SITE QUALITY FACTORS AFFECTING *ACER SACCHARUM, QUERCUS RUBRA AND QUERCUS ALBA* ABUNDANCE AND HEIGHT GROWTH RATES IN YOUNG EVEN-AGED STANDS LOCATED IN CENTRAL MISSOURI

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

SITE QUALITY FACTORS AFFECTING *ACER SACCHARUM, QUERCUS RUBRA AND QUERCUS ALBA* ABUNDANCE AND HEIGHT GROWTH RATES IN YOUNG EVEN-AGED STANDS LOCATED IN CENTRAL MISSOURI

presented by Joshua H. Stevens,

A candidate for the degree of Master of Science, and hereby certify that in their opinion it is worthy of acceptance.

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Dr. Rose-Marie Muzika

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Dr. Randy Miles

DEDICATION

My family, my friends, my colleagues, my inspiration.

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The foundation of my career in forestry started at the University of Missouri-Columbia Forestry Department. As an undergrad I developed relationships with most of the faculty and in the course of studies for this advanced degree I leaned on many of them for assistance at some point. I'd like to thank many of the faculty at MU for being available and willing to provide insight into topics new to me.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

LIST OF TABLES

HYPOTHESIS

Soil base saturation, plant available water capacity and landscape position influence the abundance and height growth rates of sugar maple, white oak, and northern red oak as young competitors in even-aged stands.

ABSTRACT

Sugar maple importance has been increasing in Missouri's forest for the previous several decades. Managers have little information to guide them with selecting silviculture treatments for managing this increasingly important species. I examined the effects that soil water, soil nutrients, and landscape position have upon the abundance and height growth rates of sugar maple, white oak, and northern red oak in young even-aged, 15-29-year-old, forests of central and east central Missouri in the Lower Missouri and Lower Osage River valleys. Relationships were examined in plots sampled in 44 stands through examination of the soil profile, individual tree characteristics and stand characteristics at 44 sites. The data and analysis showed that sugar maple abundance is positively correlated with soil base saturation and height growth rate is positively correlated with AWC. White oak abundance was negatively correlated to soil base saturation. Northern red oak abundance occurred over a range of sites and no trends were observed with the measured factors. White and northern red oak growth rates were each negatively correlated with soil pH. The data from this study suggested that sugar maple is most competitive with more shade intolerant oaks on fertile sites with a mesic moisture regime.

CHAPTER 1: INTRODUCTION

I examined the effects that soil available water capacity, soil nutrients and landscape position have upon the abundance and height growth of sugar maple, northern red oak, and white oak. The study occurred in young even-aged (15-29 years old) forests of central and east central Missouri in the Missouri and Osage River valleys.

Oak and hickory dominate the region today and historically (Braun 1950). According to historical accounts sugar maple's local range was limited to north facing slopes in rough topography in major river valleys like the Missouri and the Mississippi rivers (Howell & Kucera 1956, Wuenscher & Valiunas 1967). Oaks dominated the higher and drier positions on the landscape. In the last half-century sugar maple has spread from the fire protected north slopes onto the ridges and exposed slopes creating a recalcitrant oak forest (Johnson et al. 2009). Today, sugar maple density is great in the understory and midstory of many of the oak-hickory forests in the major river valleys regardless of aspect or topographic position.

Historical disturbances, primarily wildland fire influenced forest dynamics and composition in central Missouri (Cutter & Guyette 1994). Anthropogenic fire disturbances have become less intense and less frequent during the 20th century. The current population of landowners has changed (Butler & Leatherberry 2004) and generally is not aggressively managing their forests as the past population. Oak reproduction tolerates systems with frequent disturbances that lower the basal area (Larsen et al. 1997, Johnson et al. 2009). The reduction in landowner-induced disturbances has resulted in an aging forest across the landscape that prohibits the accumulation of oak reproduction.

Sugar maple regeneration success increases with lower frequency and lower intensity disturbances (Rochow 1972, Nigh et al. 1985). Sugar maple seedlings can persist in the shaded understory for 15-30 + years with little to no height growth until they are released by a disturbance to the canopy (Marks & Gardescu 1998, McClure et al. 2000). Sugar maple seedlings less than one inch caliper diameter have been found to have roots 20 to > 40 years old (Trimble et al.1986). I have personally observed many sugar maple stumps that are 4 inches diameter in their 7^{th} decade of growth.

In 2004, Belden and Pallardy (2009) reported a regeneration failure of *Quercus* spp. in central Missouri that was correlated to an increase in sugar maple in all size classes on most sites. Sugar maple saplings and small trees fill the midstory waiting to occupy the overstory. Oak seedlings, saplings and small tress are mostly absent. This development is common across the entire study area. These forests appear destined to conversion from oak canopy to sugar maple canopy.

However, there are many factors that influence this potential. Following a disturbance many plants that colonize a site will not reach maturity. Competition and differential growth rates are important aspects of stand development (Canham & Marks 1985, Oliver 1980). Soil, geology, aspect and location on the landscape are a few of the site factors that affect a plant's ability to compete. Will the mature maple forests be healthy? Surely the answer depends on site.

In the late 1970s the Missouri Department of Conservation (MDC) started clearcutting oak stands as a new silvicultural practice. The midstory and larger understory sugar maple was cut and allowed to re-sprout along with all the other trees. Some stands had no pre-harvest sugar maple and some had high densities. Those stands have developed and currently there is disagreement among managers as to the best approach for influencing future development. How do we manage them? With a group of species that have widely different traits, is it possible to manage them together?

These young even-aged stands will provide insight that mid-rotation and uneven-aged stands cannot. The general local prescription has been to eradicate the sugar maple to provide the oaks space to grow. Built into this prescription is the goal of increasing light reaching the ground to encourage oak regeneration ground flora diversity to attract wildlife.

In an attempt to quantify where sugar maple versus oak might be appropriate to manage, this study aims to find correlations in site conditions for productivity of sugar maple, and our two most common oaks; white oak and northern red oak. The study area is located in the Outer Ozark Border in central and east-central Missouri. A regression model was developed to determine whether soil base saturation, plant available water capacity, landscape position effect abundance or height growth rates of the selected species.

CHAPTER 2: LITERATURE REVIEW

The Role of Sugar Maple in Missouri Forests

Missouri lies on the southwestern edge of the range of sugar maple (Godman et al. 1990, Figure 1). Sugar maple abundance is historically limited in Missouri to mesic sites protected from fire in the lower elevation portions of hillslopes of tributaries in major river valleys (Howell & Kucera 1956, Wuenscher & Valiunas 1967).

In southern Illinois where the climate and physiography are similar to Missouri, General Land Survey records indicated that sugar maple (grouped with black maple) comprised an estimated 2.1 % of species in the area (Leitner & Jackson 1981). White oak and black oak were reported as the most abundant species.

In the Missouri River hills of central Missouri, sugar maple-basswood forests were reported in Boone County as recently as 1955. The Douglass and Schnabel Woods of Boone County, Missouri, consisted of sugar maple in all size classes on protected northern slopes (Kucera & McDermott 1955). Those same authors cited the Industrial World and Commercial Advertiser from 1880 as stating that sugar maple was an abundant species in Boone County.

The earliest report of sugar maple abundance increasing outside of its historical range in the lower Missouri River Valley was documented by Wuenscher & Valiunas (1967). In 1972 Rochow documented the high abundance of sugar maple saplings under a white oak dominated upland forest in the Thomas S. Baskett Wildlife & Research Education Area (Baskett) in Boone County, MO.

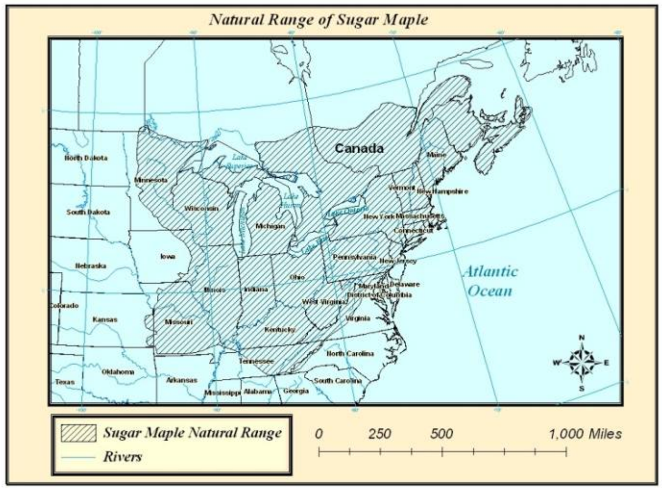


Figure 1. The natural range of sugar maple (Godman et al. 1990).

Today, the dominant forest community of the lower Missouri River valley is oak/hickory overstory with an abundance of sugar maple saplings in the mid- and under-stories and a lack of oak seedlings and saplings (Rochow 1972, Nigh et al. 1985, Pallardy et al. 1998, Belden & Pallardy 2009). In southeast Boone County, oak importance has generally been decreasing on all site types while sugar maple importance is increasing (Pallardy et al. 1998, Belden and Pallardy 2009). This is occurring across much of the study area and even other portions of Missouri's forests.

In the years preceding 1949, there was an estimated 287 mbf of sugar maple in Missouri (King et al. 1949). In 2003 there was a net 453,148 mbf of sugar maple estimated in Missouri (Moser et al. 2005), an increase of 1,578 times. This increase is mostly attributed to a lack of frequent wildfires (Abrams 1992, Nigh et al. 1985).

Effects of Available Water Capacity on Sugar Maple Abundance

Sugar maple is most common on mesic sites (Hinckley et al. 1979, Nigh et al. 1985 and Pete & Loucks 1977, Whitney 1991). Researchers in central Illinois found sugar maple to be more common on soils with an available water capacity (AWC) > 7.6 cm in the A horizon (Adams & Anderson 1980). Another southern Illinois study by Fralish (1976) found sugar maple on the footslopes in soils with AWC values ranging from 8.4-14.7 cm for the total soil profile above bedrock.

In a study examining the occurrence and abundance of sugar maple in Missouri, Nigh et al. (1985) found a correlation between AWC and sugar maple abundance. The researchers were surprised to find that in central Missouri sugar maple densities are relatively greater on xeric glades, suggesting that sugar maple has a duel site preference similar to bur oak or several other species. The authors hypothesized that the calcium concentrations in the soil enhanced the drought tolerance threshold of sugar maple (Nigh et al. 1985, Pallardy et al. 1998).

On more mesic sites sugar maple is an intrinsic accumulator in the seedling layer (Johnson et al. 2009, Jenkins & Parker 1998,). No studies were found relating soil AWC to sugar maple height growth potential.

Effects of AWC on White & Northern Red Oak Abundance

Oaks are associated with sites that have smaller AWC values (Hinckley et al. 1979, Nigh et al. 1985). On the Hoosier NF in Indiana, Morrissey et al. (2008) inventoried clearcut stands in the stem exclusion stage and found that oaks have a greater relative density on drier aspects.

White oak growth is positively correlated with proximity to the ridge or summit (McClurkin 1963). In southern Illinois white oak has greatest abundance on soils with an AWC range of 10-25 cm for all horizons combined above the fragipan or bedrock (Fralish 1988). In the glaciated portion of central Illinois white oak abundance is greatest on sites with an average AWC of 4.4 cm of the A horizon while northern red oak is more common on sites with an average AWC of 7.6 cm of the A horizon (Adams and Anderson 1980).

Site requirements for germinants and seedlings vary from those of mature trees and can change over time (Johnson et al. 2009). Oak reproduction typically dominates drier sites in the eastern Midwestern US (Johnson et al. 2009, Jenkins & Parker 1998, Villwock 2011).

Effects of Soil Base Saturation and pH on Sugar Maple Abundance and Height Growth

Sugar maple decline has been occurring in the northeastern US and southeastern Canada intermittently over the past several decades (Duchesne et al. 2005, McWilliams et al. 1996). Atmospheric acid deposition has been implicated in the decline (Foster et al. 1992, Yanai et al. 1999, Bailey et al. 2005, Kogelmann & Sharpe 2006). Acid rain accelerates soil acidification, particularly on weathered soils with limited base cation availability, by displacing base cations from the exchange sites and increasing the availability of hydrogen, aluminum (Al) and manganese (Mn) concentrations in the soil. Soils with greater concentrations of exchangeable Al and Mn have been shown to produce sugar maple trees with greater concentrations of these elements in their foliage (Juice et al. 2006, Park & Yanai 2009).

Sugar maple gets most of the Ca needed for cellular function from the mineral soil and pools the majority of it in woody biomass (Fujinuma et al. 2005). Of lesser importance are pools in the forest floor (Rochow 1975) and atmosphere.

A primary function of Ca in plants is to regulate many of the physiological functions affecting growth and stress response. Some of these functions include: water and solute movement; cell division; cell wall synthesis; damage repair from stress; plant defense signaling; respiratory metabolism; structural chemistry and woody support tissues (McLaughlin & Wimmer 1999). Increased base cation concentrations in the soil have been found to significantly increase the mycorrhizal root colonization of sugar maple seedlings (Coughlan et al. 2000, Juice et al. 2006).

Large concentrations of soil base cations have been found to increase sugar maple's ability to withstand stressors such as insect defoliation, droughts and physical wounds (Horsley et al. 2000, Huggett et al. 2007). Bailey et al. (2004) found sugar maple mortality increases in stands that have a history of two or more moderate insect defoliations coupled with an upper B horizon Ca saturation <2% or Mg saturation <0.5%. In the lower B horizon, Ca saturations <4% levels were shown to less reliably produce the same effect. This suggests that base cation saturation levels can buffer sugar maple health against outside disturbances.

Kogelmann and Sharpe (2006) found that soil pH and exchangeable Ca and Mg were inversely related to the availability of exchangeable manganese (Mn) which is considered toxic to sugar maple. Sugar maple abundance decreases on sites having greater levels of exchangeable Al and Mn. Al and Mn interfere with root uptake of Ca and Mg (Cronan & Grigal 1995 and St. Clair and Lynch 2005*a*). At a soil pH > 5.0 Ca is generally abundant and competitive with Al in the soil solution (McLaughlin & Wimmer 1999).

Dijkstra & Smits (2002) reported that sugar maple produces a high proportion of fine-roots deep into the soil providing access to nutrients in the B horizons. Base cation concentrations in the upper B horizon are correlated with foliar concentrations of base cations and sugar maple health and abundance (Van Breemen et al. 1997, Finzi et al. 1998, Bailey et al. 2004). This suggests that chemical measurements of the entire B horizon, particularly the upper B horizon, are warranted in studies examining soils and maple trees.

