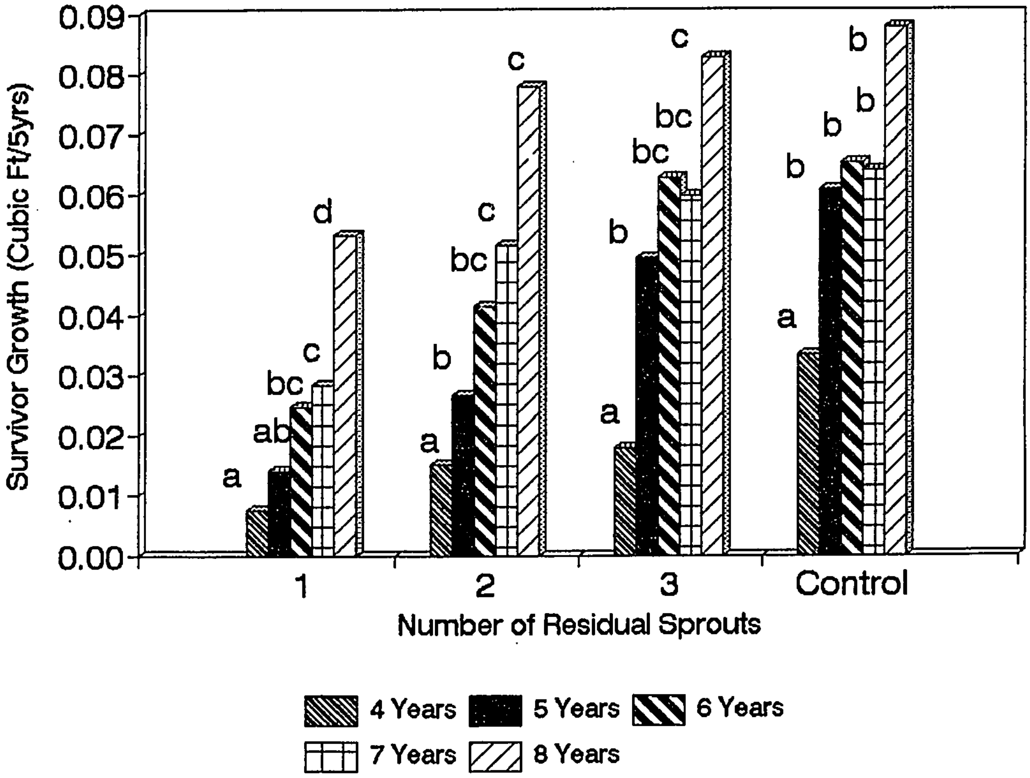

Figure 8. Effects of age of sprouts on survivor growth. Bars in group with different letters differ significantly (p<0.1).

quality the greater the growth. Another factor that could affect growth was the precipitation after the year following harvesting. For example, the year after the 1977 harvesting annual precipitation was high, which might have created favorable growth conditions for the 8 year old sprouts. The year after the 1978 harvest precipitation was low which resulted in limited growth of the 7 year old sprouts.

Ingrowth

In general, stump diameters significantly affected ingrowth at sprout age 7 years. Number of residual sprouts significantly affected ingrowth at sprout ages 5, 6, 7, and 8 years, and not at age 4 years. There were no interaction among stump diameters and number of residual sprouts for all age groups.

Stump Diameters. Stump diameter at time of thinning did not consistently affect ingrowth (Figure 9). For 7-year-old sprouts, ingrowth for the 10-inch diameter stump was significantly higher than the other stump diameter classes. There was no apparent reason for this finding.

Number of Residual Sprouts. The unthinned residual sprouts (control) showed the highest ingrowth at sprout ages 6, 7, and 8 years (Figure 10). At sprout age 5 years, ingrowth of 3 residual sprout was significantly lower than the other coppice thinning levels. Ingrowth of 2 residual

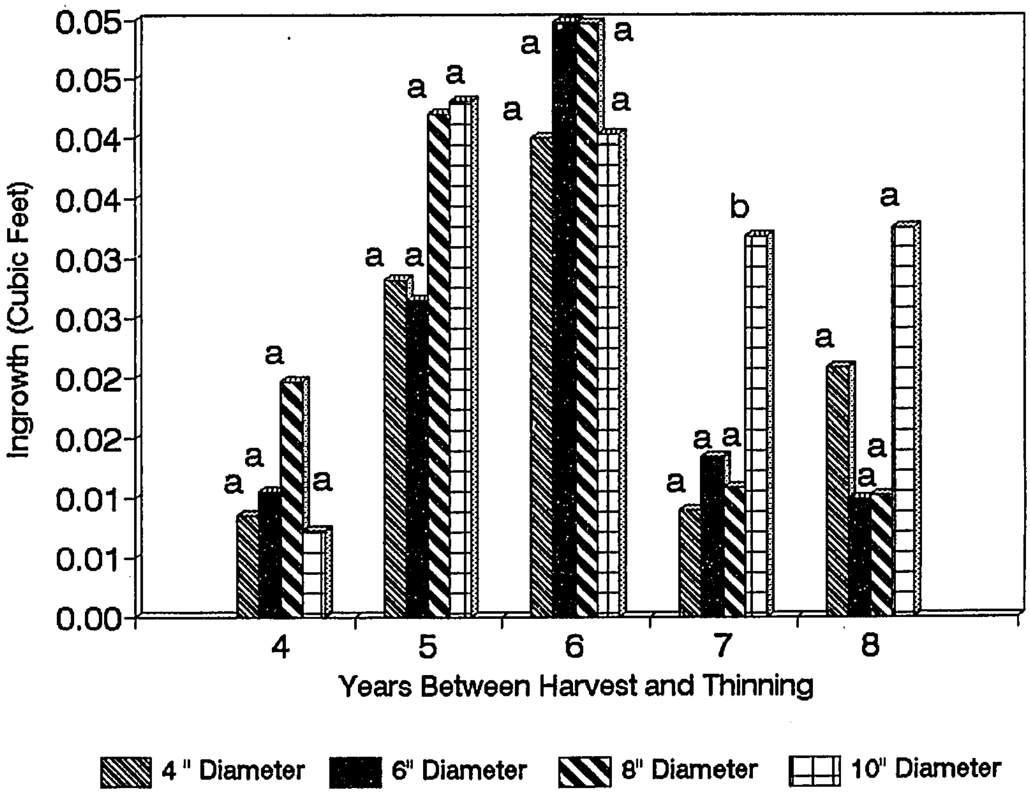

Figure 9. Effects of stump diameter on ingrowth. Bars in group with different letters differ significantly ($p<0.1$).

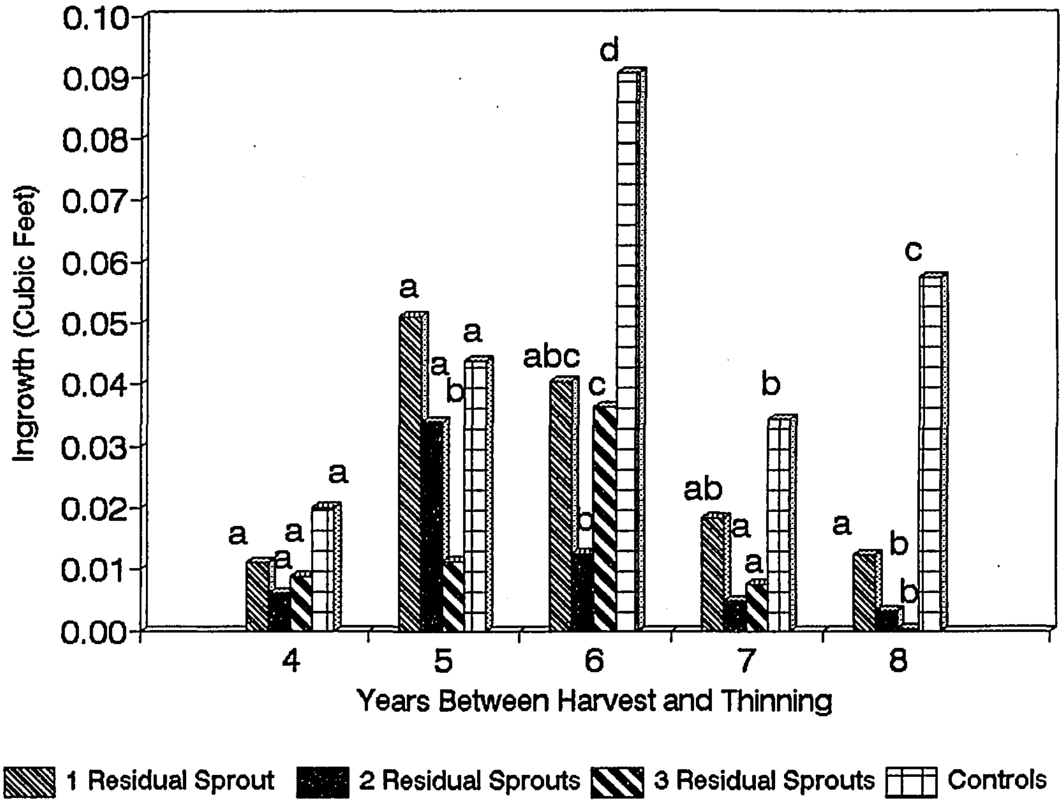

Figure 10. Effects of number of residual sprouts on ingrowth. Bars in group with different letters differ significantly (p<0.1).

sprouts At sprout age 6 years was lower than that of 3 residual sprouts and the unthinned control. At sprout age 8 years, ingrowth of 1 residual sprouts was significantly higher than ingrowth of 2 and 3 residual sprouts. Higher ingrowth of unthinned controls could be due to a larger number of sprouts available to grow into the smallest size class. The next highest ingrowth, found in the 1 residual sprout class, was the result of sprouting. Sprouting was higher at the 1 residual sprout level perhaps because of more access to food, water, and sunlight. There was greater opportunity for new buds to be released and sprouts to establish themselves.

<u>Age of Sprouts</u>. The age of sprouts significantly affected ingrowth (Figure 11). Furthermore, the interaction among age of sprouts and number of residual sprouts was significant, but the interaction between age of sprouts and stump diameter was not significant. The interaction among age of sprouts, stump diameters, and number of residual sprouts was not significant.

The highest ingrowth at 1 and 2 residual sprouts was at sprout age 5 year. The highest ingrowth at 3 and the uncut residual sprouts was at sprout age 6 year.