Sugar maple has been found to be less common on sites with small amounts of soil Ca and Mg (Van Breemen et al. 1997, Liu & Tyree 1997, Christopher et al. 2006, Juice et al. 2006, Kogelmann & Sharpe 2006). Sugar maple is more likely to exhibit symptoms of decline (Adams & Hutchinson 1992, Liu & Tyree 1997, Duchesne et al. 2002), and have decreased photosynthetic rates (Ellsworth & Liu 1994, Liu et al. 1997, Juice et al. 2006), increased crown dieback (Moore et al. 2008, Juice et al. 2006), decreased aboveground biomass growth rates (Liu & Tyree 1997, Kobe et al. 2002, Duchesne et al. 2002, Schaberg et al. 2006, Juice et al. 2006, Long et al. 2009, Moore et al. 2008, Park & Yanai 2009), decreased regeneration density (Schreeg et al. 2005, Juice et al. 2006, Moore et al. 2008), and decreased root growth (Adams & Hutchinson 1992, Juice et al. 2006, Park et al. 2008) on soils with small concentrations of exchangeable base cations.

Sugar maple survival rates increase with increasing site fertility (Schreeg et al. 2005). Sugar maple is generally found growing on soils with a pH range of 3.7-7.3 (Godman et al. 1990). In Missouri, sugar maple is most abundant on sites with greater soil pH values (Belden & Pallardy 2009, Kabrick 2011, Nigh et al. 1985, Villwock 2011 and Ware et al. 1992). In Wisconsin and Michigan, sugar maple grows best on sites with the greater pH as well (Guldin & Lorimer 1985, Pete & Loucks 1977). In Kentucky, Muller (1982) found sugar maple dominated old growth and second growth stands when the soils contained higher pH, CEC, % base saturation, and higher concentrations of K, Ca, Mg & P. Sugar maple biomass can increase as soil pH increases up to a soil pH of 7 (Cogliastro et al. 2003 and Coughlan et al. 2000).

Long et al. (2009) found that sugar maple basal area increment (BAI) decreased where foliar Ca and Mg were low or where foliar Mn was high in 76 northern hardwood stands over a 59-year period. Sugar maple growing on soils with adequate amounts of Ca and Mg were found to have positive BAI while stands with deficient soils produced smaller growth rates.

Stand level basal area growth of sugar maple increases with soil lime applications, (Juice et al. 2006, Long et al. 1997, Long et al. 2011, Moore et al. 2000, Moore & Ouimet 2006,). Amending acidic soils with $CaCl_2$ increases sugar maple seedling growth (Kobe et al. 2002) crown vigor (Moore & Ouimet 2006), basal growth, wound closure time and decreases branch dieback of sugar maple (Huggett et al. 2007). Additions of lime to soil also increase Ca concentrations in sugar maple root biomass (Juice et al. 2006).

Generally, base cations are leached from the summit, shoulder and upper backslopes and deposited on benches and footslopes (Racine 1971, Aguilar & Arnold 1985, Bailey et al. 2004, St. Clair et al. 2005). However, topography does not always play the most prominent role governing the distribution of base cations. Kabrick et al. (2011) and Johnson et al. (2000) found that topography plays a minor role in base cation distribution in the Missouri Ozarks. Bedrock mineralogy is the greatest contributor of base cations to the mineral soil in the Ozarks. Bedrock formations rich in Ca & Mg concentrations weather and deposit into the subsoil. Soils with base cation-rich gravel content provides Ca and Mg to the soil profile when it weathers. Soils <1m deep had nearly 5 times greater concentration of exchangeable Ca than deeper soils in the Ozark study.

Effects of Soil Base Saturation and pH on White & Northern Red Oak Abundance

White oak occurs on acid, neutral, or basic sites in the Ozarks (Steyermark 1940). White oak abundance is greatest on the neutral to acidic sites (Hallett & Hornbeck 1997, Schmoldt et. al. 1985 and Ware et al.1992). Soil pH has been negatively correlated with white oak growth on mine spoils in southwestern Virginia (Showalter et al. 2007). White oak reproduction is more abundant on less fertile sites (Villwock 2011).

Pete and Loucks (1977) examined hardwood stands in Wisconsin and found that white oak and northern red oak are most abundant on sites with average to below average nutrient status. Schreeg et al. (2005) found that oak growth rates slightly declined as sites become less fertile.

Bigelow and Canham (2002) found that saplings of northern red oak were in greatest abundance on soils with a pH of 4.3. A similar trend was reported when exchanging the variable “soil pH” for “soil exchangeable Ca” in the model. The authors suggested that northern red oaks affinity for soils with a small Ca is likely related to its competitive inabilities on soils with greater Ca. Cogliastro et al. (2003) examined soil properties in a young plantation showing that northern red oak has a better growth rate on soils with a pH slightly less than alkaline. Northern red oak has been found to have greater survival and less abundance on poor fertility sites (Schreeg et al. 2005).

Despite the negative correlation between northern red oak abundance and pH or base cation concentrations, the health of this species appears to be related to soil base concentrations and soil pH. Drought induced stress increases mortality and rates of decline on sites with lesser soil pH and lesser soil base cation concentrations (Demchik & Sharpe 2000).

Effects of Landscape Position on Sugar Maple Abundance

Tree species distribution has long been shown to be related to landscape or slope position and has been attributed to many things, including differences in the supply of water (Brady & Weil 2002) and Ca and Mg (Dijkstra & Smits 2002, Kabrick et al. 2011, Van Breemen et al. 1997). Some of this variability in Ca and Mg supply among landscape positions is related to additions of newer parent materials such as loess placed on top of the residuum derived soil which adds Ca and/or Mg (Boerner and Sutherland 1997).

Sugar maple is most abundant on mesic protected sites with seedling abundance increasing on a variety of sites (Abrams 1990, Adams & Anderson 1980, Bahari et al. 1985, Belden & Pallardy 2009, Canham et al. 1996, Casperson & Kobe 2001, Cogliastro et al. 2003, Fralish 1976, Fralish 1994, Frey et al. 2007, Groninger & Long 2008, Iverson et al. 1997, Phelps 1976, Walters and Reich 1997, Wuenscher & Kozlowski 1971). Others have shown that sugar maple is most abundant on N and NE facing slopes (Muller 1982, Whitney 1991). In central Missouri, sugar maple abundance is increasing on mesic slopes, upland ridges and southern exposed slopes (Belden & Pallardy 2009). Today sugar maple saplings dominate upland white oak forests, juniper glades, steep hill slope forests, mesic coves and bottomlands (Belden & Pallardy 2009, Rochow 1972).

Effects of Landscape Position on White & Northern Red Oak Abundance

In Central Hardwood forests, oaks have greatest abundance on exposed aspects and mid and upper slope positions due to reduced competition from mesic cohorts (Hilt 1985, Heiligmann et al. 1985, Iverson et al. 1997, Groninger & Long 2008 and Ware et al.1992). White oak saplings are most abundant on southern aspects and white oak adults are most abundant on southwestern and northwestern aspects (Collins & Carson 2004).

Pete and Loucks (1977) examined hardwood stands in Wisconsin and found that white oak and northern red oak are most abundant on landscape positions with average to below average moisture status. In southern Illinois on the Shawnee NF, Groninger and Long (2008) examined clearcuts 15-26 years post harvest and found that northern red oak dominates the upper and middle slope but is absent on the lower slope. White oak and sugar maple occur on all slope positions (see Table 1).

Table 1. Crown Class Dominance by Slope Position. From Groninger & Long (2008) showing canopy dominance in the upper two crown classes for the three study species.

	Crown Class Dominant & Codominant		
	Sugar Maple	**Northern Red Oak**	**White Oak**
Upper slope	30%	70%	45%
Middle slope	20%	40%	25%
Lower slope	5%	0%	20%

White oak abundance increases on xeric exposed southwesterly aspects and ridges (Fralish 1976). Fralish found white oaks are most abundant on ridges and drought prone sites, while northern red oak are most abundant but rarely dominant on mesic protected sites. Northern red oak abundance decreases on exposed southwesterly aspects (Abrams 1990, Adams & Anderson 1980, Bahari et al. 1985, Belden & Pallardy 2009, Fekedulegn et al. 2004, Fralish 1976, Fralish 1994, Groninger & Long 2008, Host et al. 1987, Iverson et al. 1997, Phelps 1976, Racine 1971, Wuenscher & Kozlowski 1971).

In the southern Appalachians of North Carolina and the forests of southern IL, mature northern red oak abundance is correlated with concave landforms where moisture accumulates and soil productivity increases (Fralish 1976 and McNab 2010). Sander (1990) found that northern red oak and white oak grow best on middle to lower slopes, coves, and on deep, well drained loam to silty clay loam soils containing a thick A horizon.

Height Growth Characteristics

Following a disturbance, many plants that colonize a site do not reach maturity. Competition among trees ensues and varying growth rates are a distinctive aspect of competition in the early stages of growth (Canham & Marks 1985, Larson 1978). Growth rates vary within a species, among species, and over a range of sites and ages (Palik & Pregitzer 1993). Lack or abundance of site resources can limit growth of some species while not influencing others (Oliver and Larson 1996).

Height growth is a better indicator of competitive abilities than diameter in young even-aged stands of hardwoods (Larson 1978, Nyland et al. 2004). Height growth rates of young trees are usually best sorted by light tolerance levels (Bazzaz 1979, Liptzin & Ashton 1999, Marks 1975) and whether they are a stump sprout or seedling (Bicknell 1982, Heiligmann et al. 1985).

Growth of Sugar Maple

Sugar maple is shade tolerant and a poor competitor of shade intolerant species when grown in full sun (Beaudet & Messier 1998, Ellsworth & Reich 1992*b,* Godman et al. 1990). Sugar maple reaches 75-80 % of its total photosynthetic capacity in just 15 % full sunlight. The high photosynthetic capacity level achieved at lesser light conditions indicates sugar maple's ability to compete for growing space under a partial overstory (Ellsworth & Reich 1992*a*). Sugar maple shoot growth is determinate, growing for a short period in the early growing season, even in forest openings with ample light throughout the season (Jacobs 1965). Sugar maple stem elongation is determined in the prior year's growing season (Jacobs 1965). This trait prohibits sugar maple from responding quickly to canopy openings and severely limits its potential compared to competitive species such as oaks. In central Missouri, sugar maple generally leafs out a month before oaks, enabling access to light not available once the leaves of the overstory oak canopy emerge.

Few reports are available concerning sugar maple growth rates. Nyland et al. (2004) found that sugar maple seedlings attained a height growth rate average of 1.9 ft./yr. for the first 8 years following a shelterwood method stand regeneration harvest but then declined in subsequent years. Bicknell (1982) examined height growth rates in a 6-year-old strip clearcut and found that stump sprout origin and advanced regeneration sugar maple had a slower height growth rate than shade intolerant pin cherry seedlings. Sugar maple will slow in growth dramatically from overhead or side competition (Godman 1969) and favors uneven-aged management or partial cuttings (Godman et al.1990, Kucera & McDermott 1956, Tubbs & Metzger 1969).

Growth of White & Northern Red Oak

White oak and northern red oak are intermediate in shade tolerance and seedlings can attain several flushes of growth during the growing season (Buckley et al. 1998, Crow 1988, Crow 1992, Hanson et al. 1986, Johnson 1979, Reich et al.1980, Rogers 1990, Sander 1990). White oak annual height growth of stump sprouts in open canopy has been found to reach 2.2 feet (Johnson 1979, Reich et al.1980). Dey et al. (1996) observed white oak stump sprouts in the Ozarks of Missouri that ranged in heights from 9-18 ft. five years post-harvest (1.8-3.6 ft./yr.). White oak seedlings established at the time of a clearcut have been found to be 2 feet tall after 10 years while stump sprouts were found to be 16-21 feet tall (McQuilken 1975).

Dey and others (2008) found that white oak stump sprouts in the Ozarks were tallest in clearcuts and group openings compared to single-tree selection harvests. Height growth rates were three times taller in clearcuts and 2.5 times taller in group openings than in single-tree selection. Oaks are poor competitors of maple in lesser light conditions (Canham et al. 1993).

Johnson (1975) found that height growth of northern red oak stump sprouts is positively correlated with site quality, age of sprouts and the number of living stems per clump. The number of living stems in the clump had the greatest influence on early height growth. Ward & Stephens (1994) found that sprout origin trees had a higher survival rate over an 85-year study period and also were more likely to become dominant trees.

Stand Development and Crown Differentiation

Young even-aged stands follow a pattern of stand development characterized by an increasing stem density for a short period (~5 years post-harvest) reaching a point of growing site saturation at crown closure (~9-13 years post-harvest). Following initiation of crown closure the stand begins to experience self-thinning and crown stratification begins to occur (Oliver 1978, Oliver 1980, Nyland et al. 2000, Ray et al. 1999).

As mixed-species stands become older, the species that dominates in the canopy may be less abundant than other species in the early years. In the crown stratification period tree crowns compete for upper positions and stratify along a gradient of height growth rates that is predictable (Guldin & Lorimer 1985). Ward & Stephens (1994) found that the percent of northern red oak in the dominant canopy position increased over the life of the 85 year old stand due to mortality of other trees in the dominant and codominant crown positions.

Shade-intolerant trees must maintain a competitive growth rate to survive while shade-tolerant species can maintain a slow growth and tolerate the low light levels. If the suppressed trees are shade tolerant they become relegated to the lower canopy positions until a crown release event (Oliver 1980). Shade tolerance rankings for sugar maple, northern red oak and white oak decreases respectively (Godman 1969, Wuenscher & Kozlowski 1971, Hinckley et al. 1978, Rogers 1990, Sander 1990, Walters & Reich 1997).

Shade-intolerant species will slow in growth and eventually die if a crown release event does not occur. Mortality rates of northern red oaks have been found to decline as they progress into more dominant crown classes (Ward & Stephens 1994). In Wisconsin, naturally regenerated northern red oak seedlings over a 6 year period experienced 46 % mortality under a closed un-treated canopy, 34 % mortality under a partially harvested canopy, and only 8 % mortality under a completely harvested canopy (Crow 1992).

Stands that have a diversity of diameters and heights are assumed to be multi-aged, but commonly the smaller trees are the same age as the bigger trees (Oliver 1978, Oliver & Larson 1996). One personal experience includes finding a 5 in. diameter at breast height (dbh) midstory sugar maple the same age (70 yrs.) as the 16 in. dbh white oak in the overstory.

Others have reported similar findings. Oliver (1978) reconstructed even-aged stands of northern red oak, red maple and black birch. The oak was dominant in all plots measured. Stem analysis reveled that at younger ages it was not dominant in height or density yet outgrew its competitors in mid-rotation. Guldin and Lorimer (1985) reconstructed stand development in Wisconsin and Michigan and found that when growth rates remain constant that some species are always shorter and have less canopy volume in the upper strata of the canopy. In southeastern Ohio, oak importance values for trees in the upper canopy increased significantly between 6 and 26 years post-harvest even though its total stem density as a relative component of the stand remained unchanged (Norland & Hix 1996).

White oak importance increased as clearcuts age in southern Indiana (Jenkins & Parker 1998). In the same study examining three harvest types, northern red oak and white oak had the greatest densities in clearcut stands versus group openings and single-tree selection harvests when examined 9-27 years post-harvest. Sugar maple densities were greatest in the single-tree selection harvests and the undisturbed reference plots.

Following a clearcut in northern lower Michigan, canopy stratification as a result of height growth differentiation along species shade tolerance gradients occurred between bigtooth aspen (*Populus grandidentata*), northern red oak and red maple (*Acer rubrum*). The aspen, which is the most intolerant, had the greatest growth rate while the red maple, the most tolerant, had the slowest growth rate (Palik & Pregitzer 1993). On several of the plots studied, the maple and/or oak did maintain height competitiveness with the aspen. The former had a great variability in height growth rates while the latter did not, as a result, they inferred reduced height growth rates of the two species as a result of competition, not individual physiology.

Hix and Lorimer (1990) found a relationship between height growth rate and position in the canopy. They discovered that as the total height of sugar maple approaches the average height of the canopy the growth rate increases. Although they did not sample oaks, they did sample a range of shade intolerant to tolerant tree species and each exhibited the same trend. They discovered a similar trend showing an increase in growth rate as a percentage of the crown is exposed. This trend only shows an increased growth rate up to about 30 % of exposed crown area after which no noticeable increase in growth rate occurred.

It is the stand initiation stage where individual tree characteristics along with site characteristics drive interspecies competition that affects trees that reach the dominant crown positions (Oliver & Larson 1996, Morrissey et al. 2008). Relative density is not a reliable measure of future stand composition in the early years of a regenerated stand.

Brashears et al. (2004) examined 13 even aged stands in West Virginia ranging in age from 2-26 years old using several common diversity metrics. He found that predictions of future stand composition from young stands require stratification by species and canopy position in data collection. This serves as a way to observe the competition factor that most diversity metrics do not.

Morrissey et al. (2008) found that oak crown class dominance increased with stand age on mid and upper slope positions, and on some lower slope positions. They attributed this competitive ability to oaks persistence. In this study factors such as growth rate and drought tolerance and were found to be influenced by physiography, aspect, pre-harvest oak levels, stump sprouting abundance and slope position.

However, sugar maple is long lived. As even-aged stands mature, sugar maple relative density increases while oaks decline (Belden & Pallardy 2009, Nigh et al. 1985, Schlesinger 1976, Tubbs 1968). Harvesting may reverse this trend. For example, in a Massachusetts clearcut examined for 42 years, sugar maple relative density pre-harvest was 10.7 %. Post-harvest its relative density decreased to 1.7 % and 42 years following the harvest was 5.2 % with an average canopy class in the under and midstory (Allison et al. 2003). In the control plots sugar maple relative density increased from 8.7 % relative density pre-harvest to 23.6 % post-harvest.

Summary

Sugar maple is most abundant and grows better on fertilite sites with a neutral to basic soil pH and a greater moisture status than oaks. It appears that these species occupy a different spectrum of site qualities while sharing many.

There are few reports concerning height growth rates as most studies up to this point examined diameter growth rates. There is clear evidence pointing to the competitive nature of the examined species. Evidence shows that in a young even-aged stand that the selected oaks will out-compete sugar maple when all factors are equal.

After reviewing the literature it is hypothesized that certain soil properties, such as soil base saturation, soil pH and plant available water capacity influence where maple occurs and where it thrives. It is assumed that landscape position influences sugar maple occurrence and vigor because it influences the above stated factors.

CHAPTER 3: STUDY AREA DESCRIPTION

This study examines young, even-aged upland forested stands in the moderately dissected lower Missouri River and lower Osage River valleys. Forty-four stands were selected for study. Stands ranged in age from 15-29 years. Limited existing pre-harvest data showed that many of the stands were dominated by white and northern red oak with a mix of black oak, shagbark hickory and several other minor species.

Historical records and remote sensing were utilized to locate even-aged stands on publicly managed property. Because of the lack of information recorded on private land forest management operations, no suitable sites were located on non-industrial private lands. Most of the publicly managed forests came under an organized forest management schedule in the late 1970s.

Thirty-five of the study sites are managed by the Missouri Department of Conservation (MDC) and eight are managed by the University of Missouri-Columbia (Table 2).

Table 2. Study Site Properties. Listing of the property names, ownership and counties of study sites. The management of Reform CA is leased to the Department of Conservation for production of forest products, wildlife habitat and public use.

Owner	Area Name	County	Acres
Missouri Department of Conservation	Daniel Boone Conservation Area (CA)	Warren	3,520
	Danville CA	Montgomery	2,655
	Little Lost Creek CA	Warren	2,899
	Painted Rock CA	Osage	1,480
	Reifsnider CA	Warren	1,388
Ameren Corp.	Reform CA	Callaway	6,759
University of Missouri	Baskett Research & Education Area	Boone	2,266

Soils

The Missouri River is considered the southern extent of the pre-Illinoian glacial advance. The Missouri River and its tributaries contained greater volumes of water flow during repeated Pleistocene floods when previous glaciers retreated (Bretz 1965, Thompson 1995). Soil parent materials were derived from glacial till, loess, colluvium and residuum from bedrock of limestone, dolomite and thin interbedded layers of sandstone (Soil Survey Staff online 2011).

The loess accumulated on the summits and in thin layers across the landscape and primarily originating from the Missouri River Valley. The loess decreases in depth northward from the Missouri River valley (Thompson 1995). Loess depths are also greater close to major tributaries including the Brushy Creek (Baskett), Auxvasse Creek (Reform) and Osage River (Painted Rock).

Glacial till is from pre-Illinoian origin and of variable thickness (Thompson 1995). Till in the area is generally eroded away closest to the Missouri River valley and becomes more prominent as distance from the river increases northward. Till occurs at the

Baskett, Danville, Daniel Boone, Little Lost Creek and Riefsnider sites. On all study sites where till occurs residuum derived soils are exposed immediately downslope. See Table 3 for a list of soils encountered at the study sites.

Soils on summits in the region are generally deep and well-drained Alfisols formed under forest in loess or till, or both. Moving downslope a thin layer of carbonate derived clayey residuum is found typically on the mid backslope as a bench over a thin exposed bedrock with thin to deep residuum derived soils on the surface. Below the mid backslope soils become deeper and more fertile and primarily of colluvial origin over older residuum. Productivity on the catena generally increases from middle backslope<upper backslope<summit<lower backslope<footslope (Honeycutt et al. 1982).

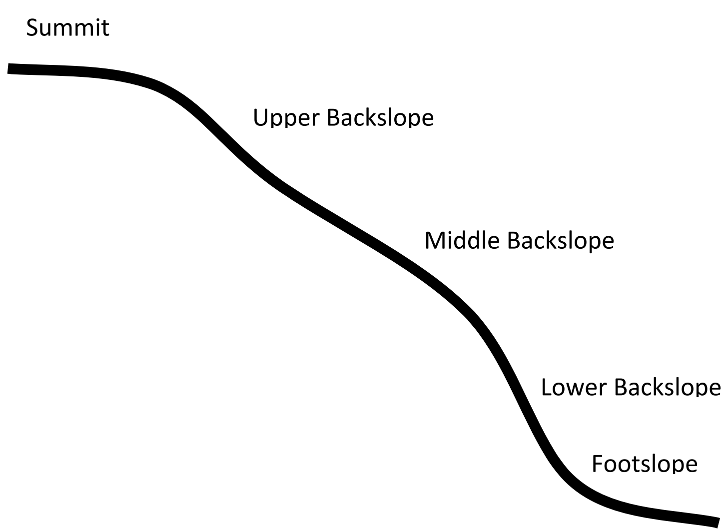


Figure 2. Landscape Positions Diagram. A depiction of a hill slope with different landscape positions labeled. The shoulder slope occurs between the summit and upper backslope.

Geology

Geology is of varying origin across the study area but predominantly carbonate. (All Geology information from the Soil Survey Staff online 2011).

The Baskett and Reform sites contain (in order from nearest to the surface down):

Mississippian-aged Burlington limestone, Chouteau Group limestone over

Devonian-aged Snider Creek Shale and Cedar Valley limestone over

Ordovician-aged Plattin limestone, Joachim dolomite, St. Peter sandstone and

the Jefferson City-Cotter Dolomite formations.

The Danville, Daniel Boone, Little Lost Creek and Riefsnider sites contain (in order from closest to the surface down):

Mississippian-aged Burlington limestone over

Devonian-aged Glen Park limestone over

Ordovician-aged Joachim limestone over

St. Peter sandstone over

Jefferson City-Cotter dolomite formations.

The Painted Rock sites contain (in order from closest to the surface down):

Jefferson City formation, argillaceous limestone/dolomite over

cherty limestone/dolomite of the Roubidoux formation

Sandstone is the only base cation deficient geology encountered in the study area. The sandstone geology is rarely on the summit and has little influence on surficial materials because its thin layer is surrounded by carbonate formations.

Landscape

The study area is on the northern edge of the Ozark Plateau physiographic province and lies in Boone, Callaway, Montgomery and Warren counties (Figure 3). Four of the sites (Painted Rock sites) lie near the northeastern edge of the Osage River Hills Subsection (landtype association (LTA) = OZ6) while the remaining study sites are located across the eastern half of the Outer Ozark Border Subsection (OZ12) (Nigh & Schroeder 2002).

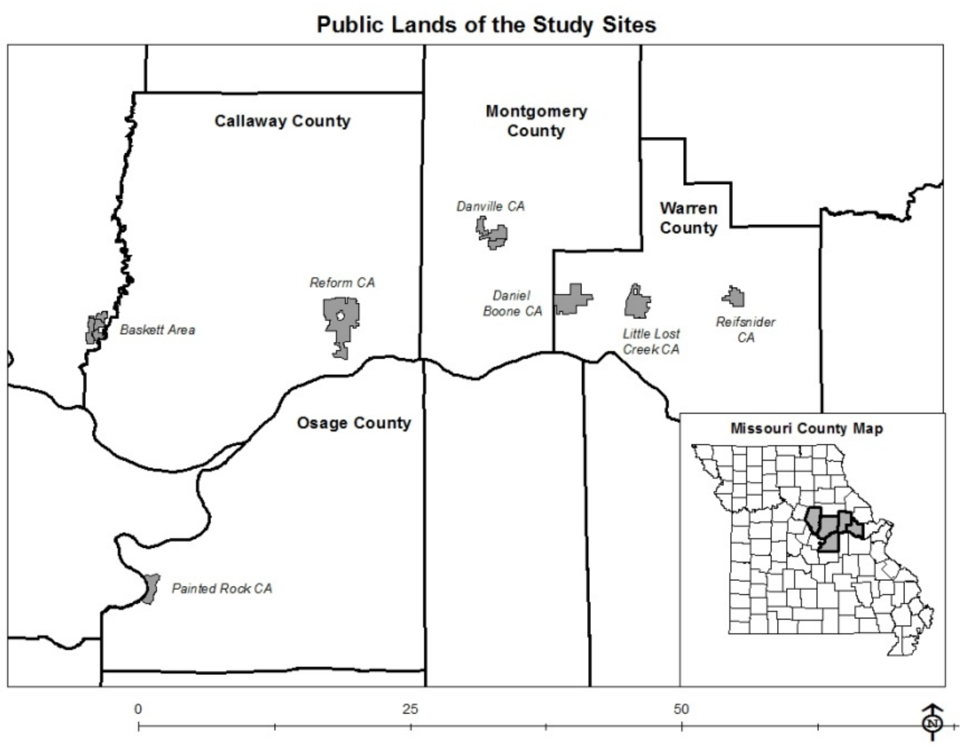


Figure 3. Study Sites Map. County map of Missouri showing location of study sites.

Natural Communities

Natural communities of the study areas as described by Nelson (2005) include: dry and dry-mesic dolomite woodland/glade complex; dry limestone/dolomite woodland; dry-mesic limestone/dolomite woodland; dry-mesic chert woodland; dry chert woodland; dry-mesic loess/glacial till woodland; dry-mesic limestone/dolomite forest; and dry-mesic-chert forest. ELTS are currently being produced for the study area and have not yet been published.

CHAPTER 4: METHODS

Plot Design

One circular fixed area plot with an area of 1/20th acre (2,178 ft^2) was established on each of the 44 study sites. Selected plots had dominant or codominant trees of white oak, northern red oak and if present, sugar maple that were in direct crown competition with each other. On several plots the selected sugar maple was intermediate or suppressed but represented the highest canopy class attained by any of the sugar maple in the stand.

A total of 93 sites were initially located from remote sensing and historical management documents retained at the managers offices. After field reconnaissance 44 sites were found to be suitable for study. Sites had to meet several requirements to qualify as suitable:

1. larger than 1 acre in area
2. slashed immediately following the harvest
3. have not received targeted herbicide treatments for species control before, during or after the harvest
4. have not received any management treatments following the harvests

Twelve sites (28%) had no sugar maple present yet we gathered information from these sites to determine if site characteristics could explain the lack of sugar maple occurrence and to increase the sample size for oaks. All sites contained northern red oak and white oak. Table 3 shows properties along with study site descriptions.

A total of 18 soil series were mapped on the study sites. Table 3 provides general information on the soil series for each for each the study sites.

Table 3. General Site Data. Site data for each study plot. Abbreviations for landform include: LB = lower backslope, MB = middle backslope, UB = upper backslope and S = summit. Aspect is degrees of azimuth.

Plot	Age	Acres	Property	Landform	Slope %	Aspect	Soil
1	25	1.4	Baskett	UB	23	66	Rocheport Bonfemme complex
4	28	4.1	Baskett	UB	20	246	Bardley Clinkenbeard complex
5	25	3.9	Baskett	MB	17	250	Winnegan loam
6	26	2.3	Baskett	UB	24	296	Winnegan Loam
7	20	1.9	Baskett	UB	7	16	Marion silt loam
10	26	1.3	Baskett	UB	15	358	Marion silt loam
12	25	3.6	Baskett	MB	25	40	Rocheport Bonnefemme complex
13	20	3.2	Baskett	S	7	326	Marion silt loam
14	18	10.7	Painted Rock	UB	20	246	Gatewood Gravois complex
17	24	5.7	Painted Rock	MB	27	322	Rueter very gravelly silt loam
18	25	2.9	Painted Rock	MB	26	288	Gatewood very gravelly silt loam
19	15	13.5	Painted Rock	UB	30	10	Rueter very gravelly silt loam
21	27	7.0	Reform	S	14	334	Weingarten silt loam
22	25	32.4	Reform	MB	7	290	GossGascRockComplex
24	17	4.4	Reform	MB	18	65	GossGascRockComplex
26	20	2.9	Reform	MB	15	88	Winfield silt loam
30	19	5.0	Reform	MB	20	90	GossGascRockComplex
31	19	2.3	Danville	MB	15	330	Gasconade rock outcrop complex
34	20	7.7	Danville	MB	10	120	Lindley loam
36	20	9.7	Danville	UB	16	306	Gos soils
40	21	11.9	Danville	MB	25	300	Goss soils
45	21	2.5	Danville	MB	4	40	Keswick silt loam
46	21	3.8	Danville	UB	30	110	GasconadeRock outcrop Complex
47	20	6.2	Danville	MB	40	118	Goss soils
48	18	9.3	Daniel Boone	UB	20	22	Chilhowie, Gasconade, Crider
54	29	8.1	Daniel Boone	MB	20	50	Chilhowie Gasconade Crider soils
55	29	4.2	Daniel Boone	MB	20	320	Goss soils
57	24	14.5	Daniel Boone	UB	18	190	Goss soils
59	19	8.1	Daniel Boone	MB	20	80	Goss soils
60	19	6.0	Daniel Boone	MB	30	260	Goss soils
62	19	4.3	Daniel Boone	MB	25	310	Goss soils
63	23	2.7	Little Lost Creek	S	12	140	Keswick silt loam
64	24	10.2	Little Lost Creek	UB	12	151	Lindley loam
71	22	7.4	Little Lost Creek	UB	18	62	Hatton silt loam
72	22	6.5	Little Lost Creek	S	13	162	Lindley loam
73	22	2.1	Little Lost Creek	UB	16	28	Keswick silt loam
76	23	2.0	Little Lost Creek	MB	22	196	Goss soils
78	22	5.3	Little Lost Creek	MB	36	280	Lindley loam
79	23	1.9	Little Lost Creek	LB	45	324	Gasconade rock outcrop complex
85	23	6.5	Little Lost Creek	LB	33	0	Goss soils
88	17	5.2	Reifsnider	S	7	120	Keswick silt loam
89	17	8.9	Reifsnider	S	9	348	Keswick silt loam
91	17	5.6	Reifsnider	UB	20	344	Keswick/Hatton silt loams
93	15	5.0	Reifsnider	UB	19	282	Goss soils

Table 4. Soil Series of the study Sites. Contains soil series, taxonomic descriptions, parent material, depth to bedrock, landform, drainage classification and landtype association (LTA). Landform abbreviations are the same as Table 3. Soils information referenced in the online soil survey. Drainage abbreviations: WD = well drained, MWD = moderately well drained, SWPD = somewhat poorly drained. LTA abbreviations: OZ6 = Osage River Hills Subsection, OZ12 = Outer Ozark Border Subsection.