There were 1,024 new sprouts originating since 1985 that were not included as ingrowth, because they were not in measurable size classes (less than 4.5 feet in height). The

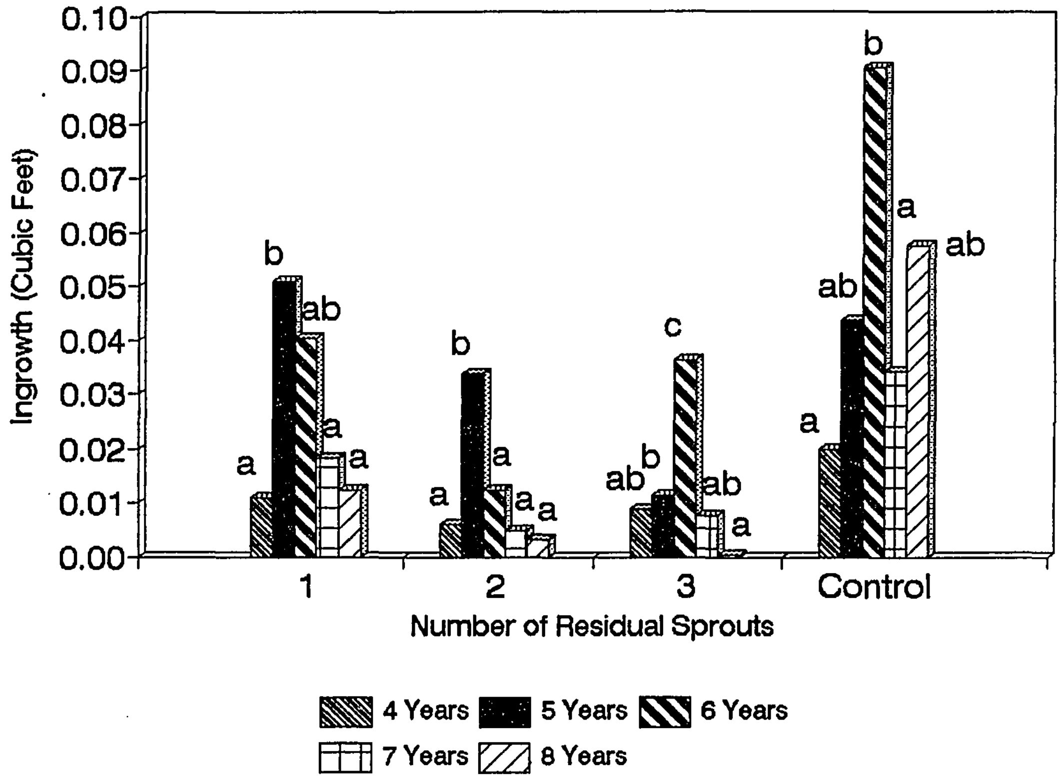

Figure 11. Effects of age of sprouts on ingrowth. Bars in group with different letters differ significantly (p<0.1).

highest percentage of these were concentrated in the unthinned controls. The new sprouts need to be monitored through time to determine their establishment pattern. Borelli et al. (1991) stated that to understand the dynamics of oak regeneration in southeastern Arizona, it will be necessary to observe natural regeneration over several years. The occurrence, growth, development, and survival of plantlets can be related to climatic cycles and varying land use practices. Observing long-term growth will help to understand when tree stands start to thin themselves naturally.

Mortality

Mortality occurs for different reasons including drought, which causes competition between trees for water and nutrients, disease or insect damage, and fire. In general, stump diameters significantly affected mortality of sprouts at age 4 and 8 years, and not at sprout age 5, 6, and 7 years. Number of residual sprouts was significant for all sprout age groups. The interaction among stump diameters and number of residual sprouts were not significant.

<u>Stump Diameters</u>. Stump diameter at time of thinning did not consistently affect mortality (Figure 12). For 4-year-old sprouts, mortality for a 10-inch diameter stump was

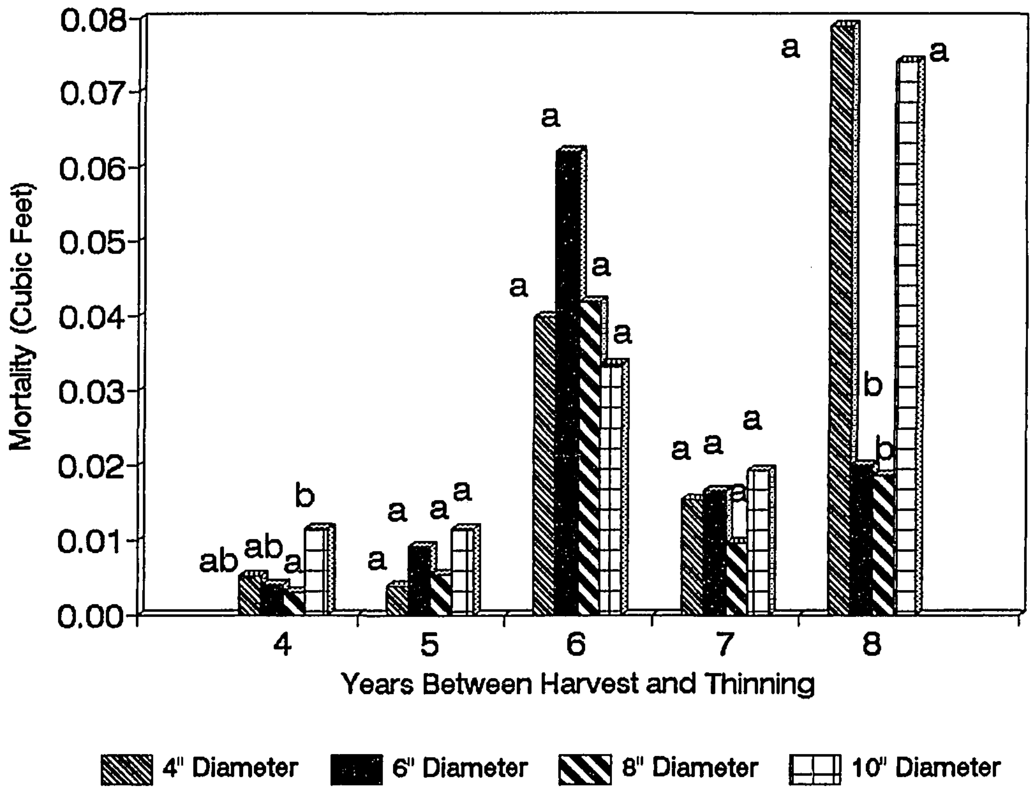

Figure 12. Effects of stump diameter on mortality. Bars in group with different letters differ significantly (p<0.1).

higher than mortality from a 6 and 8-inch diameter stump. At sprout age 8 years, mortality for a 4-inch diameter was higher than that for a 6 and 8-inch diameter stump.

Number of Residual Sprouts. The unthinned residual sprouts had the greatest mortality (Figure 13). High mortality in the unthinned control could be due to competition for food, sunlight, and water. Shade also could play an important role, because after the release of the dormant buds and growth of new sprouts, hormones are produced in the growing leaves which act as a sink for materials moving from the stump (Wilson 1968). Shade can restrict sprout growth by reducing leaf growth and production of growth regulators (Wilson, 1968). The mortality in the 1 and 2 residual sprout classes could be due to physical damage by humans or animals.

Age of Sprouts. Age of sprouts significantly affected mortality (Figure 14). Furthermore, the interaction among age of sprouts and number of residual sprouts significantly affected mortality, but among age of sprouts and stump diameter was not. The interaction among age of sprouts, stump diameters, and number of residual sprouts was not significant.

For 6 and 8-year-old sprouts, the unthinned sprouts had the highest mortality (Figure 14). For 7-year-old sprouts, the unthinned sprouts had the next highest mortality.

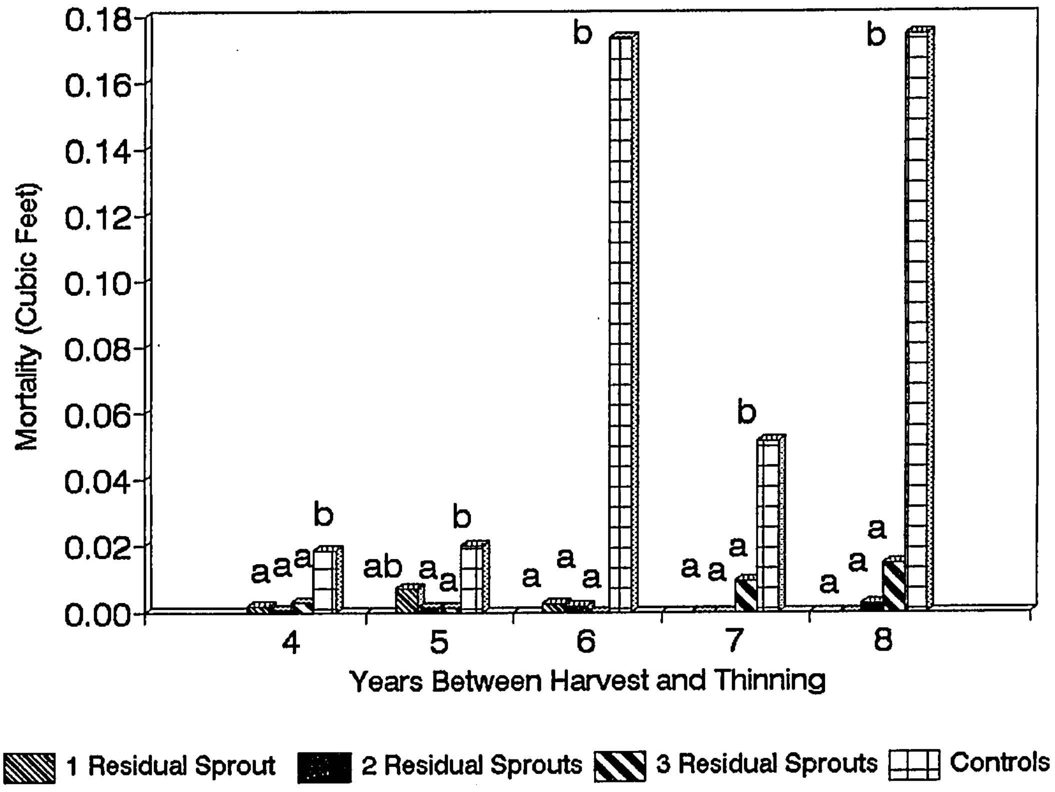

Figure 13. Effects of number of residual sprouts on mortality. Bars in group with different letters differ significantly ($p<0.1$).

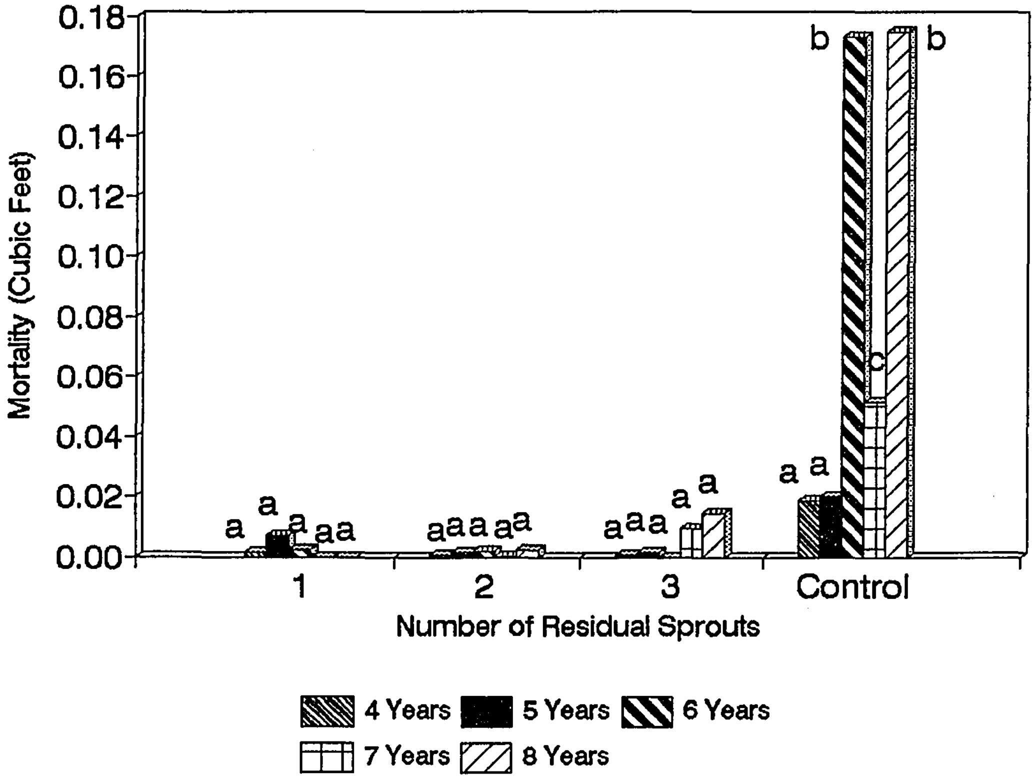

Figure 14. Effects of age of sprouts on mortality. Bars in group with different letters differ significantly (p<0.1).