Soil Series	Taxonomy	Parent Material	Depth	Landform	Drainage	LTA
Bardley	very-fine, mixed, active, mesic typic hapludalf	Colluvium over Clayey Residuum from Dolomite w/ Interbedded Limestone/Sandstone	Moderately Deep	Summit, BS	WD	OZ12
Bonfemme	fine, smectitic, mesic typic hapludalf	Loess over Limestone/Dolomite Residuum	Moderately Deep	BS	WD	OZ12
Chilhowie	very-fine, mixed, semiactive, mesic typic hapludalf	Residuum from Interbedded Shale/Limestone	Moderately Deep	Summit, BS	WD	OZ12
Crider	fine-silty, mixed, active, mesic typic paleudalf	Loess over Limestone Residuum	Very Deep	Summit, BS	WD	OZ12
Clinkenbeard	clayey-skeletal, mixed, superactive, mesic typic argiudoll	Residuum & Colluvium from Limestone/Dolomite	Moderately Deep	BS	WD	OZ12
Gasconade	clayey-skeletal, mixed, superactive, mesic lithic hapludoll	Residuum from Limestone	Shallow/Very Shallow	BS	SWED	OZ12
Gatewood	very-fine, mixed, active, mesic oxyaquic hapludalf	Colluvium over Residuum from Limestone/Dolomite/Shale	Moderately Deep	Summit, BS	MWD	OZ6
Goss	clayey-skeletal, mixed, active, mesic typic paleudalf	Colluvium over Residuum from Cherty Limestone/Cherty Dolomite/Shale	Very Deep	Summit, BS	WD	OZ12
Gravois	fine-silty, mixed, active, mesic aquic paleudalf	Loess & Pedisediment over Loamy & Clayey Residuum from Dolomite	Very Deep	Summit, BS	MWD	OZ12
Hatton	fine, smectic, mesicc oxyaquic vertic hapludalf	Loess & Silty Pedisediment over Weathered Till	Very Deep	Summit	MWD	OZ12
Keswick	fine, smectitic, mesic aquertic chromic hapludalf	Loess or Loamy Sediment over Weathered Till	Very Deep	Summit, BS	SWPD	OZ12
Lindley	fine-loamy, mixed, superactive, mesic typic hapludalf	Till, some with thin Loess over	Very Deep	BS	WD	OZ12
Marion	fine, smectitic, mesic aquertic chromic hapludalf	Loess or Loess over Pedisediment	Very Deep	Summit	SWPD	OZ12
Rocheport	fine-silty, mixed, superactive, mesic oxyaquic hapludalf	Loess over Residuum from Limestone	Deep	BS	MWD	OZ12
Rueter	loamy-skeletal, siliceous, active, mesic typic paleudalf	Colluvium over Residuum from Cherty Limestone	Very Deep	Summit, BS	SWED	OZ6
Weingarten	fine-silty, mixed, active, mesic fragic hapludalf	Loess & Colluvium over Residuum from Cherty Limestone & Dolomite	Very Deep	Summit, BS, FS	WD	OZ12
Winfield	fine-silty, mixed, superactive, mesic oxyaquic hapludalf	Loess	Very Deep	Summit, BS	MWD	OZ12
Winnegan	fine, mixed, superactive, mesic oxyaquic hapludalf	Glacial Till	Very Deep	BS	MWD	OZ12

Data Collection

Soils

At each plot one pit was excavated with hand tools to a depth of 1 m or to bedrock for shallower soils. The soil profile was described in the field using the methods described in the Soil Survey Manual (1993) and the Field Book for Describing and Sampling Soils (Schoeneberger et al. 1998). Horizons were identified and data recorded included:

1. depth of the horizon
2. Munsell color
3. texture by field estimation
4. percent coarse fragments by ocular estimation
5. structure (grade, size and type) and
6. root size and density.

Features such as manganese concentrations, mottling and silt or clay coats were also recorded. Parent material and total pit depth was recorded. Drainage was estimated primarily from color after the field data was collected using standard procedures used during soil survey mapping. The field data were compared to the mapped soil unit for verification. A sample with a volume of approximately 0.3 liters was collected from the surface A horizon, upper set of B horizons and lower set of B horizons for analysis at the UMC Soil Characterization Laboratory.

Landscape Position

The site variables collected were aspect, slope and landscape position. Four landscape positions were categorized: summit, upper backslope, middle backslope and lower backslope. Landscape position was determined by the data collector using the model in Figure 2 and the Field Book for Describing and Sampling Soils (Schoeneberger et al. 1998) for guidance.

Trees

Each tree in the plot with a height greater than 4.5 feet was measured. Data collected included:

1. species
2. dbh
3. origin (seed or sprout)
4. total height and
5. crown class.

Height was measured to the nearest foot using a height pole with a spotter an adequate distance away to confirm a true measurement. Crown class was visually estimated with five classes (Figure 4):

1. Dominant trees are taller in height on all four sides of the crown than adjacent neighbor trees.
2. Codominant trees are even in height with no more than two adjacent neighbors and have at least two sides with ample exposure to sunlight.

3. Intermediate trees receive direct sunlight on the top of the canopy but the sides are the same height or shorter than adjacent neighbors.

4. Suppressed trees are dominated by adjacent neighbors and receive little if any direct sunlight on the top of the canopy. Many suppressed trees are in the main canopy but relegated to the lower half.

5. Understory trees are not in the main canopy but below it. Their total height is shorter than the height of the bottom of the main canopy. Understory trees receive no direct sunlight.

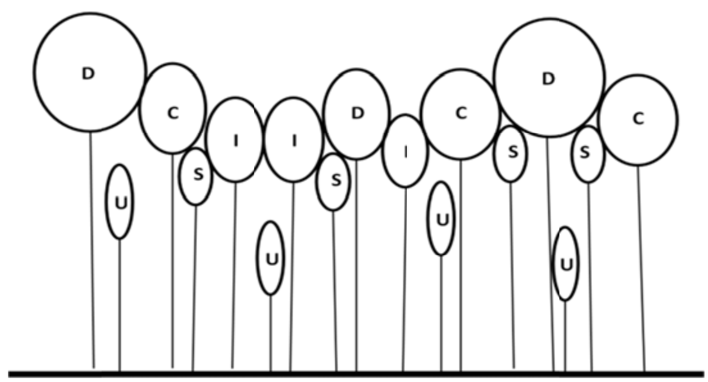


Figure 4. Canopy Model. An illustrated model of the canopy classification scheme. Abbreviation codes: D = dominant, C = codominant, I = intermediate, S = suppressed, U = understory.

Stem Analysis

Two to three trees per plot were sampled for stem analysis (SA) to reconstruct growth rates. White oak, northern red oak, and if present, sugar maple, were selected for SA. Trees selected for SA had a crown class of dominant or codominant while a few of the sugar maples were intermediate or suppressed because no taller sugar maples were in the stand.

All SA trees were stump sprouts. The tallest sprout on a stump was selected for measurement. The width of the canopy of the SA trees was measured in two perpendicular directions. All SA stems were cut at ground level and felled. Total height of the tree and height to bottom of canopy was measured after the tree was felled. We marked and cut every 2 feet moving up the stem to the terminal bud on the tallest twig. A thin cross-section sample was collected from each 2-foot mark on the bole of the tree. Bud scars could be used to age the terminal leader for the previous several years of growth. The lowest cross-section was cut from the stump at ground level to get total age of the tree.

Cross-section samples were brought to the Dendrochronology laboratory at UMC and prepared by band saw or power hand planer and sanding one surface with 150-grit sandpaper for oak and 600-grit sandpaper for the sugar maple. Tree rings of oak were counted with the aid of 10-20-power scope when needed and samples of maple were counted after 20x magnification.

CHAPTER 5. ANALYSIS

Soil Base Saturation

Soil samples from three depths including the surface horizons, upper B horizons and the lower B horizons, were analyzed at the University of Missouri-Columbia Soil Characterization Laboratory following procedures outlined in the Soil Survey Laboratory Methods Manual (Soil Survey Staff, 1996) to determine:

1. NH_4OAc extractable bases in meq/100 g of Ca, Mg, Na and K
2. the cation exchange capacity (CEC) and
3. the percent base saturation-sum method, BS).

Percent BS for the total profile was determined by multiplying the sample BS by the horizon thickness of the sampled area and dividing by the total soil depth. The 3 figures were summed to get the total profile BS.

Percent Hydrogen (pH)

Soil pH was determined in the laboratory for each of the three depths using the methods described in the Soil Survey Laboratory Methods Manual (Soil Survey Staff, 1996) for determining pH in water concentration.

Soil Available Water Capacity

Available soil water holding capacity (AWC) was estimated by multiplying the horizon thickness by the predicted value for volumetric water content (Table 5), then multiplied by the soil material mass (rock fragments not included) divided by the rooting zone depth of the total profile. The values were then summed to provide the total soil AWC above bedrock.

Table 5. Predicted Volumetric Water Content Values. For prediction of soil available water capacity. Figures taken from USDA NRCS Missouri online soil survey.

Texture Class	Volumetric Water Content (cm/cm) Model Variable
Loam	0.20
Silt Loam	0.21
Silty Clay Loam	0.20
Silty Clay	0.17
Clay Loam	0.20
Clay	0.17
Sandy Loam	0.07

Landscape Position

Each plot has a landscape position value. Landscape position was transformed to four classes based on Ruhe's (1975) classifications and designated a number classification for model input (Figure 2):

1. 1 = summit
2. 2 = upper backslope
3. 3 = middle backslope and
4. 4 = lower backslope

Statistical Analysis

Data analysis was performed using the SAS statistical software (version 9.2, SAS Institute, Inc., Cary, NC, USA). The GLIMMIX procedure was used for linear regression for abundance models and the response variable, species TPA, was transformed to a negative binomial distribution and the link function was logit. The Genmod procedure (SAS statistical software) was used for linear regression for the growth rate models including the difference in growth rate models.

Three separate analyses were used to determine the effects of three parameters: soil available water capacity in centimeters (AWC), soil base saturation (BS) or pH and landscape position (summit, upper backslope, middle backslope and lower backslope). Response variables were periodic annual increment at age 15 (PAI15), and the difference in species growth rates. The abundance response variable is the TPA of the selected species. Table 6 shows the parameter values for all models. For growth models, data from the 120 SA trees was used. White oak and northern red oak trees were sampled for SA on all 44 plots while sugar maple samples were collected on 32 plots. PAI15 was calculated for each of the SA trees by averaging the growth rate of the tree from the first year following harvest to 15 years following harvest. The year 15 was selected because the youngest stand age sampled is 15 years. Some trees were older than the stand age presumably because their small size at time of slashing causing them to be overlooked. In a few cases the SA tree is one or two years younger than the stand age. In this case we took the first 15 years of growth for the tree when figuring PAI15. For the difference in species growth rate parameters the difference of PAI at year 15 post-harvest for each tree was subtracted to get the difference. Analyses were conducted on each sugar maple, white oak and northern red oak PAI15 individually. The difference in PAI15 (white oak vs. sugar maple and northern red oak vs. sugar maple) was also examined. I wanted to determine if any of the selected parameters influence the variation in growth rates between sugar maple and the oaks.

The information-theoretic approach based on the Kullback-Leibler information was used. Model parameters were pre-selected based from information gathered from the literature review. Each model set was compared using the Akaike's Information Criterion with second order bias correction (AICc) scores as outlined by Anderson (2008). Predictor variables were removed one at a time and AICc scores were compared to determine which model has the best fit. Models with AICc scores within two points are considered statistically similar.

Table 6. Model Parameters Values. Landscape position values are 1 = summit, 2 = upper backslope, 3= middle backslope and 4 = lower backslope.

Plot	Sugar Maple TPA	White Oak TPA	Northern Red Oak TPA	Sugar Maple PAI15	White Oak PAI15	Northern Red Oak PAI15	Difference in White Oak/Sugar Maple Growth	Difference in Northern Red Oak/Sugar Maple Growth	Available Water Capacity	Base Saturation (%)	pH	Landscape Position
1	1180	120	80	1.52	1.93	2.13	-0.61	-0.2	5.88	42.0	5.5	2
4	540	340	100	1	1.73	1.24	-0.24	0.49	9.71	38.4	4.9	2
5	760	300	80	1.07	2.2	2	-0.93	0.2	10.88	74.1	5.7	3
6	500	60	180	1.37	1.73	2	-0.63	-0.27	10.75	88.0	6.5	2
7	1480	120	40	1.87	2.07	2	-0.13	0.07	22	54.5	4.8	2
10	1000	180	200	1.93	1.87	1.8	0.13	0.07	19.02	63.9	4.8	2
12	100	380	220	1.18	2.6	2.67	-1.49	-0.07	5.02	45.0	5.0	3
13	780	120	20	1.6	2.27	2.4	-0.8	-0.13	22.12	46.0	4.8	1
14	700	200	620	1.78	1.76	2.4	-0.62	-0.64	7.58	76.3	6.0	2
17	1240	20	120	1.1	2.07	1.53	-0.43	0.54	6.93	79.0	6.3	3
18	3060	140	140	1.18	1.6	1.67	-0.49	-0.07	6.01	97.0	7.1	3
19	1680	140	380	2.07	2.27	2.07	0	0.2	13.12	72.0	5.6	2
21	740	300	40	1.38	2	2.4	-1.02	-0.4	10.72	44.9	5.1	1
22	960	100	40	2.27	2.53	2.53	-0.26	0	19.64	42.2	5.9	2
24	740	200	500	1.87	1.79	2	-0.13	-0.21	17.4	65.9	5.1	3
26	720	220	420	1.53	2	2.2	-0.67	-0.2	14.68	45.9	4.9	3
30	440	200	80	1.51	2.27	1.6	-0.09	0.67	16.48	35.2	4.8	3
31	160	320	160	1.73	1.67	1.69	0.04	-0.02	4.27	43.3	5.0	3
34	0	540	280	NA	1.48	1.83	NA	NA	7	85.6	6.7	3
36	0	260	320	NA	2.07	2.53	NA	NA	7.81	24.5	4.9	3
40	0	240	240	NA	2.13	1.73	NA	NA	7.18	27.0	4.9	3
45	0	280	320	NA	2	2.13	NA	NA	16.13	28.1	4.6	3
46	640	260	420	1.48	1.87	2.33	-0.85	-0.46	5.65	52.9	5.4	2
47	360	60	220	1.5	1.24	1.73	-0.23	-0.49	4.9	100.0	7.5	3
48	380	460	500	1.4	1.67	2.53	-1.13	-0.86	10.87	60.7	5.1	2
54	0	320	160	NA	2.07	1.87	NA	NA	19	32.9	4.9	3
55	200	280	220	1.33	2	2	-0.67	0	9.31	57.0	5.2	3
57	0	300	480	NA	1.93	2	NA	NA	8.68	34.4	6.4	2
59	0	560	300	NA	2.27	2.07	NA	NA	4.07	29.0	5.2	3
60	0	700	600	NA	1.8	1.47	NA	NA	9.52	56.8	5.5	3
62	580	240	260	1.67	2.13	2.13	-0.46	0	9.49	25.3	4.8	3
63	0	680	160	NA	2.4	2.27	NA	NA	15.19	37.3	4.9	1
64	120	1000	120	1.33	2.27	2.13	-0.8	0.14	18.74	59.1	5.4	2
71	140	520	140	1.69	2.13	2.4	-0.71	-0.27	12.71	29.1	4.5	2
72	0	460	140	NA	2.33	1.8	NA	NA	1.94	33.8	4.8	1
73	0	460	120	NA	1.87	2	NA	NA	3.72	34.4	6.0	2
76	0	560	160	NA	2.27	2.27	NA	NA	2.92	28.7	4.9	3
78	340	800	120	1.29	1.78	2	-0.71	-0.22	9.41	23.0	4.6	3
79	1260	120	160	1.13	2.19	2	-0.87	0.19	5.83	89.9	7.0	4
85	560	180	580	1.2	2.13	2.2	-1	-0.07	7.89	42.5	3.8	4
88	500	340	280	1.54	1.93	2	-0.46	-0.07	19.05	36.2	4.9	1
89	340	440	60	1.53	1.87	1.8	-0.27	0.07	19.05	31.9	4.7	1
91	700	980	200	2.36	1.8	2.13	0.23	-0.33	19.51	39.7	5.0	2
93	600	160	300	1.33	1.67	1.6	-0.27	0.07	7.11	59.4	5.3	2

CHAPTER 6. RESULTS

Soil Base Saturation-

Base saturation values for the sites range from 23 % to 100 % (Table 9). The mean base saturation is 50 with a standard deviation (SD) of 21. Soil pH (water) was used rather than BS for the white and northern red oak models. The pH values ranged from 3.8 to 7.5. The mean pH value is 5.3.

BS values are averaged for each of the study properties and shown in Table 7. Three of the sites at Painted Rock were in the 70's range and one has a BS value of 97 %.

Table 7. Average Base Saturation Values of Study Properties.

Area	Average BS Value
Painted Rock	81%
Baskett	56%
Danville	52%
Reform	47%
Daniel Boone	42%
Little Lost Creek	42%
Reifsnider	42%

Soil Available Water Capacity

AWC values for the sites ranged from 1.9 cm to 22.1 cm of the total soil profile above bedrock or to a depth of one meter. The mean AWC value is 11.02 cm with a SD of 5.8 cm with a range of 20.18 cm. The AWC values were averaged by study property and are shown in Table 8.

Table 8. Average AWC Values of Study Properties.

Area	Average AWC Value (cm)
Reifsnider	16.2
Reform	15.7
Baskett	13.2
Daniel Boone	10.1
Little Lost Creek	8.7
Painted Rock	8.4
Danville	7.6

Landscape Position

Plots were established on each of the landscape positions but unfortunately not enough even aged stands exist on summits and lower backslopes in the study area (Table 9). Only two plots were established on lower backslopes. Only six plots were established on summits. This sample size is too small to provide confidence in the results. The models did not show a strong correlation between landscape position and abundance or height growth for any of the species.

Trees

A total of 5,871 trees were measured on the 44 plots, of these 17%, or 1,023 trees sampled were of seed origin (Table 9). 1,175 (20 %) are sugar maple, 735 (13%) are white oak and 515 (9 %) are northern red oak. Mean diameter at breast height for the trees on all the plots was 1.9 inches with a standard deviation of 1.5 in. . The maximum diameter measured was 9.5 in. and the minimum was 0.1 in. Stand ages range from 15-29 years old with a mean of 22 and a standard deviation of 3.6 years. Twelve plots had no sugar maple occurrence. All plots had white and northern red oak.

Of the majority of plots where sugar maple is present it dominates in relative density measures (Figures 5 & 6). For all plots combined, the mean number of sugar maple trees per acre was 734, while it was 333 for white oak and 234 for northern red oak. Sugar maple has an advantage ratio of over 2:1 for white oak and over 3:1 for northern red oak.

Table 9. Summary Statistics.

Origin		Count			
Seedling		1,023	17%		
Sprout		4,848	83%		
Total		5,871			
	# of Plots	**# of Trees Sampled**		**Proportion Sprout Origin**	
Summit	**6**	608			
Upper Backslope	**16**	2,248			
Middle Backslope	**20**	2,660			
Lower Backslope	**2**	355			
Sugar Maple	**32**	1,175		96%	
White Oak	**44**	735		78%	
Northern Red Oak	**44**	515		87%	
		Mean	**Min**	**Max**	**Std. Dev.**
Stand Age (year)		22	15	29	3.6
DBH (cm)		4.7	0.3	24.1	3.7
Height (ft)		19.7	5	57	9.6
TPA		**Mean**	**Min**	**Max**	**Std. Dev.**
	Total	2669	1260	10120	1479.5
	Sugar Maple	734	0	3060	583
	White Oak	333	20	1000	232
	Northern Red Oak	234	20	620	161
Growth Rate (ft/yr)		**Mean**	**Min**	**Max**	**Std. Dev.**
	Sugar Maple	1.25	0.74	2.06	0.3
	White Oak	1.46	0.95	2.27	0.3
	Northern Red Oak	1.54	1	2.53	0.4
Soil Properties		**Mean**	**Min**	**Max**	**Std. Dev.**
	Sample Depth (cm)	80	38	122	22
	AWC	11.02	1.94	22.12	5.8
	% Base Saturation	50	23	100	21
	pHwater	5.3	3.8	7.5	0.8

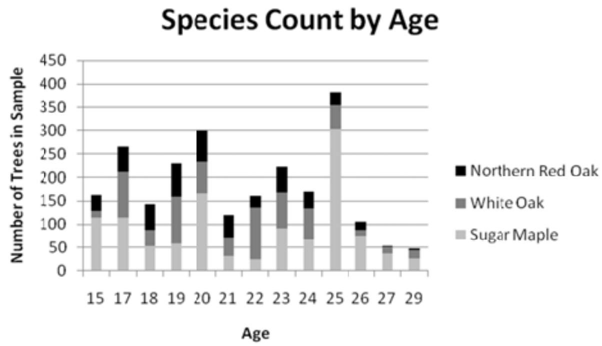


Figure 5. The number of trees sampled by age for three selected species.

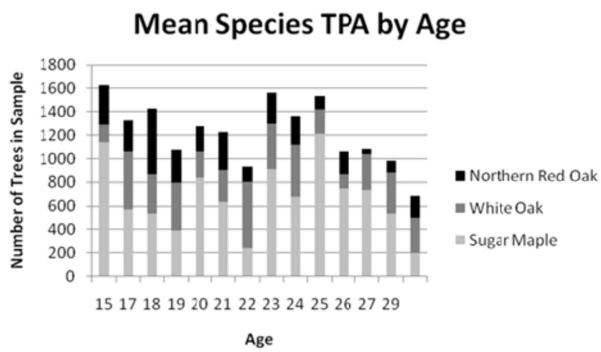


Figure 6. The average trees per acre (TPA) by age for three selected species.

Abundance

The data shows that northern red oak abundance remains about the same regardless of soil BS, sugar maple abundance increases with increasing soil BS and white oak abundance decreases with increasing BS (Table 10).

Table 10. Number of trees sampled and their percentage of the total for plots that contained less than and greater than 50 % saturation.

	Number of Trees Sampled		
	Base Saturation < 50 %	**Base Saturation > 50 %**	
	26 Plots	**18 Plots**	**Total**
Sugar Maple	439 (37%)	736 (59%)	**1175**
White Oak	488 (41%)	247 (20%)	**735**
Northern Red Oak	261 (22%)	254 (21%)	**515**
Total	**1188**	**1237**	**2425**

Sugar Maple

Two models best fit the data for sugar maple (Table 11). The sugar maple abundance model with the smallest AICc score is the most reduced model. If the AICc score is within 2 points for any models they are considered statistically significant (Anderson 2008). For sugar maple abundance there are two models that are similar. The data were transformed to a negative binomial distribution and the model output was transformed using the inverse log in order to normalize the data set. This caused the predicted curves to become exaggerated on the right tail.

Table 11. Abundance Model Comparisons. For the three species. Each row in the Models column represents a separate model run with the specified parameters. BS = soil base saturation, AWC = available water-holding capacity, LP = Landscape position. Values in the AICC column are the Akaike's Information Criterion values for the model. The lowest AICC value provides the best fit while values within 2 points are considered statistically equal.

Models	Models	AICC	P Values
Maple Abundance =	BS + AWC + LP	587	BS = 0.01, AWC = 0.2, LP = 0.6
	BS + AWC	580	BS = 0.02, AWC = 0.2
	BS	579	BS = 0.06
White Oak Abundance =	BS + AWC + LP	595	BS = 0.005, LP = 0.2, AWC = 0.8
	BS + AWC	588	BS = 0.002, AWC = 0.6
	BS	585	BS = 0.02
Red Oak Abundance =	BS + AWC + LP	567	BS = 0.8, LP = 0.3, AWC = 0.4
	LP + AWC	564	LP = 0.3, AWC = 0.4
	LP	562	LP = 0.2

The model finds that sugar maple abundance is positively influenced by soil exchangeable base saturation and available water capacity in combination (Figure 7 & Table 12). Landscape position was not significant in any models.

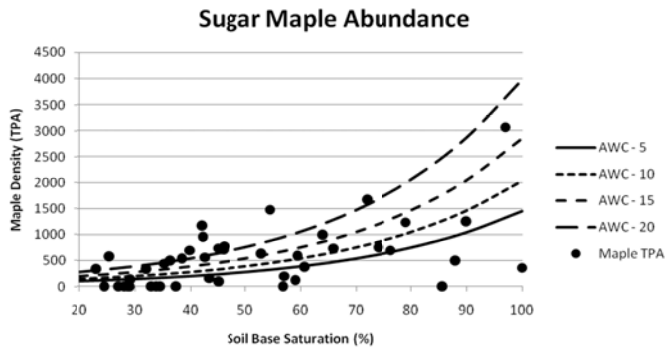


Figure 7. Sugar maple Abundance Model Prediction Line Graph. Site values are plotted as 'MapleTPA' and the predicted curves are shown for varying AWC values. Right tails are exaggerated due to effects of anti-log function.

Table 12. Analysis of Maximum Likelihood Parameter Estimates for sugar maple Abundance Model 1.

Sugar Maple Abundance Model 1							
Parameter	DF	Estimate	Standard Error	Lower Limit	Upper Limit	Wald Chi-sq	P
Intercept	1	3.6458	1.0754	1.5379	5.7536	11.49	0.0007
Base saturation	1	0.033	0.0146	0.0045	0.0616	5.14	0.0234
AWC	1	0.0671	0.0546	-0.0398	0.174	1.51	0.2186
Dispersion	1	3.5315	0.7444	2.0726	4.9904		

The model (Figure 7 & Table 12) uses BS and AWC as predictor values to predict that as BS rises so does the abundance of sugar maple. The parameter BS is significant in this model while AWC is not. However, the model predicts that as AWC increases sugar maple abundance increases as well. When these two parameters are coupled together the effect on sugar maple abundance intensifies.

The second model (Figure 8 & Table 13) is statistically equal and uses BS as the only predictor variable. The same positive correlation is seen. As BS increases in the model so does abundance. The P value increases from 0.02 to 0.06 from model one to the reduced model. The inverse log function was used to transform the data back and caused exaggeration in the right tail.

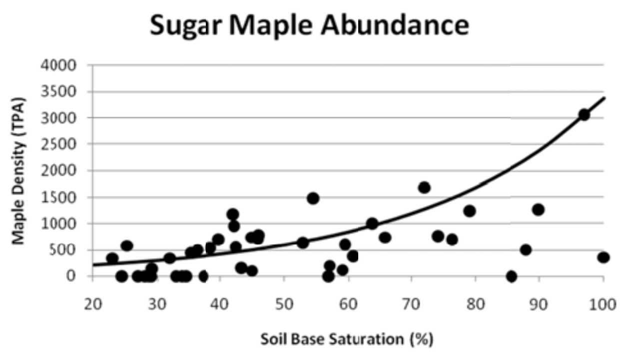


Figure 8. Sugar Maple Abundance Model 2 Prediction Line Graph.

Table 13. Analysis of Maximum Likelihood Parameter Estimates for sugar maple abundance model 2.

Sugar Maple Abundance Model 2							
Parameter	DF	Estimate	Standard Error	Lower Limit	Upper Limit	Wald Chi-sq	P
Intercept	1	4.6545	0.8307	3.0263	6.2827	31.39	<.0001
Base saturation	1	0.03468	0.009551	-0.0014	0.0593	3.5	0.0612
Dispersion	1	3.6588	0.7668	2.1559	5.1617		

Simpler metrics reveal the same trend. The mean soil exchangeable base saturation for the plots with no sugar maple is 38 % with a standard deviation of 17 %. The mean soil exchangeable base saturation for the plots with sugar maple is 55 % with a standard deviation of 20 %.

The model results validate the hypothesis that exchangeable base cations in the soil positively influences maple abundance. The data do not show a relationship of abundance with landscape position. While AWC is not significant in any of the models, the model with BS and AWC are statistically the same as the reduced model.