Growth Estimates

Gross Growth

Gross growth (GG) is the summation of survivor growth and ingrowth. In general, stump diameters significantly affected GG at sprout ages 4 and 7, and not at sprout ages 5, 6, and 8 years. Number of residual sprouts significantly affected GG at all sprout ages. The interaction among stump diameters and number of residual sprouts was not significant.

Stump Diameters. Stump diameter at time of thinning Generally did not consistently affect GG (Figure 15). For 4-year-old sprouts, GG for a 4-inch diameter stump was lower than GG from a 6 and 8-inch diameter stump. At age 7 years, GG for a 4-inch diameter stump was lower than that for an 8 and 10-inch diameter stump.

Number of Residual Sprouts. The unthinned sprouts and 3 residual sprouts had the greatest GG at sprout ages 5 and 6 years (Figure 16). While the the 1 residual sprout showed the lowest GG at sprout ages 4 and 7 years. There was no significant differences between the GG of 3 residual sprouts and the control at sprout ages 5, 6, 7, and 8 years. The reason that the unthinned sprout had a high GG was mortality was not included.

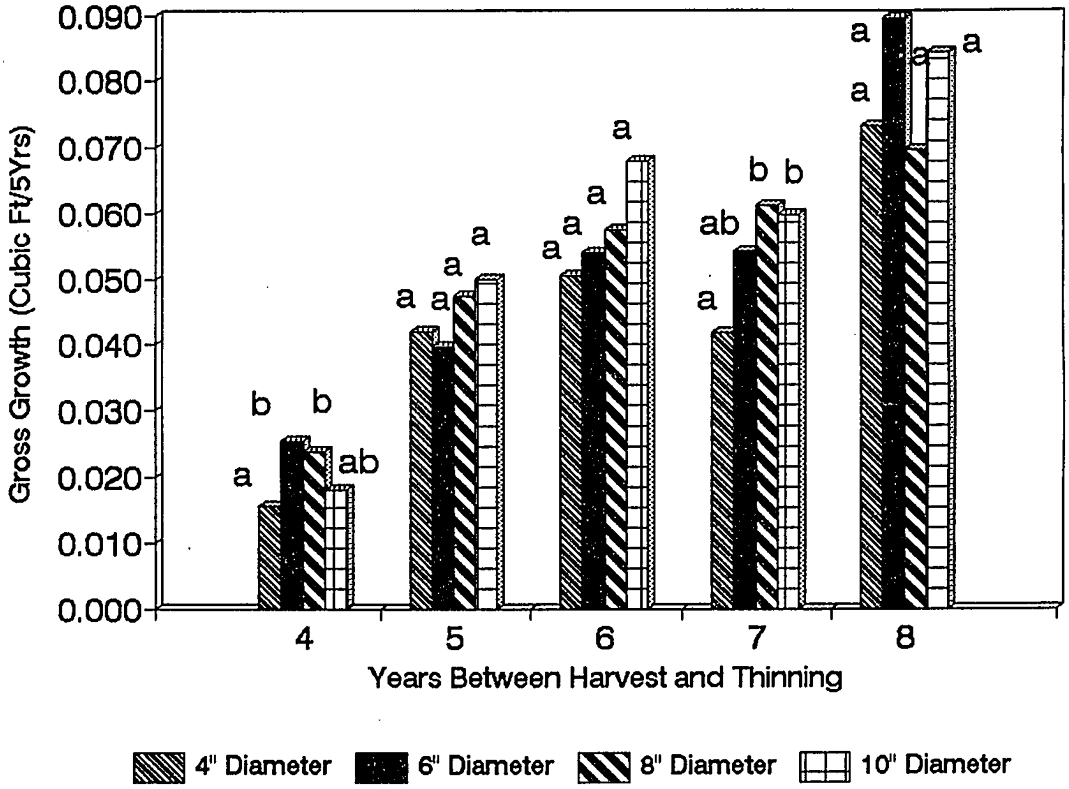

Figure 15. Effects of stump diameter on gross growth. Bars in group with different letters differ significantly ($p<0.1$).

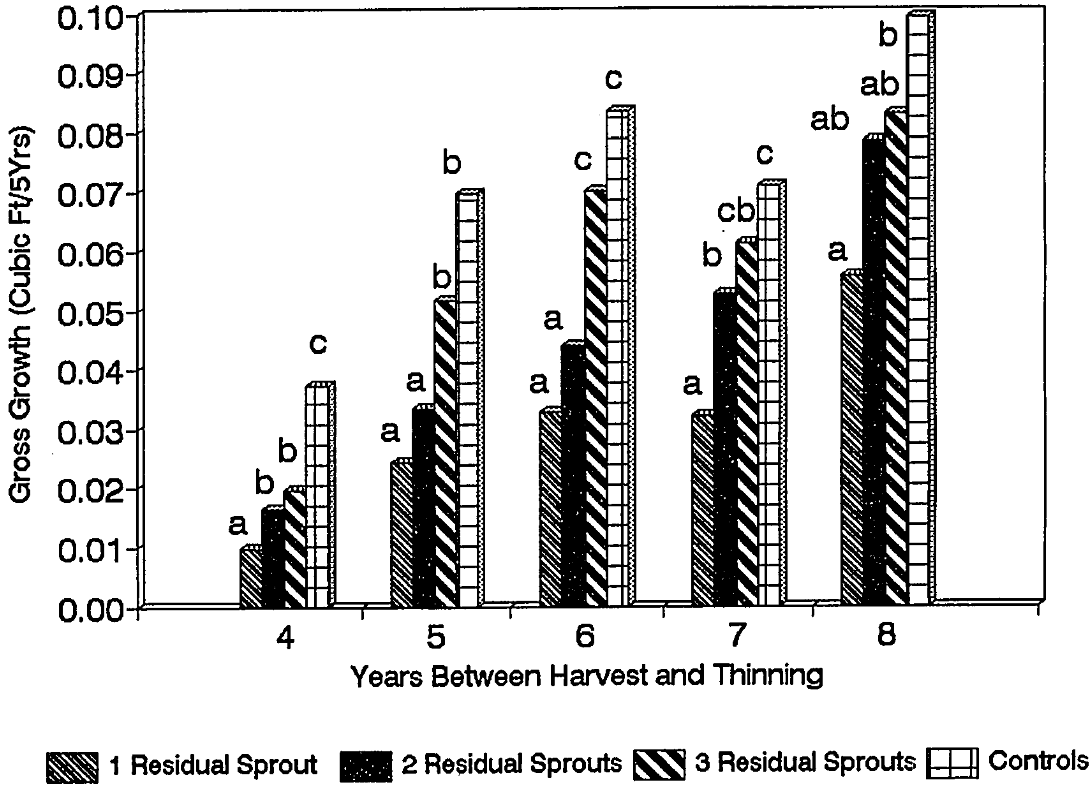

Figure 16. Effects of number of residual sprouts on gross growth. Bars in group with different letters differ significantly (p<0.1).

<u>Age of Sprouts</u>. Age of sprouts significantly affected GG (Figure 17). The interaction between age of sprouts and number of residual sprouts was significant, but the interaction between age of sprouts and stump diameter was not. The interaction among age of sprouts, stump diameters, and number of residual sprouts was not significant.

Eight-year-old sprouts had the highest GG at 1 and 2 residual sprouts treatment. Four-year-old sprouts had the least GG at all coppice thinning levels. There were no significant differences between age 5, 6, 7, and 8 years at 3 residual sprouts and the unthinned sprouts.

Net Growth

When mortality is subtracted from gross growth estimates, the result is net growth (NG). NG often is used as an initial approximation of the allowable cut, the latter volume representing the volume of wood that can be harvested on a sustainable basis.

In general, stump diameters significantly affected NG at sprout ages 4 and 7 years, but not at sprout ages 5, 6, and 8 years. Number of residual sprouts significantly affected NG at all sprout ages except sprouts at age 8 years. The interaction among stump diameter and number of residual sprouts was not significant.

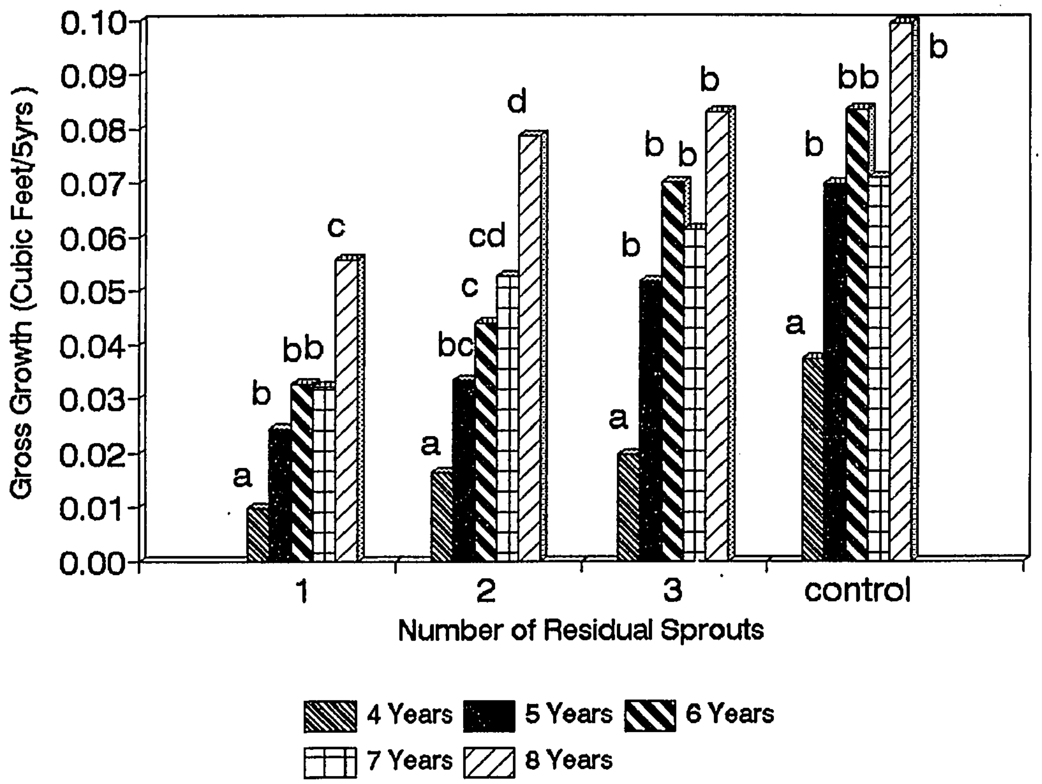

Figure 17. Effects of age of sprouts on gross growth. Bars in group with different letters differ significantly ($p<0.1$).

Stump Diameters. Stump diameter at time of thinning Generally did not consistently affect NG (Figure 18). For 4-year-old sprouts, NG for a 4-inch diameter stump was lower than NG from a 6 and 8-inch diameter stump. At sprout age 7 years, NG for a 4-inch diameter stump was lower than that for an 8 and 10-inch diameter stump.

Number of Residual Sprouts. The unthinned control had the highest NG at sprout ages 4 and 5 years (Figure 19). At sprout age 7 years, 2 residual sprouts, 3 residual sprouts, and the unthinned controls were similar. At sprout age 8, NG for 1 residual sprout was similar to the other thinning levels, because mortality was low in the 1 residual sprouts. The 3 residual sprout class at sprout age 6 years had the highest NG because of the high mortality level in the unthinned control.

Age of Sprouts. Age of sprouts significantly affected NG (Figure 20). Furthermore, the interaction among age of sprouts and number of residual sprouts was significant, but among age of sprouts and stump diameter was not. The interaction among age of sprouts, stump diameters, and number of residual sprouts was not significant.

Eight-year-old sprout had the highest NG at the 1 and 2 residual sprouts treatment. The lowest NG was at sprout age 4 years.

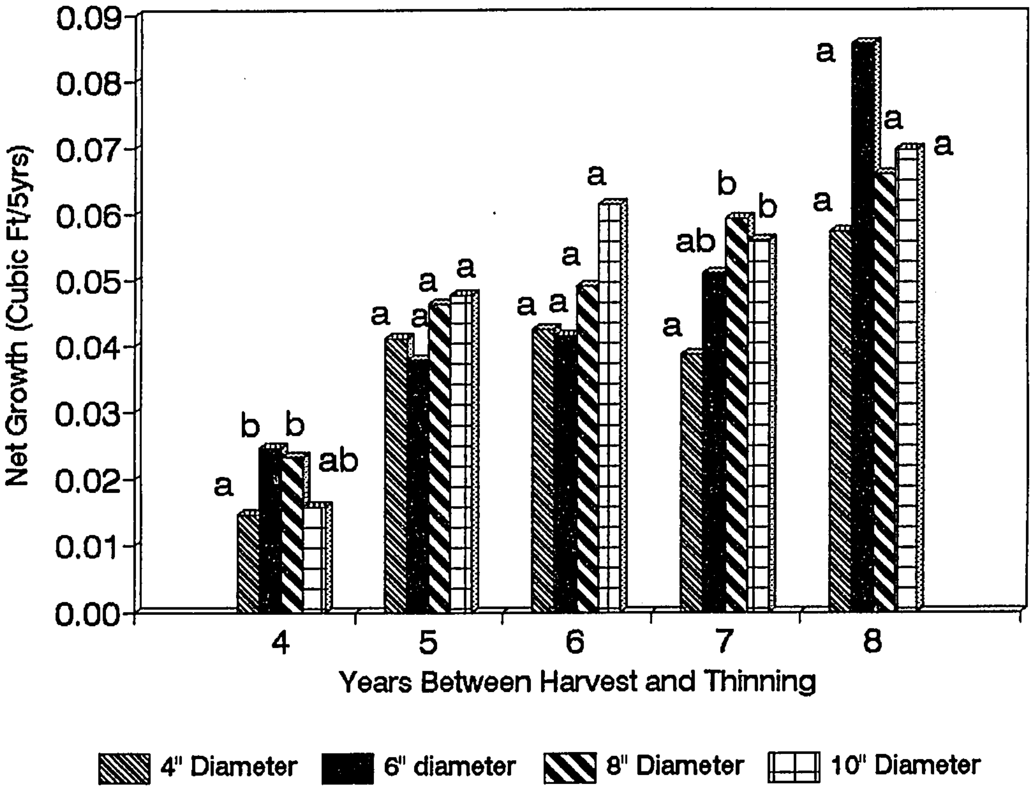

Figure 18. Effects of stump diameter on net growth. Bars in group with different letters differ significantly (p<0.1).

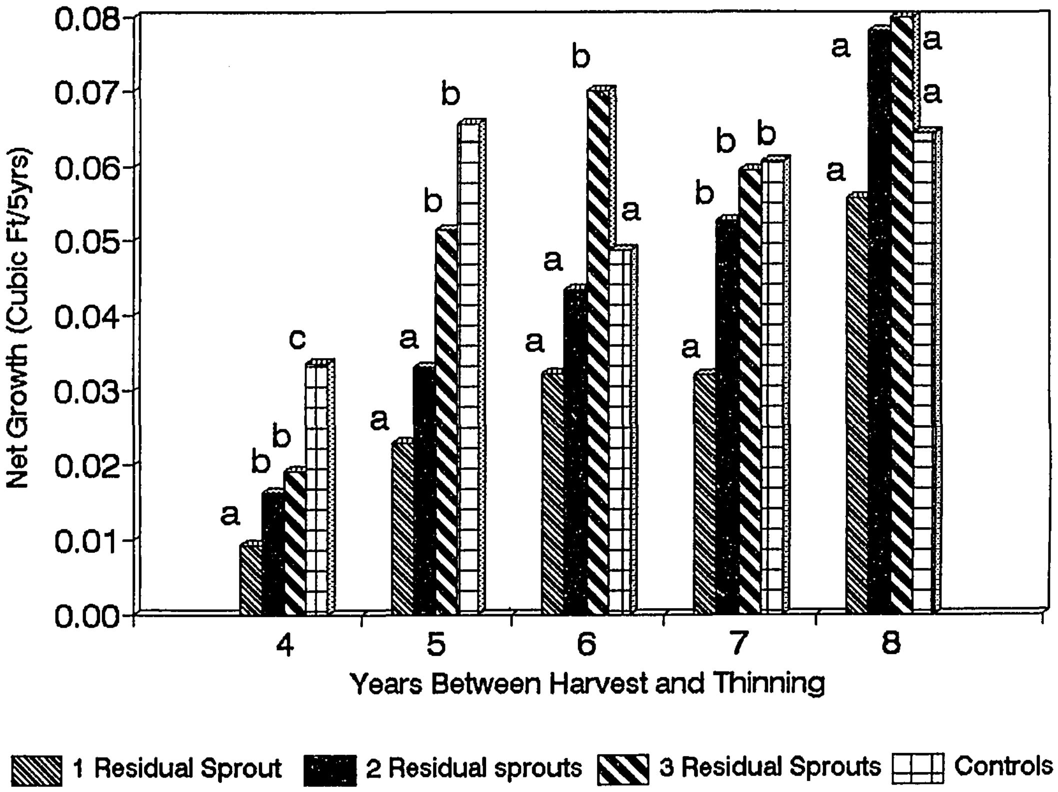

Figure 19. Effects of number of residual sprouts on net growth. Bars in group with different letters differ significantly (p<0.1).

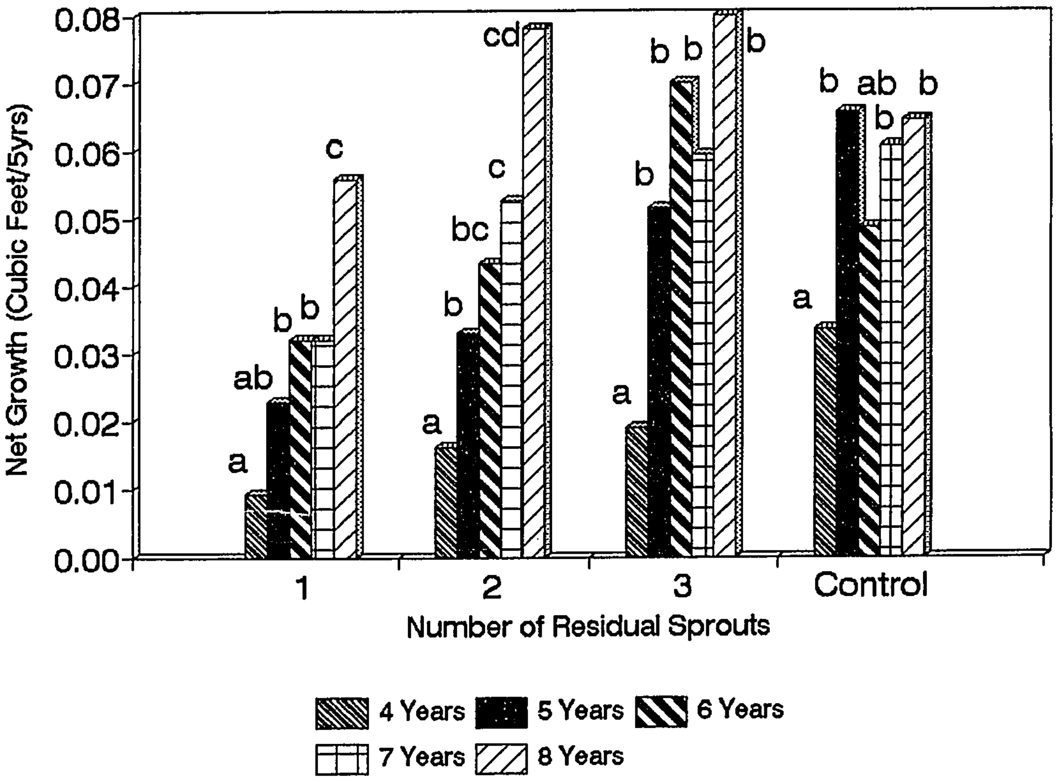

Figure 20. Effects of age of sprouts on net growth. Bars in group with different letters differ significantly (p<0.1).

Yield Estimates

Yield in 1985

The 1985 data on yield estimates were collected by Bennett (1990) and analyzed by this author. In general, stump diameters significantly affected yield at sprout age 4 years, but not at sprout ages 5, 6, 7, and 8 years. Number of residual sprouts were for each sprout age group was significant. The interaction between stump diameters and number of residual sprouts was not significant.

Stump Diameters. Stump diameter at time of thinning did not consistently affect yield (Figure 21). For 4-year-old sprouts, yield for a 4-inch diameter stump was lower than yield from an 8 and 10-inch diameter stump.

Number of Residual Sprouts. The highest yield was in the unthinned control (Figure 22). The lowest yield was in the 1 residual sprout class. At sprout age 7 and 8 years, the yield for the 3 residual sprout class was similar to the yield of the unthinned control because the growth of 3 residual sprouts approached the growth of unthinned sprouts. The effects of coppice thinning were not clear. The residual sprouts probably needed more time to express consistent growth difference.