White Oak

The data and model show white oak abundance is negatively influenced by soil base saturation (Figure 9 and Table 14). Landscape position and soil available water capacity are found non-significant with this analysis. BS is significant in each of the model trials.

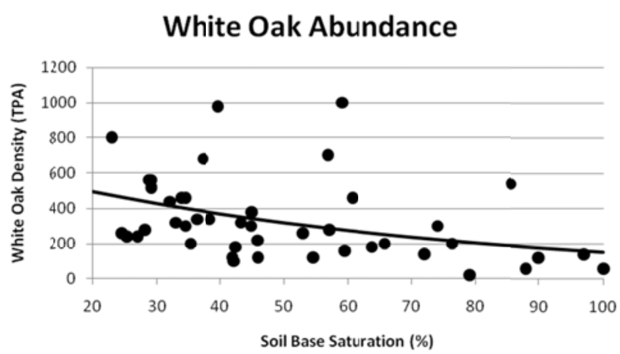


Figure 9. White Oak Abundance Model Prediction Line Graph.

Table 14. Analysis of Maximum Likelihood Parameter Estimates for white oak Abundance Model.

White Oak Abundance Model							
Parameter	DF	Estimate	Standard Error	Lower Limit	Upper Limit	Wald Chi-sq	P
Intercept	1	6.5064	0.259	5.9988	7.0141	631.09	<.0001
Base saturation	1	-0.0147	0.0048	-0.0241	-0.0053	9.36	0.0022
Dispersion	1	0.3968	0.0806	0.2387	0.5548		

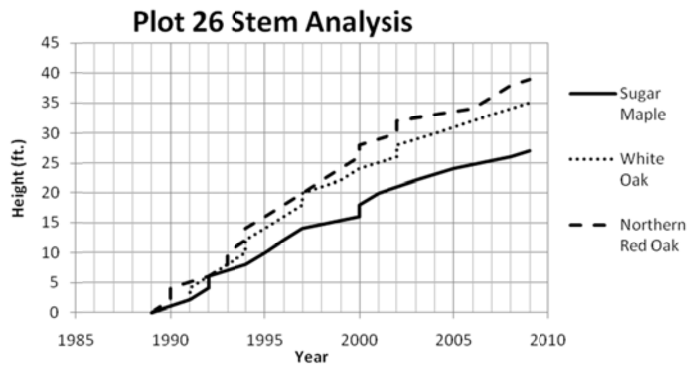
Northern Red Oak

The data shows no correlation between the parameters and northern red oak abundance (Table 11). For each of the model trials LP is consistently the most significant parameter albeit at low confidence.

Height Growth Rate

Northern red oak consistently had the greatest growth rate with an average of 2.03 ft./year. White oak average growth rate was 1.99 ft./yr. while sugar maple was 1.52 ft./yr. It is common for growth rate to halve or quarter from the early to later years when examining the first 29 years.

Sugar maple's growth had an overall greater decline as they became increasingly outpaced and shaded. Figure 10 shows an example of expected sampled growth rates of the three species using data from two plots. See Appendix 2 for stem analysis graphs for each plot.



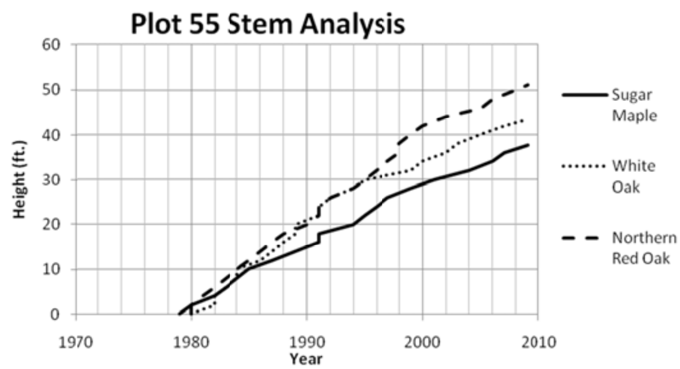


Figure 10. Stem Analysis Line Graphs for Plots 26 & 55.

Figure 11 shows the number of trees by height for the three selected species. The shorter heights are dominated by sugar maple while the taller heights are dominated by the oaks.

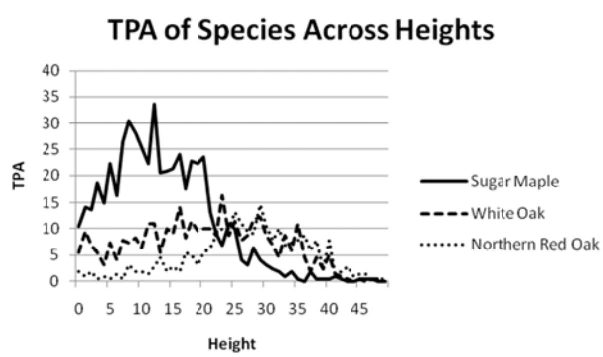


Figure 11. Trees per Acre with Species Across Heights.

Table 15 shows each model set tested, AICc value and parameter significance for each of the three species growth rate models. The model in each set with the smallest AICc score has the best fit. The P values show the significance of the parameters. A parameter is regarded as significant if its P value is lower than 0.05.

The data and models show that sugar maple height growth rate is positively correlated with AWC (see Figure 12 and Table 16). White oak and northern red oak height growth rates showed no relationship with BS but did produce a negative correlation with soil pH (see Figures 13-14 and Tables 17-18). White oak and northern red oak models are plotted together with the data for comparison (see Figure 15).

Table 15. Growth Rate Model Comparisons.

Models		AICC	P Values
Maple Height Growth Rate =	AWC + pH + LP	26	AWC = 0.005, pH = 0.8, LP = 0.5
	AWC + LP	23	AWC = 0.003, LP = 0.5
	AWC	23	AWC = 0.001
White Oak Growth Rate =	pH + AWC + LP	27	pH = 0.03, AWC = 0.7, LP = 0.4
	pH + LP	20	pH = 0.01, LP = 0.4
	pH	14	pH = 0.007
Red Oak Growth Rate =	pH + AWC + LP	41	pH = 0.2, AWC = 1.0, LP = 0.8
	pH + LP	34	pH = 0.2, LP = 0.8
	pH	30	pH = 0.16

Sugar Maple

The sugar maple height growth rate model with smallest AICc score is the most reduced model with the soil available water capacity parameter having a P value of 0.001. We can see in Table 13 that AWC is a highly significant parameter for each of the models. Landscape position is not significant for all models. The predicted line graphed over the data point's fits well.

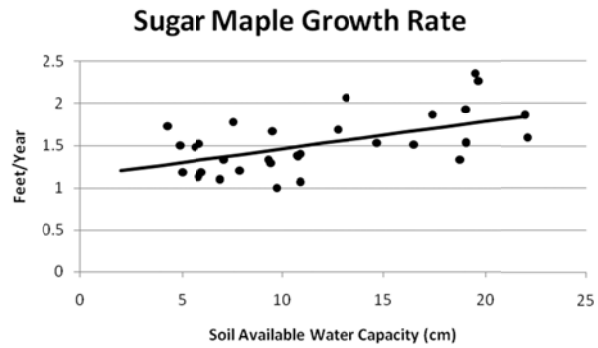


Figure 12. Sugar maple growth rate regressions with data points from the stem analysis trees on the 44 plots.

Table 16. Parameter estimates for sugar maple growth rate model.

Maple Growth Rate					
Parameter	Estimate	Standard Error	DF	t Value	P
Intercept	1.1342	0.1191	30	9.52	<.0001
AWC	0.03261	0.009046	30	3.6	0.0011

White Oak

The white oak growth rate model with the most reduced parameters has the lowest AICc score and soil pH as the significant parameter. As soil pH increases the height growth rate of white oak was found to decrease. The predicted line fit over the data shows a good fit.

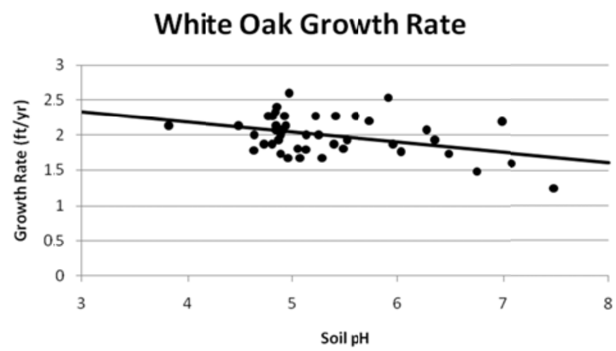


Figure 13. White oak growth rate regressions with data points from the stem analysis trees on the 44 plots.

Table 17. Parameter Estimates for white oak Growth Rate Model.

White Oak Growth Rate					
Parameter	Estimate	Standard Error	DF	t Value	P
Intercept	2.7611	0.2761	42	10	<.0001
pH	-0.144	0.05121	42	-2.81	0.0074

Northern Red Oak

The northern red oak growth rate model also had the lowest AICc score with the most reduced parameter. As soil pH values increase the height growth rate of northern red oak is found to decrease. The model doesn'**t** predict with great confidence as pH has a P value of 0.16, but the general trend is revealed. The predicted line over the data shows a good fit.

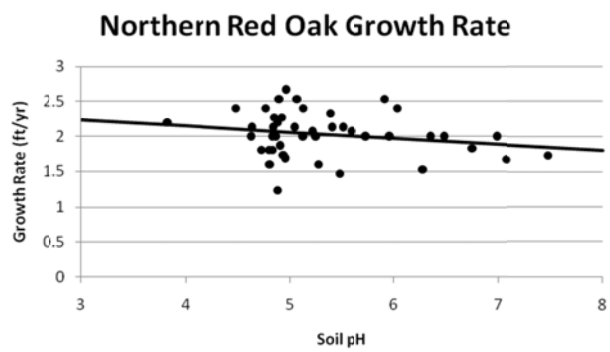


Figure 14. Northern red oak growth rate regressions with data points from the stem analysis trees on the 44 plots.

Table 18. Parameter Estimates for northern red oak Growth Rate Model.

Red Oak Growth Rate					
Parameter	Estimate	Standard Error	DF	t Value	P
Intercept	2.4909	0.3334	42	7.47	<.0001
pH	-0.08651	0.06185	42	-1.4	0.1692

Difference in Height Growth Rates

The predicted lines of the growth rates of white and northern red oak were plotted together to show their correlation. The data and model shows that at more acidic soil pH levels white oak has a slightly greater height growth rate while at more basic soil pH levels northern red oak has the greatest growth rate. The apex of the two lines is between a pH of 5 and 6.

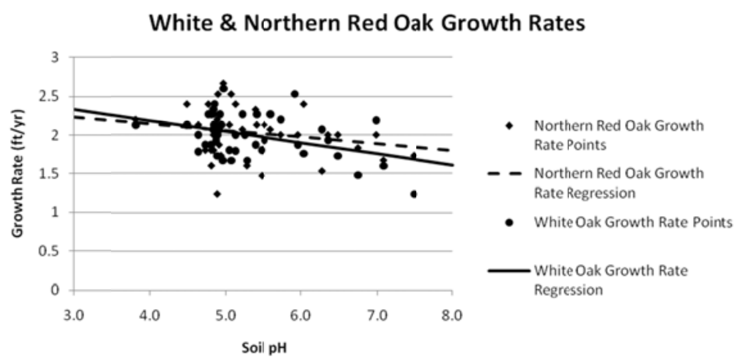


Figure 15. White and northern red oak growth rate regressions with data points for each species from the stem analysis trees on the 44 plots.

The difference in height growth rates is significant between northern red oak and sugar maple, but not between white oak and sugar maple. The difference in growth rates between northern red oak and sugar maple decreases as soil available water capacity increases (see Figure 16 and Table 19). Sugar maple growth rate is less than northern red oaks for all plots sampled. Sites with an AWC around 5 cm are predicted to produce sugar maple with a growth rate nearly a foot less. At sites with an AWC of 15 cm sugar maples growth rate is only 6 inches (15.24 cm) less than northern red oaks.

Sugar maples growth rate is not predicted to equal northern red oaks until AWC is approaches 25 cm.

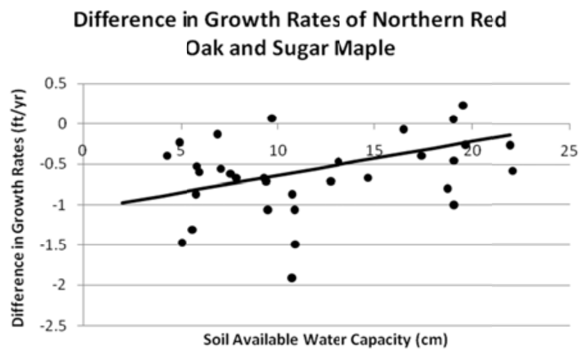


Figure 16. A plot of the points showing the difference in growth rates between northern red oak and sugar maple with predicted regression overlaid.

Table 19. Difference in northern red oak growth rate and sugar maple growth rate model comparisons.

Models	Models	AICC	P Values
Difference in Northern Red Oak	pH + AWC + LP	41	AWC = 0.02, LP = 0.5, pH = 0.4
Growth Rate and Sugar Maple Growth	AWC + LP	41	AWC = 0.02, pH = 0.3
Rate =	AWC	39	AWC = 0.04

Sugar maple was found to be more common in all the crown classes except dominant on sites with AWC values greater than 11 cm (Table 20). However, the sample size dropped from 44 plots to 16 plots for sites with an AWC greater than 11 cm while the percent of dominant sugar maple trees only declined from 15 % to 13%.

Table 20. The number of trees sampled in each crown class by species and crown class with percentage of the total in each column. The top half of the table shows all plots while the lower half shows the plots in the upper half of the soil available water capacity gradient data.

	Crown Class-Number of Trees Sampled					
	Dominant	**Codominant**	**Intermediate**	**Suppressed**	**Understory**	**Total**
All Plots						
Sugar Maple	31 (15%)	73 (16%)	169 (40%)	362 (64%)	540 (69%)	**1175 (48%)**
White Oak	78 (37%)	164 (36%)	150 (36%)	138 (24%)	205 (26%)	**735 (30%)**
Northern Red Oak	100 (48%)	215 (48%)	100 (24%)	66 (12%)	34 (4%)	**515 (21%)**
Total	**209 (9%)**	**452 (19%)**	**419 (17%)**	**566 (23%)**	**779 (32%)**	**2425**
Plots AWC >11, N = 16						
Sugar Maple	12 (13%)	40 (23%)	71 (45%)	153 (67%)	204 (72%)	**480 (52%)**
White Oak	36 (40%)	76 (44%)	65 (41%)	52 (23%)	65 (23%)	**294 (32%)**
Northern Red Oak	41 (46%)	58 (33%)	22 (14%)	22 (10%)	14 (5%)	**157 (17%)**
Total	**89 (10%)**	**174 (19%)**	**158 (17%)**	**227 (24%)**	**283 (30%)**	**931**

CHAPTER 7. DISCUSSION

Soil Base Saturation

Much of the Missouri River Hills region has abundant loess on the summits that erodes to the lower landscape positions. The extensive limestone formations in the area also contribute to the base cation concentrations levels in the soils.