Age of Sprouts. The age of sprouts significantly affected the 1985 yield (Figure 23). Furthermore, the

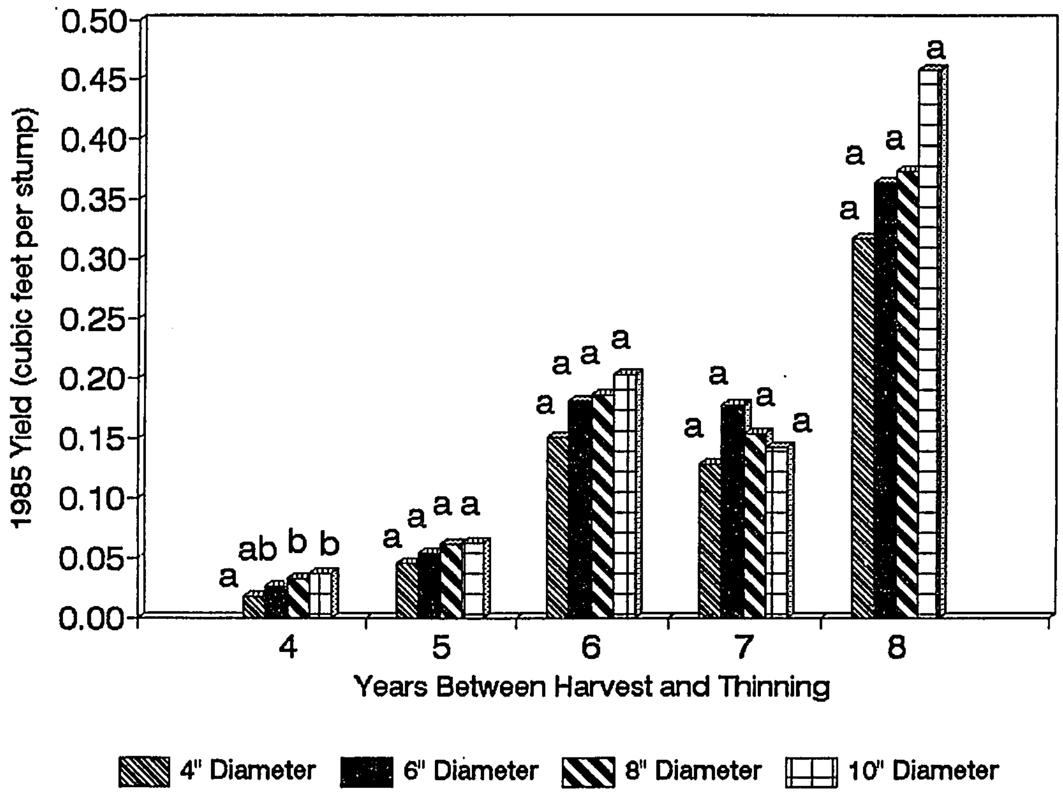

Figure 21. Effects of stump diameter on yield in 1985. Bars in group with different letters differ significantly ($p<0.1$).

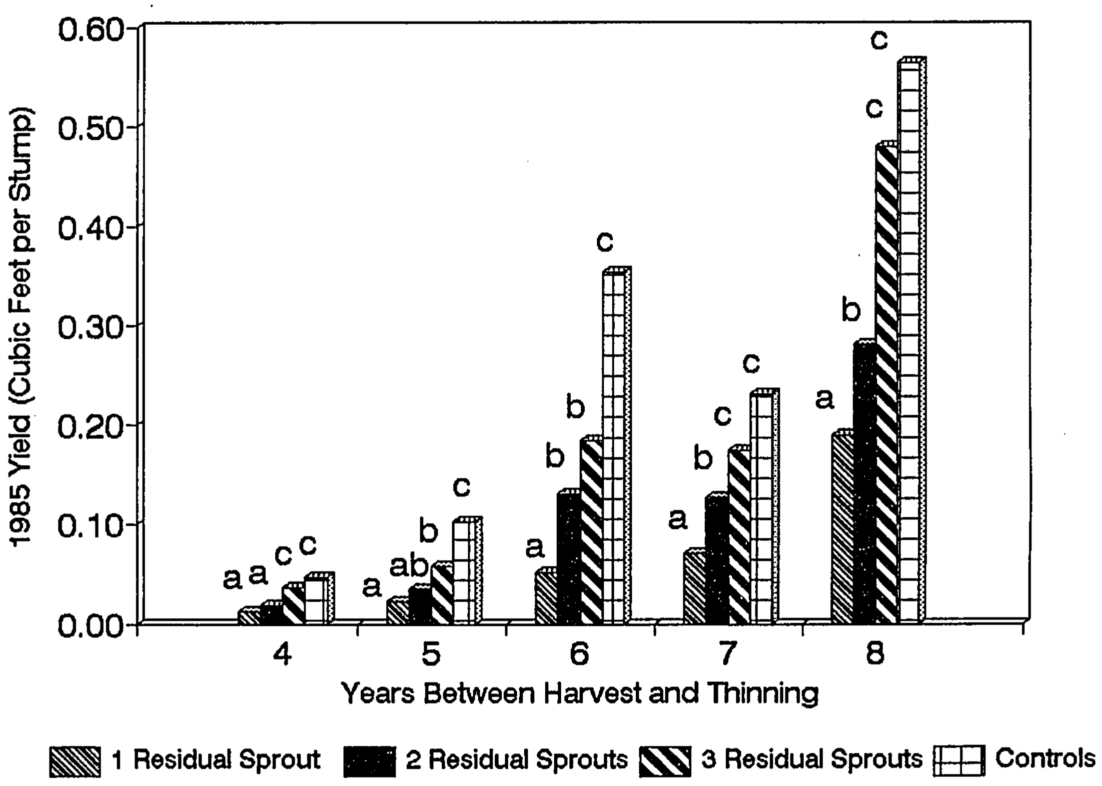

Figure 22. Effects of number of residual sprouts on yield in 1985. Bars in group with different letters differ significantly (p<0.1).

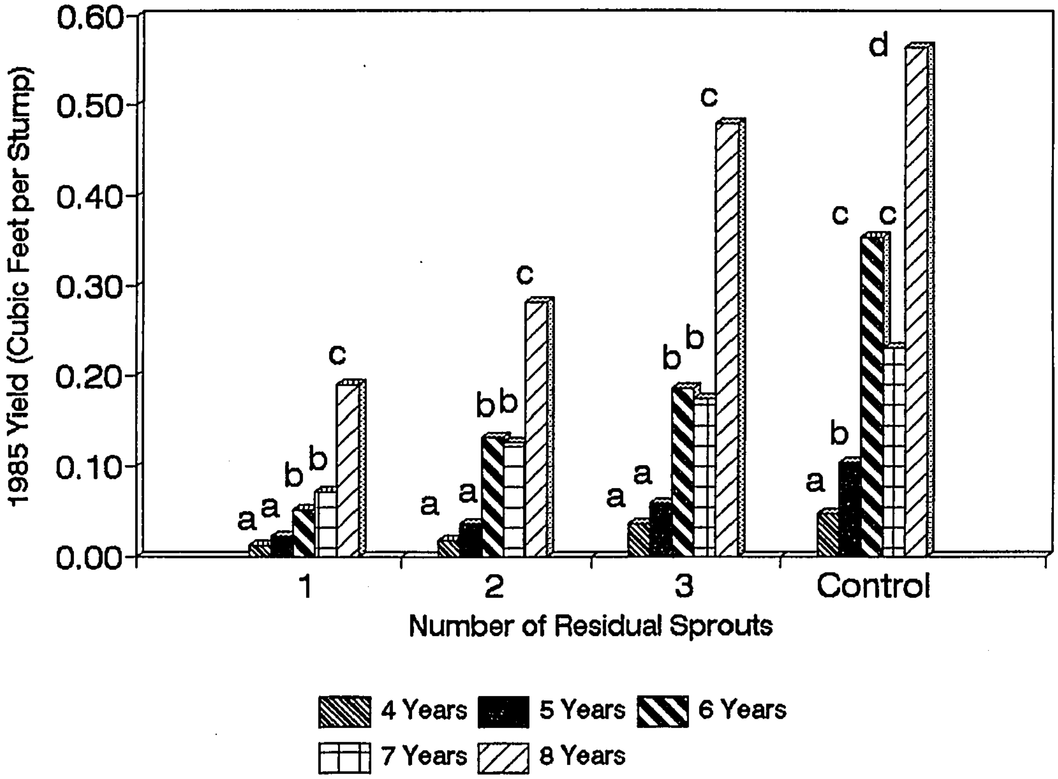

Figure 23. Effects of age of sprouts on yield in 1985. Bars in group with different letters differ significantly (p<0.1).

interaction among age of sprouts and number of residual sprouts was significant, but the interaction among age of sprouts and stump diameter was not. The interaction among age of sprouts, stump diameters, and number of residual sprouts was not significant.

Eight-year-old sprouts had the highest yield, and it was significant at all age groups. The lowest yield was at age 4 years. However, the yield among 6 and 7 year was not significant because perhaps the site quality of 7-year-old sprouts affected the yield. Daniel et al. (1979) indicated that soil quality is one of the chief constraints on silviculutral practices. As soils become deeper, less stony, and better supplied with nutrients and water, the silvicultural options increase in number and variety.

Yield in 1990

In general, stump diameters significantly affected yield in 1990 at sprout ages 4, 6, and 7 years, and not at sprout ages 5 and 8 years. Number of residual sprouts significantly affected yield at all sprout ages. The interaction between stump diameters and number of residual sprouts was not significant.

Stump Diameters. Generally, stump diameter at time of thinning did not consistently affect yield (Figure 24). For 4-year-old sprouts, yield for a 4 and 10-inch diameter stump

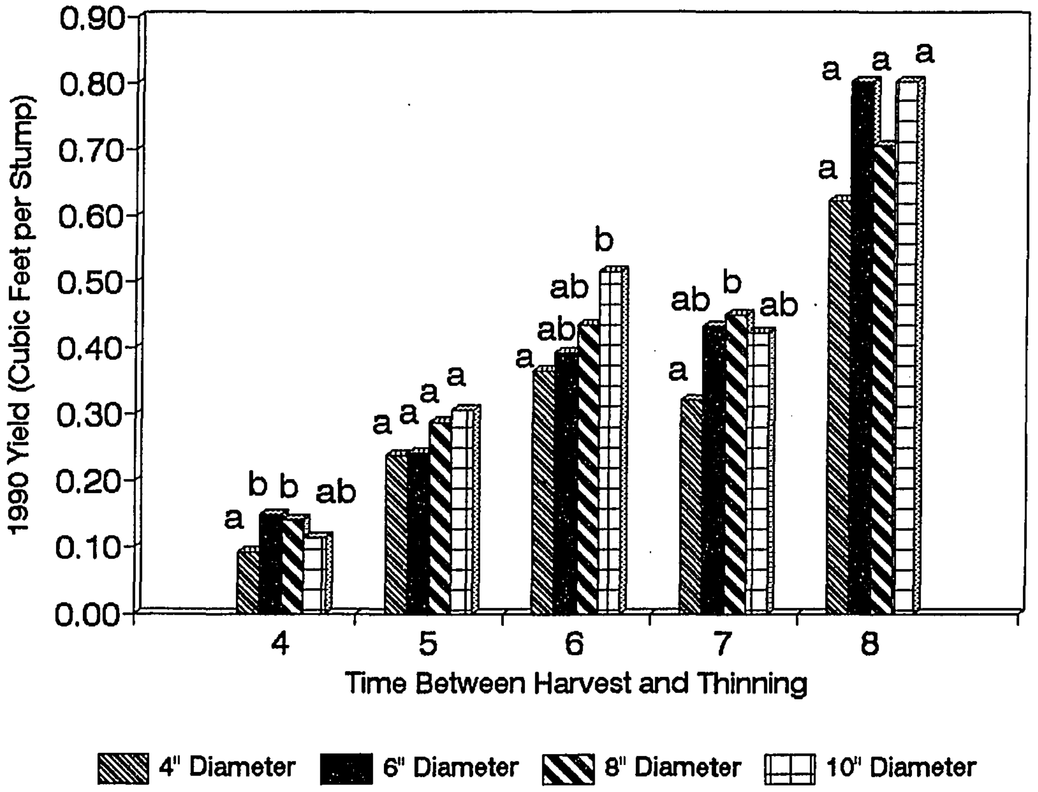

Figure 24. Effects of stump diameter on yield in 1990. Bars in group with different letters differ significantly (p<0.1).

were lower than yield from a 6 and 8-inch diameter stump. At sprout age 6 years, yield for a 10-inch diameter stump was lower than that for a 4-inch diameter stump. For 7-year-old sprouts, yield for a 4-inch diameter stump was lower than yield from an 8-inch diameter stump.

Number of Residual Sprouts. The unthinned control had the highest yield at sprout age 4 years (Figure 25). The 1 residual sprout class had the lowest yield. Starting at sprout age 5 years, yield for the 3 residual sprouts class was not different when compared to yield of the unthinned control. There was not a significant difference at sprout age 7 years between yield of 2 residual sprouts and 3 residual sprouts. At sprout age 8 years, there was not a significant difference between yield of 2 residual sprouts and yield of 3 and unthinned residual sprouts. Two and 3 residual sprouts yield was approaching the yield of unthinned sprouts.

Age of Sprouts. Age of sprouts significantly affected 1990 yield (Figure 26). The interaction among age of sprouts and number of residual sprouts was significant, but the interaction between age of sprouts and stump diameter was not. The interaction between age of sprouts, stump diameters, and number of residual sprouts was not significant. Eight-year-old sprouts had the highest yield. Four-year-old sprouts had the least yield. There was not a

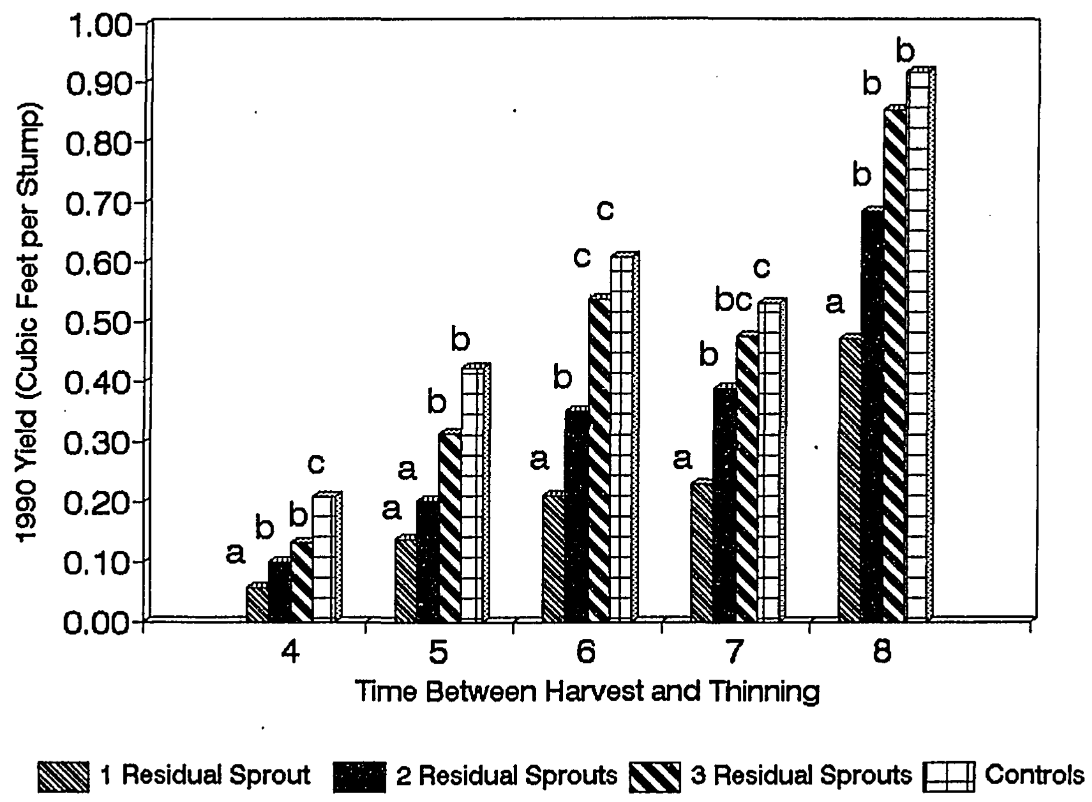

Figure 25. Effects of number of residual sprouts on yield in 1990. Bars in group with different letters differ significantly (p<0.1).

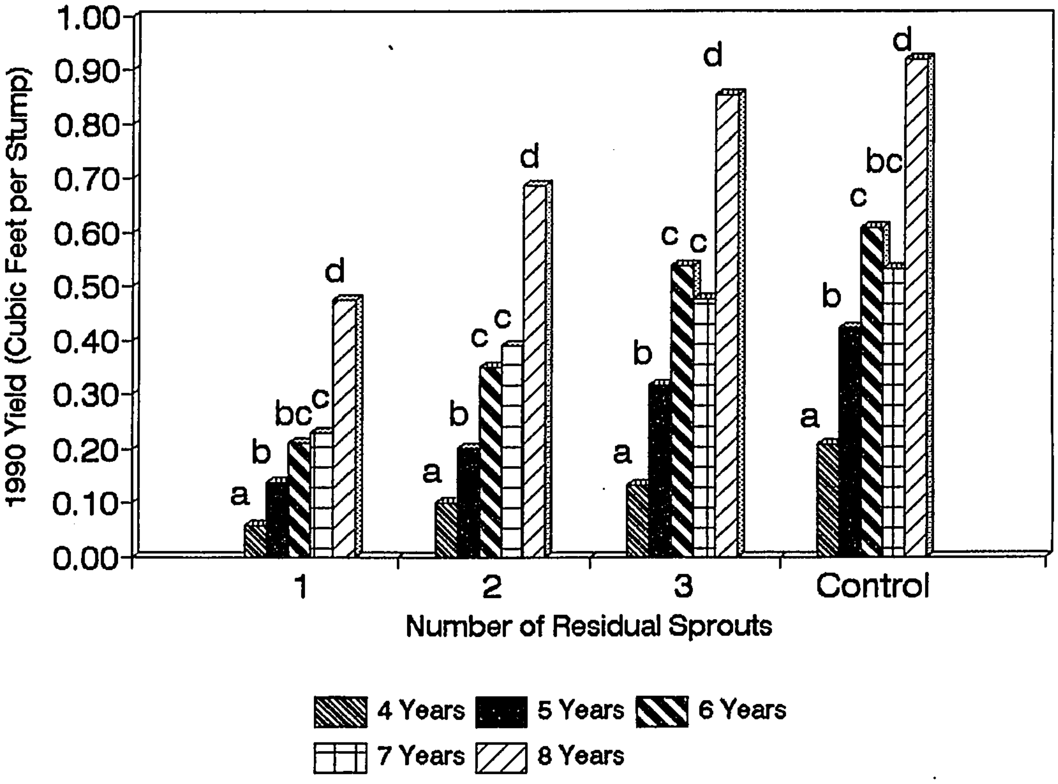

Figure 26. Effects of age of sprouts on yield in 1990. Bars in group with different letters differ significantly (p<0.1).

significant difference between sprout age 6 and 7 years. The reason could due to site quality or annual precipitation differences.

Biological Rotation Age

Biological rotation age is defined at the point of culmination of mean annual increment (Avery and Burkhart 1983). An alternative is to define rotation age as the age at which annual growth rate (in either biomass or economical terms) falls below some arbitrary, acceptable level (Daniel et al. 1979). In this study, the initial definition is more appropriate.

The estimated biological rotation age of Emory oak sprouts is based on source data collected earlier by Touchan (1986), as illustrated in Figure 27. The figure shows that the culmination of growth in total cubic feet per year is approximately at 45 years, after which the mean annual increment declines gradually. At the culmination point, biomass production is maximized. Emory oak sprouts are approximately 6 to 8 inches in DRC at this rotation age. However, to maximize profit, the sprouts might be cut earlier.

Smith (1962) stated that thinning can shorten the rotation age by making crop trees grow to the desired size at an earlier age. Daniel et al. (1979) also indicated

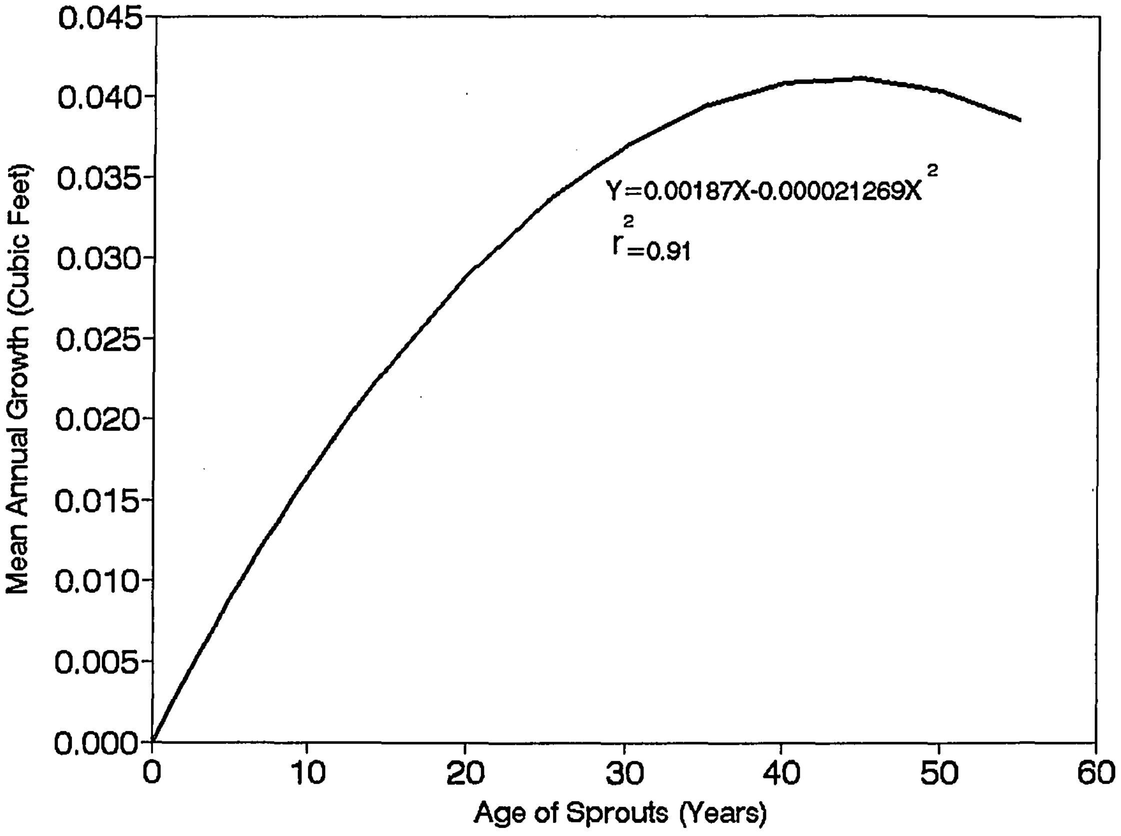

Figure 27. The relationship between MAG and age of Emory oak sprouts in southeastern Arizona.

that thinning can shorten rotation length, if the criteria used is the achievement of a diameter rather than the culmination of MAG.

This study is in agreement with the above authors on their statements. For example, the number of residual sprouts for each sprout age group significantly affected MAG (Figure 28). MAG for the unthinned control was lower than the thinned coppice sprout at all ages. For 8-year-old sprouts, MAG for 1 residual sprout was higher than that for the 2 residual sprouts, 3 residual sprouts, and the unthinned control. Moreover, it was noticed that many sprouts from stumps with 1, 2, or 3 residual sprouts were between 4 and 5 inches DRC approached the 6 to 8 inches DRC target. This study, therefore, showed that coppice thinned sprouts grew faster than unthinned sprouts, and coppice thinned sprouts will reach the size class as represented by the rotation age estimated originally in a shorter period of time. As a consequence, fuelwood cutters in southeastern Arizona should be able to harvest the coppice thinned sprouts more frequently than the unthinned sprouts.