No apparent trend can be seen from the data concerning BS values and other site properties. Many of the shallow soils reported high BS values as limestone bedrock and gravel was typically a component of those soils. In situ weathering provides a great concentration of base cations.

The distribution of BS values is not an ideal distribution for modeling as the Painted Rock values are exceptionally large while all the other values are grouped around the 40's. A data set with a greater distribution is preferred and might reveal currently undetected correlations.

Soil Available Water Capacity

The literature review revealed that soil AWC has a positive effect on sugar maple abundance and growth rates. Oaks are known for their tolerance of poor sites while sugar maple is not. This study confirms this notion and found that sugar maple has greater height growth potential and greater densities on sites with greater AWC. No relationship between oak abundance or growth and AWC. This is indicative of white and northern red oaks ability to colonize and grow well on soils with low and high AWC.

Landscape Position

Unfortunately the population of even-aged stands in the study area is too small to provide adequate variation. Broadening the study area was considered but control of other variables would have been reduced. Other studies have noted each species preference for certain positions on the landscape. The methods of this study could have provided similar results with an adequate sample size. We know from previous studies (Hilt 1985, Heiligmann et al. 1985, Iverson et al. 1997, Groninger & Long 2008, McClurkin 1963) that landscape position is a significant variable in estimating abundance and growth of the study species

Clearcutting in the study area was not practiced until the late 1970's. While the practice has been widely implemented there are not an adequate number of site varieties available in the target age group of 15 years and older. This study encountered two sites on the lower backslope from which to collect data. While many of the study sites had harvested area on the lower backslope, the lower backslope area was too small to install a 1/20th acre plot with adequate buffer. Using different data collection strategies will likely overcome this problem.

Landscape preferences for each of the selected species have been widely studied (Godman et al. 1990). Sugar maple occurs on protected slopes and on the lower and foot slope positions. The results for this study for abundance and height growth rate support this finding. The preferred landscape positions for sugar maple are positions typically with the greatest abundance of base cations and AWC.

This studies finding of white oaks preference for drier and nutrient poorer soils agrees with other studies finding that white oak is more common on ridges and middle backslopes and on exposed aspects (Kabrick et al. 2011, Rogers 1990 & Villwock 2011).

Northern red oak's reported distribution across the landscape is wide (Kabrick et al. 2011, Sander 1990 & Villwock 2011). This studies finding of northern red oaks affinity for sites with more acid pH is likely more suggestive of competitive factors rather than species requirements.

Abundance

White oak is more common on poorer sites while sugar maple is more common on fertile sites. Northern red oak abundance seems unaffected by base saturation. This study concurs with previous findings that sugar maple is most abundant on soils with greater BS and greater AWC (Belden & Pallardy 2009, Fralish 1976, Hinckley et al. 1979, Muller 1982, Nigh et al. 1985, Sander 1990, Schreeg et al. 2005). The loess derived silt loams provide adequate AWC values.

This study agrees that white oak is most common on soils with fewer base saturations. In the Missouri Ozarks, (Kabrick et al. 201, Villwock 2011, Ware et al. 1992) white oak abundance has been found to decrease on better sites and the decrease was attributed to increased competition from more mesic species. Long and Groninger (2010) found oaks most abundant on the sites with lesser nutrient status in southern Illinois.

A trend in northern red oak occurrence cannot be detected by the data and any of the parameters we tested. Its distribution does not seem to be limited to sites with any of the properties that we tested. It is found on sites with high and low base saturation and available water capacities. Again, time will likely affect this outcome.

Height Growth Rate

Sugar maple attains its greatest height growth rates on soils with greater AWC values. Height growth ranged from 1 to 2.36 ft/yr (see Table 7) across a range of sites of low AWC to greater AWC. Better sites have a loamy texture and are deeper.

White and northern red oak's height growth rate increases as soil pH decreases. Oaks are most competitive on older soils in the study area. This is presumably due to competitiveness of other species, particularly sugar maple, rather than the trees response to greater nutrient availability (Bigelow and Canham 2002, Cogliastro et al. 2003, Demchik & Sharpe 2000, Schreeg et al. 2005, Villwock 2011).

Stand Dynamics

Light availability seems to have a greater impact upon sugar maple growth rate than AWC (Figure 17). It has been previously found that sugar maple growth rate in full sun rarely equals that of more shade tolerant oaks (Bazzaz 1979, Marks 1975) and once sugar maple is shaded from the side or top, growth rates decline (Godman 1969). See the height growth rates graphed for plots 6 and 79 in Figure 17. Visual observations made in older stands shows this trend as well. Once the decline in growth rate loses pace with competitive oaks it seems relegated to wait while the oaks continue up.

Where is sugar maple competitive with oak in the canopy and where is it not? After inherited biological traits such as shade tolerance and regeneration ecology are considered, soil properties determine the competitiveness of sugar maple. Our findings support this conclusion as can be seen in the height growth rate graphs of the three species. Sugar maple has a great affinity for fertile sites with larger AWC.

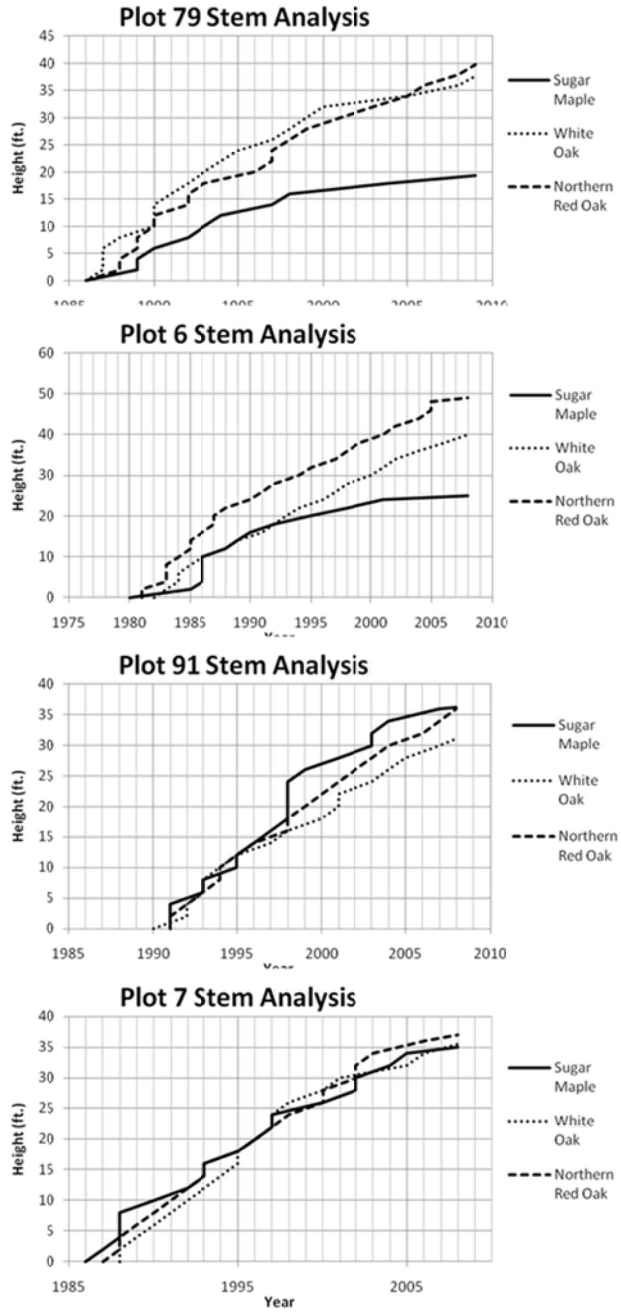


Figure 17. Stem analysis of select species on plots with increasing AWC values. Plot 79 (sugar maple growth rate = 0.74 ft/yr, AWC = 5.83 cm), plot 6 (sugar maple growth rate = 0.81 ft/yr, AWC = 10.75 cm), plot 91 (sugar maple growth rate = 2.06 ft/yr, AWC = 19.51 cm) & plot 7 (sugar maple growth rate = 1.55 ft/yr, AWC = 22 cm).

CHAPTER 8. IMPLICATIONS FOR MANAGEMENT

As new information about stand development and forest soils become available, new metrics for measuring productivity become increasingly important to the manager. AWC values can be easily determined on the landscape using soil maps developed from the U.S. National Soil Survey. The developing ELT maps for the state of Missouri also provide insight into where the best sites for sugar maple management exists because they are based on the U.S. National Soil Survey soil maps. Remote sensing technology can reveal high priority sites. Many of these sites will likely already contain abundant and competitive populations of sugar maple.

Managers should use the Soil Survey and ELT maps to identify sites having greater relative AWC and pH or base cation values on the landscape and the potential for producing sugar maples capable of competing with oaks. Loess and exposed limestone rock fragments or outcrops are indicators of nutrient rich soils in the study area. Identifying where sugar maple can be productive on the landscape is the first step.

The sites examined in this study seem poised for future stand composition to be an overstory dominated by northern red oak with white oak in the codominant and intermediate crown classes. Sugar maple will mostly be relegated to the suppressed and sometimes intermediate crown classes with slow growth rates. On some sites where few oaks occur sugar maple will likely become a codominant figure.

Where sugar maple is to be managed, thinning stands in years 10-15 will provide the best time of entry to do a targeted crop tree release on the more prominent stems. At this time growth rate has declined minimally. Exact timing will be site dependent. The mesic and higher nutrient sites can be thinned later as sugar maple is more competitive with other species. Poorer sites should be thinned sooner to prevent loss in growth.

When managing oaks on sites with larger values of AWC, BS or pH, thinning early is critical to prevent loss of growth. While this study finds that oaks are poor competitors on sites with high AWC, BS or pH values, other studies show that oaks can attain high growth rates on these sites when competition is controlled. On lesser quality sites delaying thinning will likely not result in a noticeable loss in growth on oaks.

On the sites with larger AWC, BS or pH values, oak and sugar maple can be grown together but the manager must be willing to sacrifice growth in one or both genus. Targeted crop tree management on a 10-year schedule can produce a first crop of northern red oak (60-100 years), second crop of white oak (80-160 years) and a third crop of sugar maple (80 to 200 years). The economic trade offs for mixed stand management have not been explored for this stand type. Constant market variability likely prevents a study from being meaningful. Intermediate thinning's can produce income in the middle years of the stands rotation before, during and after the harvest of northern red oak crop trees.

The implications for long-term sustainability of oak forests are questionable when a significant amount of sugar maple occurs in the stand. Regeneration and recruitment of oaks has found to be poor below a sub canopy of tolerant saplings and trees (Belden & Pallardy 2009, Lorimer et al. 1994). Pre-commercially treating the stand to eliminate sugar maple and creating canopy gaps to recruit oak advance regeneration is essential. If the stand is carried to full-rotation with sugar maple as the final crop considerations for oak regeneration should be explored.

The lack of oaks on lower and protected slopes in this study is likely due to the absence of wildfires and the mesophication of these sites (Wuenscher & Valiunas 1967, Nowacki & Abrams 2008). Restoring fire to every landscape to retain historical natural communities is not practical. Groninger and Long (2008) proposed working to retain oaks on the upper and midslope xeric sites and focusing lower slope management on more mesic species. Periodic droughts will likely influence future composition of these stands as more mesic species succumb to drought induced mortality (Morrissey et al. 2008).

White oak regeneration has been found to be most successful in clearcuts and group openings in the Ozark Highlands (Kabrick et al. 2008). Intermediate harvests are bests for maintaining long-term sustainability of sugar maple (Bédard & Majcen 2001, personal observations). In fact, many of the forests in the study area have been managed by high-grade harvesting for the previous decades and more likely for the previous two centuries. This method of harvesting promotes sugar maple.

Clearcutting seems to prohibit hickory regeneration (Norland & Hix 1996) and this study supports that. Hickory comprised 6 % of total species sampled in this study while Forest Inventory and Analysis (2010) found that hickory comprises 9 % of all live growing stock. Hickories survival abilities will likely increase its relative density similar to oaks as the stand ages.

Sugar maple responds well to gap creation and can be considered competitive growing on the better sites (Jones & Thomas 2004). Managers should consider group openings and intermediate harvests on the lower backslopes and footslopes to manage for sugar maple mixed forests. Clearcuts for regenerating oaks should be considered on the upper landscape positions above the lower backslope and on nutrient poor soils.

This information can be used to identify sites where sugar maple should not be considered. In the study area many of these sites currently contain sugar maple in the understory. It is not known whether the sugar maple will remain a part of the stand for the full rotation, but knowing that it is not competitive and has a slow growth rate does provide predictability and allows the manager insight of stand development.

Findings from this study will allow managers to focus resources to become more productive. A more diverse suite of products will become available to the marketplace sooner as a result of implementing the results of this study. Central Missouri is not known for producing high quality sugar maple but it does have the sites to produce it.

CHAPTER 9. CONCLUSION

Sugar maple abundance is increasing in nearly all forest types in Central Missouri. Managers have little information to aid them in managing this species of gaining importance. Basic information such as where to retain sugar maple, where to eliminate and where to ignore is lacking. This study helps managers make decisions about where and where not to grow sugar maple.

Sugar maple in the Missouri and Osage River valleys of central Missouri is most abundant on soils with greater exchangeable base cations and soils with more available water capacity. It is more competitive with oaks on sites with higher available water capacity where sugar maple growth rate increases. White and northern red oak growth rates increases on sites with lower soil pH. The results of this study enable managers to better predict adequate sites for growing sugar maple, white oak and northern red oak.