Similar results have been reported elsewhere. For example, Lowell et al. (1989) conducted a study on the effect of early thinning on coppice-regenerated scarlet oak (*Quercus coccinea*), black oak (*Quercus velutina*), and white oak (*Quercus stellata*) in southeastern Missouri, and found

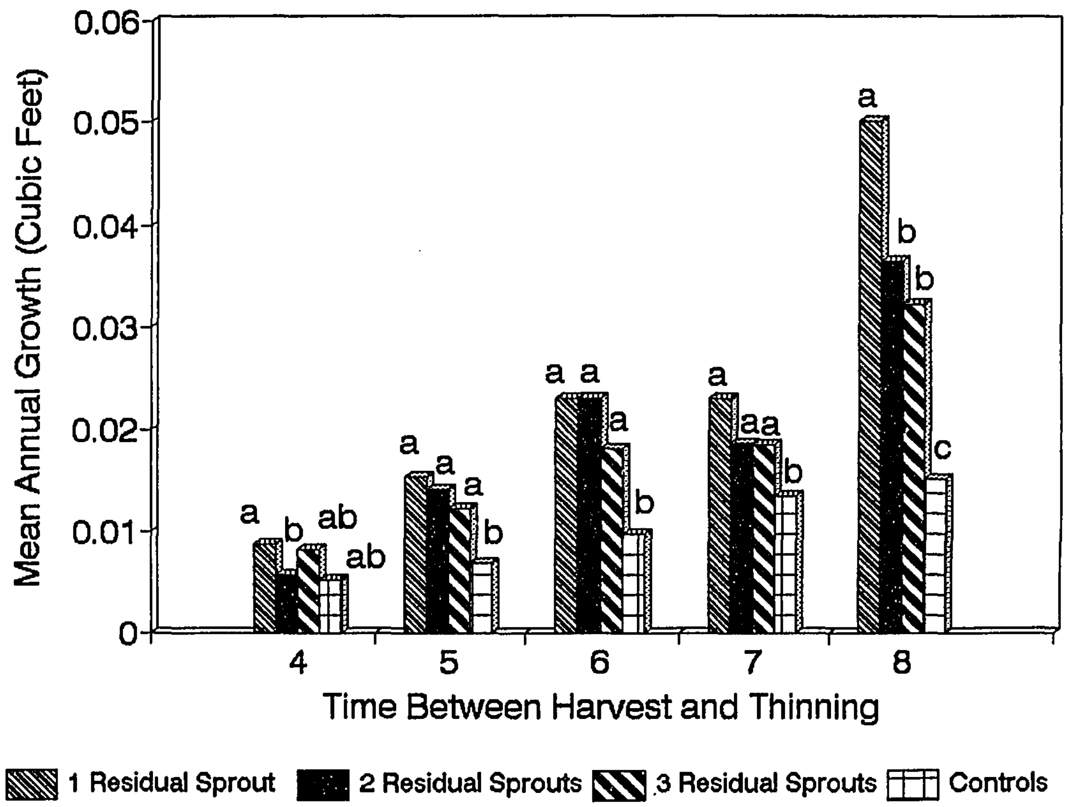

Figure 28. Comparison between MAG of thinned sprouts and unthinned sprouts (Control). Bars in group with different letters differ significantly (p<0.1).

that thinning clumps of sprouts significantly increased diameter growth of residual sprouts. Johnson and Rogers (1984) predicted 25th-year dbh of thinned stump sprouts of northern red oak (*Quercus rubra*) in southwestern Wisconsin, and their model showed that diameters of individual stems can be maximized when clump thinning was done as early as 5 years after harvest. Other reports have also shown a significant increase in growth of oak stump sprouts when clump thinning was done as early as 5 years after harvest (Lamson 1983 and Mitchel et al. 1985). High quality stems resulted when cutting practices promoted initiation of a sprout at or below ground line when clumps were thinned early to a single stem (Stroempl 1983, Johnson and Godman 1983).

Site quality could be an important factor in increasing or decreasing the biological rotation age of the trees. Daniel et al. (1979) indicated that trees on a poorer site take a longer time to reach the culmination point than trees on a better site.

In this study, it was difficult to determine how the coppice thinning treatments would affect the biological rotation age of individual Emory oak sprouts, because the sprouts are still growing at increasing MAG rates (Figure 27). A longer period of study is needed to determine the effects of coppice thinning treatments on the biological rotation age of Emory oak. However, the time required for sprouts to reach the size classes defined originally by the estimated rotation age appears to be shortened.

MANAGEMENT IMPLICATIONS

This study has a bearing on the choices that managers of the Emory oak woodlands might make. In particular, this study helps to explain the effects of stump diameter at the time of harvest, differing numbers of residual sprouts after coppice thinning, and age of sprouts at the time of coppice thinning on the growth and yield of Emory oak sprouts. From the results of the study, a number of management implications can be made.

The effects of stump diameter at the time of harvest on the subsequent growth of the sprouts was inconclusive. It is anticipated that fuelwood gatherers will have a tendency to cut the larger trees, since larger trees require less labor to harvest a given volume of firewood. However, larger trees also are more likely to have heart rot and other diseases (Touchan 1986, Callison 1989). Removal of larger trees could result in a reduction of disease in the oak woodlands. There is one negative impact of harvesting larger trees, and that is eliminating the number of trees that produce seeds. Frequent clear-cutting without leaving trees for seed production will weaken the productivity of the stand.

This study found that growth of residual sprouts depends on the number of sprouts left after thinning.

Survivor growth, gross growth, net growth, and yield were lowest for stumps with 1 residual sprout, except for NG at age 8-years-old sprouts. There were no significant differences in NG between 1, 2, or 3 residuals sprouts and the unthinned controls when considered as a clump. However, for individual sprouts at age 8 years, the MAG per sprout increased as the number of residual sprouts per stump was reduced. Based on this relationship, it is recommended that 1 residual sprout be left when thinning sprouts. With 1 residual, the growth will be concentrated on a single stem. This means that the stem will reach a specified diameter in a shorter period of time. The analysis indicated that there were no significant differences between the NG of 1 residual sprout and the other thinning coppice levels. For the fuelwood cutter, a single large sprout translates into reduced labor in harvesting, relative to multiple smaller sprouts. It also allows the fuelwood cutters to harvest the area more frequently.

When selecting residual sprouts in prescribing thinning, the first criteria should be size. At age 7 or 8 years, the largest sprouts will have a DRC of 2 to 3 inches and will be 8 to 10 feet tall. The second criteria should be the residual sprout vigor. No sprouts with insect damage, browsing damage, or evidence of disease should be selected as a residual sprout. In general, the largest healthy sprout in stump should be the residual sprout.

The age of the sprouts at the time of thinning significantly affects growth. If the sprouts are thinned too soon, resprouting will occur. Resprouting can reduce the value of thinning greatly. When thinning is delayed for too long, potential growth will be lost to competition and mortality.

Smith (1962) stated that the first thinning of a stand should occur when the crowns or root systems begin to interfere with each other. Daniel et al. (1979) agreed, stating that the first thinning should be prior to the onset of serious between tree competition. Johnson and Rogers (1984) found that delaying the thinning of red oak sprouts after 5 years of age substantially decreased 25 year dbh growth. In this study, there was an increase in the mortality of the control sprouts in the 6th year (Figure 14). Based on those results, it is recommended that thinning be conducted in the 5th-year of the sprouts growth.

Proper timing of thinning can reduce the rotation age of Emory oak sprouts, if the rotation is based on achievement of a specified diameter. In this study, it was observed that sprouts from stumps with 1, 2, or 3 residual sprouts were almost 4 to 5 inches in DRC, indicating that the thinned sprouts were approaching the usable size class. Regardless of the criteria for their ultimate harvest, thinned coppice sprouts will be ready for harvest before their unthinned counterparts. This, in turn, might allow a more frequent harvesting, which is beneficial from the viewpoint of the fuelwood harvester and, because of more frequent entry into a woodland, the forest manager concerned with multiple use objectives.

The following preliminary schedule of treatments can serve as a guide to managers who are utilizing Emory oak for fuelwood:

0 years: Growth of sprouts begins with the harvesting of the original trees. If the previous stand is harvested in the springtime, the new sprouts can appear by fall.

5 years: Thin the clumps of sprouts to 1 residual sprout. The residual sprout should be the largest sprout with good vigor. Sprouts can be thinned after 5 years. However, delaying thinning can reduce diameter growth in the residual sprouts. More than 1 residual can be left. (The data collected in this study showed no significant differences in the volume growth per stump when 2 or more residual sprouts were left). However, since more sprouts are competing for nutrients,

water, and sunlight, the growth per sprout will be less resulting in reduced diameter growth and postponement of harvest.

Harvest time: Trees should be harvested after they reached specified diameter. A diameter of 6 to 8 inches DRC should be achievable in 20 to 30 years.

The recommendations offered are based on a relatively short period of data collection. With further study, the recommendations likely might be refined or modified.

SUMMARY AND CONCLUSIONS

Bennett (1990) studied the effects of coppice thinning on growth and yield of Emory oak in southeastern Arizona one year after coppice thinning. His research was continued by the author to study in more detail the effects of coppice thinning on survivor growth, ingrowth, mortality, gross growth, net growth, yield, and the biological rotation age of Emory oak sprouts.

Growth Components

Survivor growth varied within each stump diameter class. Of the 4 stump diameter classes evaluated, no particular diameter class had the highest growth. For 4-year-old sprouts, survivor growth for 4-inch diameter stump was lower than survivor growth from a 6-inch diameter stump. At sprout age 7 years, survivor growth for 4-inch diameter stump was lower than that for an 8-inch diameter stump. The number of residual sprouts for each age group significantly affected survivor growth. The unthinned sprouts showed the highest survivor growth at age 4-year-old sprouts. Survivor growth for 1 residual sprout was lower than the other thinning levels. At sprout age 7 and 8, the 2 and 3 residual sprouts were not different from the unthinned residual sprouts. This indicates that survivor growth of 2 and 3 residual sprouts started to reach that of unthinned sprouts. Sprout at age 8 had the highest growth. Sprouts at age 4 had the lowest growth.

Stump diameter did not affect ingrowth in all age groups significantly, except at sprout age 7 years. Sprouts at age 7 years, ingrowth for a 10-inch diameter stump was significantly higher than the other stump diameter classes. The number of residual sprouts significantly affected ingrowth. The unthinned residual sprouts showed the highest ingrowth at sprout ages 6, 7, and 8 years. At sprout age 8 years, ingrowth of 1 residual sprouts was significantly higher than ingrowth of 2 and 3 residual sprouts. Ingrowth was higher in the unthinned controls; this could be due to the larger number of sprouts available to grow into the smallest size class. Resprouting was higher at 1 residual sprout perhaps because of increased access to food, water, and nutrients. The highest ingrowth at 1 and 2 residual sprouts was at sprout age 5 year. Sprout at age 6 years showed the highest ingrowth was at the 3 residual sprouts and the uncut residual sprouts.

Stump diameters did not affect mortality consistently. At sprout age 8 years, mortality for 4-inch diameter stump was higher than that for 6-and 8-inch diameter stump. Mortality for 10-inch diameter stump was higher than that for a 6 and 8-inch diameter stump at sprout age 4 years.

Unthinned sprouts had the highest mortality. The high mortality level in the unthinned sprouts could due be to the high competition for food, sunlight, and water. Age of sprouts were significant. The highest mortality level was occurred at sprout age 6 and 8 years.

Growth Estimates

Generally, stump diameter at time of thinning did not consistently affect GG. At age 4 years, GG for 4-inch diameter was lower than that for a 6 and 8-inch diameter stump. GG for 4-inch diameter stump was lower than that for an 8 and 10-inch diameter stump at age 7 years. Of the 3 coppice thinning levels, the unthinned sprouts and 3 residual sprouts had the greatest GG at sprout ages 5 and 6 years. The 1 residual sprout showed the lowest GG at sprout ages 4 and 7 years. Of the 5 sprout age groups, sprout age 8 years had the highest growth at 1 and 2 residual sprouts class, and sprout age 4 years had the lowest growth at all coppice thinning levels.

Stump diameters significantly affected NG at sprout age 4 and 7 years. At sprout age 4 years, NG for 4-inch diameter stump was lower than that for a 6 and 8-inch diameter stump. NG for a 4-inch diameter stump was lower than that for an 8 and 10-inch diameter stump at sprout age 7 years. Of the 3 coppice thinnings the 1, 2, and 3 residual sprouts and unthinned sprouts were not significantly different at age 8 years. Age significantly affected NG. Eight-year-old sprouts had the highest NG at 1 and 2 residual sprouts class. The lowest NG was at sprout age 4 years.

Yield Estimates

For 4-year-old sprouts, yield for 4-inch diameter stump was lower than yield from 8 and 10-inch diameter stump. Of the 3 coppice thinnings applied at similar age groups, the greatest yield was in the unthinned control. The lowest yield was in the 1 residual sprout class. Of the 5 sprout age groups, sprout at age 8 years had the highest yield, and the lowest yield was at sprout age 4 years.

For 4-year-old sprouts, yield for 4 and 10-inch diameter stump were lower than yield from 6 and 8-inch diameter stump. At sprout age 6 years, yield for 10-inch diameter stump was lower than that for an 4-inch diameter stump. For 7-year-old sprouts, yield for 4-inch diameter stump was lower than yield from a 8-inch diameter stump. Of the 3 coppice thinning, the 1 residual sprout had the lowest yield. Starting at sprout age 5 years, yield for the 3 residual sprouts class was not different when compared to yield of the unthinned control. At sprout age 8 years, there was not a significant difference between yield of 2 residual sprouts and yield of 3 and unthinned residual sprouts. Of the 5 sprout ages, sprout at age 8 years had the highest yield. Sprouts at age 4 years had the lowest yield.

Biological Rotation Age

The effects of coppice thinning on possibly shortening the rotation age was not clear. Those sprouts are still growing at increasing MAG rates. This study needs to be continued for a longer period of time to define the point of culmination. However, rotation age based on diameter class appears to be shortened. Determining the effects of coppice thinning on shortening the biological rotation is important to the land manager to maximize profit.

Future Research

The effects of stump diameter on the growth and yield of Emory oak were inconclusive. The number of residual sprouts significantly affected growth. Survivor growth, GG, NG, and yield were lowest for stumps with 1 residual sprouts, except for NG at age 8-years-old sprouts. There was no significant differences in NG between 1, 2, or 3 residual sprouts and the unthinned controls when considered as a clump. However, individual sprouts at age 8 years, the MAG per sprout increased as the number of residual sprouts per stump was reduced. Based on this relationship, it is recommended that 1 residual sprout be left when thinning sprouts. Age of the sprouts at the time of thinning, greatly affected growth components, growth estimates, and yield estimates. In this study, there was an increase in the mortality of the control sprouts in the 6th year. Based on those results, it is recommended that thinning be conducted in the 5th year of the sprouts growth. Proper time of thinning also might reduce the rotation age of Emory oak sprouts, if the rotation is based on achievement of a specified diameter.

Finally, Emory oak regeneration patterns should be monitored for a longer period of time to further refine these recommendations. At the same time, more studies are needed, for example,

1. Investigation of the physiological relationships between Emory oak stumps and sprouts, such as the effects of hormones on sprout growth, formation of dormant buds in Emory oak, etc.,
2. Investigation of the effects of the root system, such as root size, spread, and carbohydrate reserve on the growth of Emory oak sprouts,
3. Comparisons of seedlings growth with sprout growth up to the rotation age growth, and
4. Studies of the effects of repeated coppice thinning

on sprout vigor.

All past, present, and future studies should be helpful in preparing comprehensive holistic forest management plans for the oak woodlands in southeastern Arizona. Such plans also might help develop more efficient management practices to meet the needs of southeastern Arizona's growing population for multiple benefits.

APPENDIX I. Least square means and their standard errors for survivor growth of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter.

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3/5 yrs									
4	.014	.002	.036	.005	.042	.004	.040	.004	.069	.008
6	.023	.002	.034	.004	.044	.003	.052	.004	.088	.010
8	.020	.002	.039	.004	.048	.005	.059	.005	.068	.007
10	.017	.003	.041	.005	.060	.009	.054	.005	.078	.008

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX II. Least square means and their standard errors for survivor growth of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts.

	Age of sprouts(yr)									
	4		5		6		7		8	
Residual sprouts	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	$Ft^3/5$ yrs									
1	.008	.001	.014	.002	.025	.003	.028	.002	.053	.006
2	.015	.002	.027	.003	.041	.006	.052	.004	.078	.008
3	.018	.002	.049	.004	.063	.008	.060	.006	.083	.010
C	.033	.003	.061	.008	.065	.005	.064	.005	.088	.010

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

APPENDIX III. Least square means and their standard errors for ingrowth of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter.

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
4	.003	.001	.006	.001	.008	.002	.002	.000	.004	.002
6	.002	.001	.005	.001	.010	.002	.003	.001	.002	.001
8	.004	.002	.008	.002	.010	.003	.002	.000	.002	.001
10	.001	.000	.009	.002	.008	.001	.006	.002	.007	.003

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX IV. Least square means and their standard errors for ingrowth of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts.

	Age of sprouts(yr)									
	4		5		6		7		8	
Residual sprouts	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
1	.002	.001	.010	.002	.008	.003	.004	.001	.003	.001
2	.001	.001	.007	.001	.003	.001	.001	.000	.001	.000
3	.002	.001	.002	.001	.007	.002	.002	.001	.000	.000
C	.004	.002	.009	.001	.018	.003	.007	.001	.012	.004

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

APPENDIX V. Least square means and their standard errors for mortality of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter.

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
4	.005	.024	.004	.003	.040	.010	.015	.003	.079	.022
6	.004	.002	.009	.004	.019	.012	.017	.003	.020	.005
8	.003	.003	.005	.003	.042	.007	.010	.003	.019	.007
10	.011	.003	.012	.005	.034	.004	.019	.006	.074	.017

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX VI. Least square means and their standard errors for mortality of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts.

	Age of sprouts(yr)									
	4		5		6		7		8	
Residual sprouts	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
1	.002	.001	.007	.003	.002	.003	.000	.001	.000	.004
2	.001	.001	.001	.000	.002	.002	.000	.001	.002	.003
3	.003	.001	.001	.002	.000	.002	.002	.005	.015	.010
C	.019	.004	.020	.006	.173	.018	.052	.006	.175	.027

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

APPENDIX VII. Least square means and their standard errors for gross growth of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter.

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3/5 yrs									
4	.016	.002	.042	.006	.051	.004	.042	.004	.073	.008
6	.025	.002	.040	.004	.054	.004	.054	.005	.090	.011
8	.024	.003	.048	.005	.058	.006	.061	.005	.070	.007
10	.018	.003	.050	.006	.068	.009	.060	.005	.084	.008

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX VIII. Least square means and their standard errors for gross growth of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts

	Age of sprouts(yr)									
	4		5		6		7		8	
Residual sprouts	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3/5 yrs									
1	.010	.002	.024	.004	.033	.004	.032	.003	.056	.006
2	.016	.002	.033	.003	.044	.006	.053	.004	.079	.008
3	.020	.002	.052	.004	.070	.008	.061	.006	.083	.010
C	.037	.004	.070	.008	.083	.006	.071	.006	.010	.010

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

APPENDIX IX. Least square means and their standard errors for net growth of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3/5 yrs									
4	.015	.002	.041	.006	.043	.0047	.039	.004	.057	.009
6	.025	.003	.038	.005	.042	.0054	.051	.004	.086	.010
8	.023	.003	.046	.005	.049	.0063	.059	.005	.066	.008
10	.016	.003	.048	.006	.061	.0100	.056	.005	.070	.008

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX X. Least square means and their standard errors for net growth of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts

	Age of sprouts(yr)									
	4		5		6		7		8	
	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
Residual sprouts	$Ft^3/5$ yrs									
1	.010	.002	.023	.004	.032	.004	.032	.003	.056	.006
2	.016	.002	.033	.004	.044	.006	.053	.004	.078	.008
3	.019	.002	.051	.004	.070	.008	.059	.006	.080	.009
C	.034	.004	.066	.009	.049	.007	.061	.005	.064	.011

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

APPENDIX XI. Least square means and their standard errors for 1985 yield of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
4	.018	.004	.041	.009	.151	.020	.129	.013	.318	.035
6	.026	.004	.054	.007	.181	.018	.177	.018	.364	.045
8	.033	.004	.061	.008	.186	.025	.154	.017	.374	.036
10	.037	.004	.063	.009	.203	.019	.143	.013	.458	.054

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX XII. Least square means and their standard errors for 1985 yield of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts

	Age of sprouts(yr)									
	4		5		6		7		8	
Residual sprouts	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft3									
1	.012	.002	.022	.004	.052	.008	.071	.005	.190	.019
2	.018	.003	.035	.006	.132	.017	.127	.011	.281	.024
3	.036	.004	.058	.008	.185	.019	.175	.015	.479	.048
C	.047	.006	.104	.013	.353	.031	.231	.025	.564	.064

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

APPENDIX XIII. Least square means and their standard errors for 1990 yield of coppice thinned Emory oak sprouts in southeastern Arizona based on stump diameter

	Age of sprouts (yr)									
	4		5		6		7		8	
Stump diam. (inches)	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
4	.093	.009	.238	.028	.366	.026	.322	.033	.623	.053
6	.149	.013	.243	.025	.392	.028	.432	.035	.802	.089
8	.141	.012	.290	.026	.435	.039	.450	.041	.705	.062
10	.115	.014	.306	.030	.515	.055	.423	.034	.800	.065

LSM = Least Square Mean
SE = Standard Error of LSM

APPENDIX XIV. Least square means and their standard errors for 1990 yield of coppice thinned Emory oak sprouts in southeastern Arizona based on number of residual sprouts

	Age of sprouts(yr)									
	4		5		6		7		8	
Residual sprouts	LSM	SE	LSM	SE	LSM	SE	LSM	SE	LSM	SE
	Ft^3									
1	.057	.009	.138	.019	.211	.024	.229	.017	.473	.044
2	.010	.010	.201	.018	.350	.039	.390	.043	.685	.052
3	.132	.009	.315	.022	.539	.046	.476	.043	.853	.069
C	.208	.018	.422	.042	.608	.043	.532	.046	.919	.097

LSM = Least Square Mean
SE = Standard Error of LSM
C = Control

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