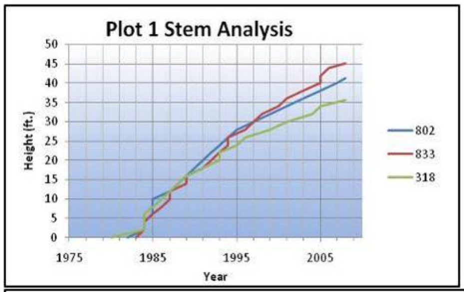
APPENDIX 1

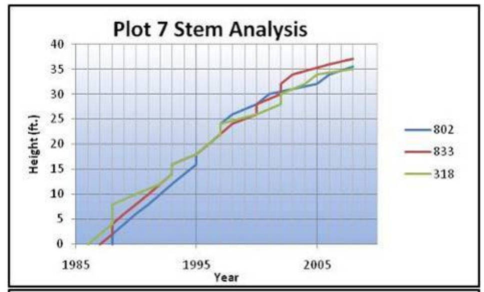
Species List

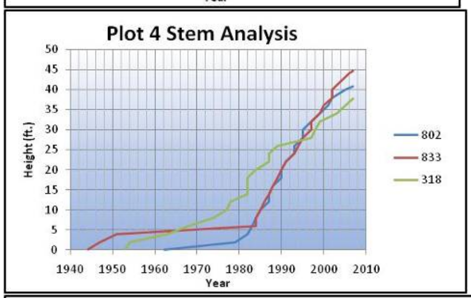
Species	Number Sampled (x)	x/N
American Basswood	2	0.0003
American Elm	22	0.0037
American Hornbeam	5	0.0009
American Sycamore	5	0.0009
Bitternut Hickory	25	0.0043
Black Cherry	140	0.0238
Black Hickory	9	0.0015
Black Oak	155	0.0264
Black Walnut	7	0.0012
Blackhaw	13	0.0022
Blue Ash	7	0.0012
Carolina Buckthorn	3	0.0005
Chinquapin Oak	54	0.0092
Eastern Hophornbeam	2	0.0003
Eastern Redbud	89	0.0152
Eastern Redcedar	49	0.0083
Flowering Dogwood	406	0.0692
Green Ash	1	0.0002
Hackberry	19	0.0032
Hawthorn spp.	43	0.0073
Hazelnut	7	0.0012
Honeysuckle	5	0.0009
Ironwood	1119	0.1906
Misc.	2	0.0003
Mockernut Hickory	41	0.0070
Northern Red Oak	515	0.0877
Pawpaw	2	0.0003
Post Oak	33	0.0056
Red Maple	6	0.0010
Red Mulberry	52	0.0089
Sassafras	226	0.0385
Service Berry	388	0.0661
Shagbark Hickory	272	0.0463
Shellbark Hickory	2	0.0003
Shingle Oak	2	0.0003
Slippery Elm	55	0.0094
Sugar Maple	1175	0.2001
White Ash	169	0.0288
White Oak	735	0.1252
Wild Plum	5	0.0009
Winged Elm	4	0.0007
Grand Total	**5871**	100

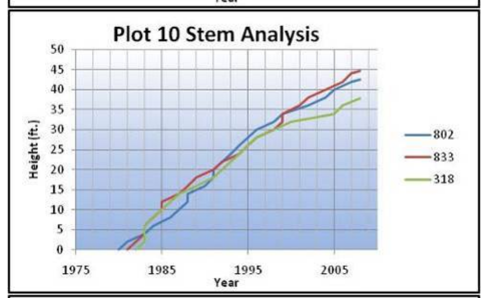
APPENDIX 2

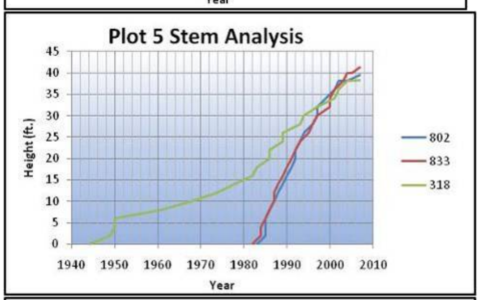
Stem Analysis Graphs
Baskett

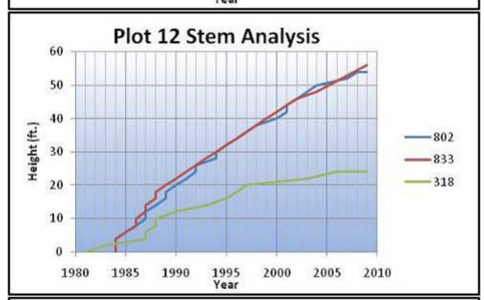


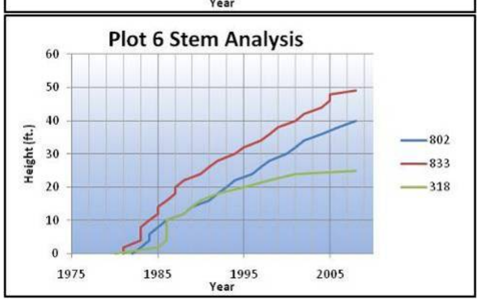


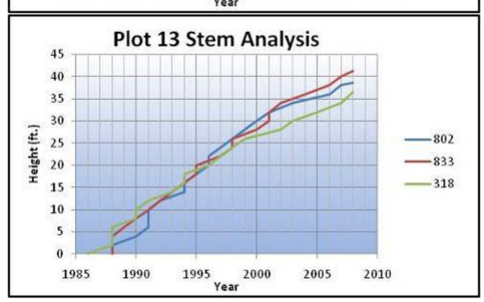




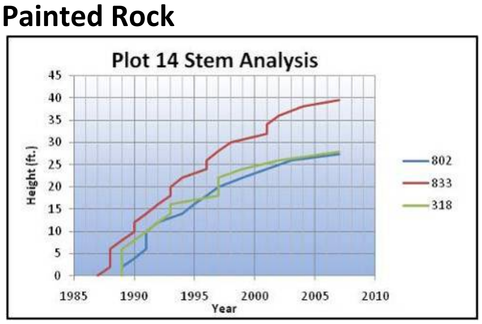


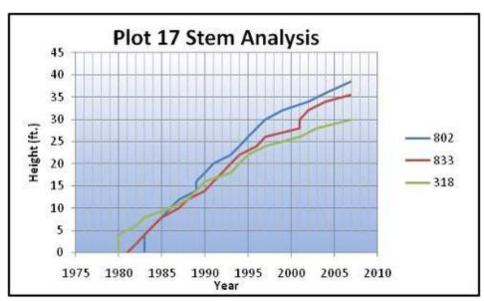


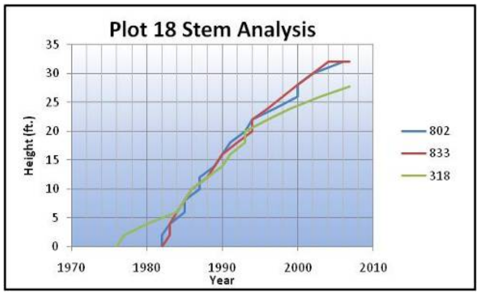


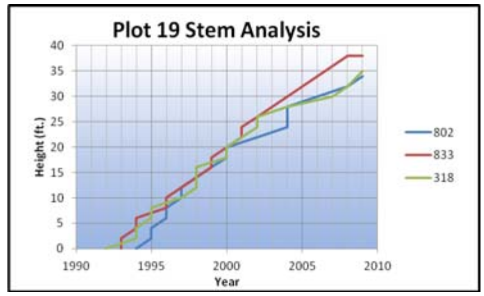


Painted Rock









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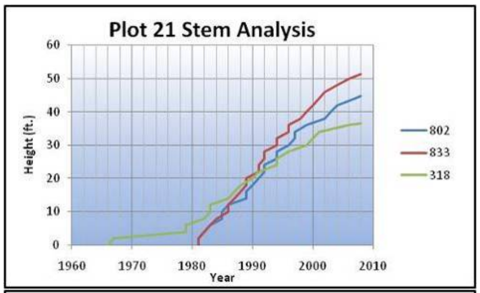

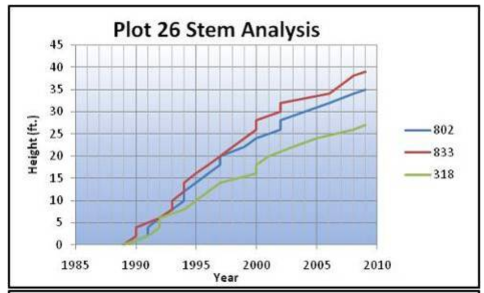

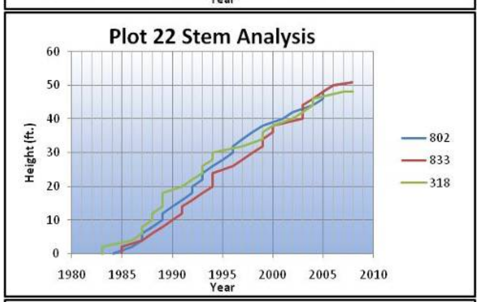

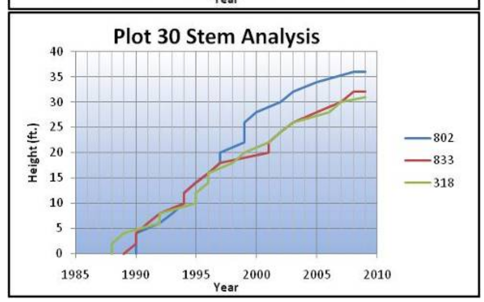

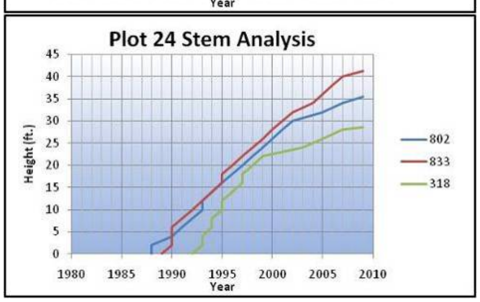

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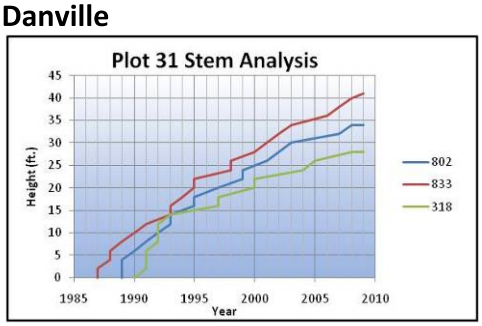

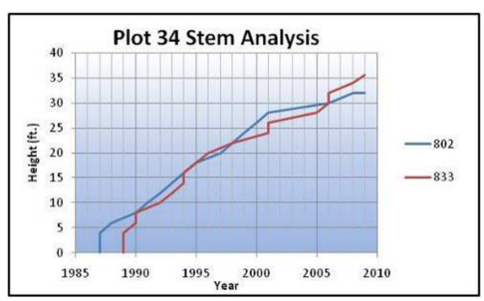

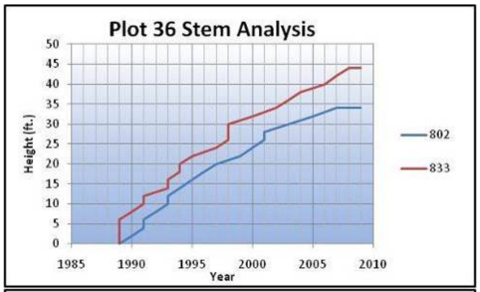

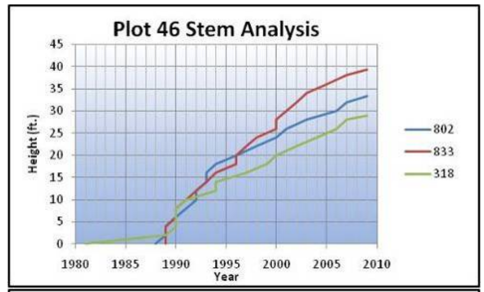

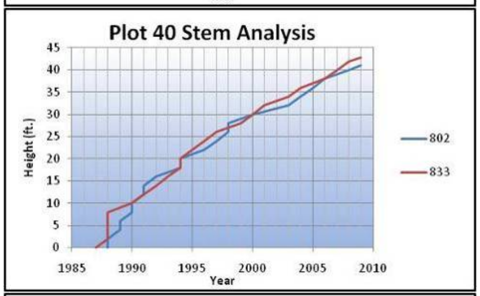

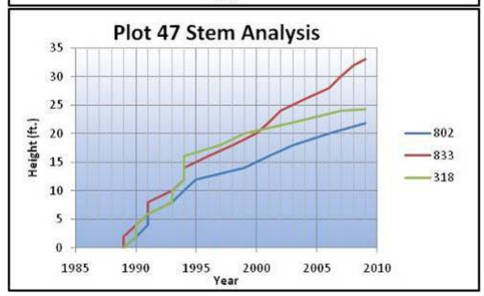

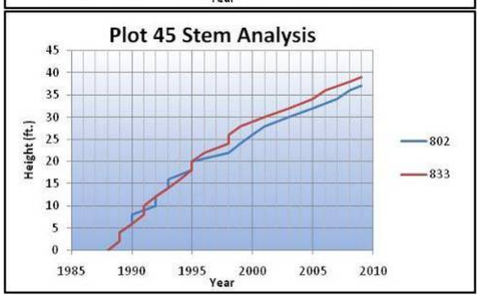

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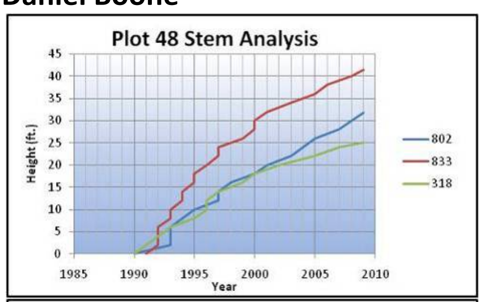
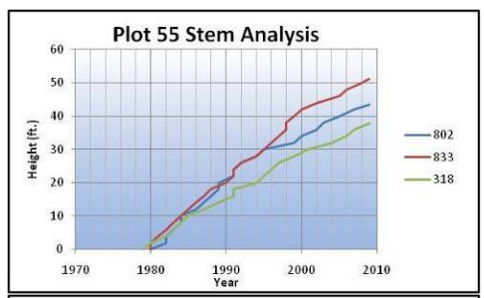
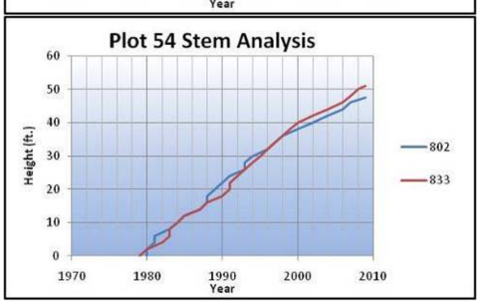
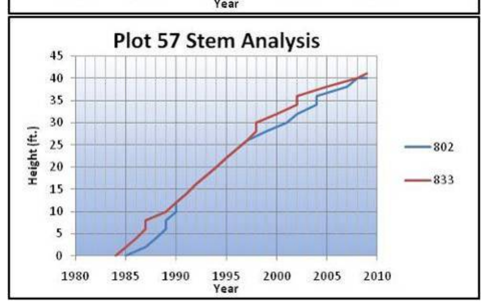
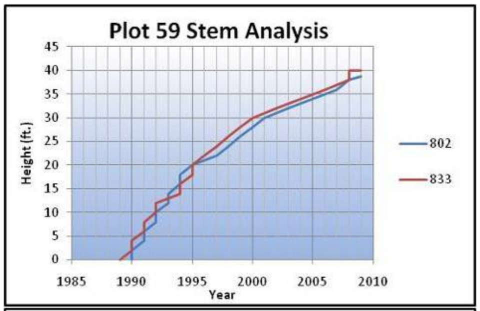
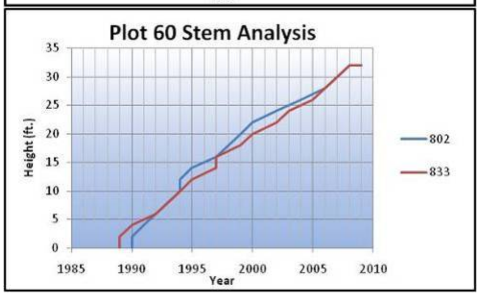


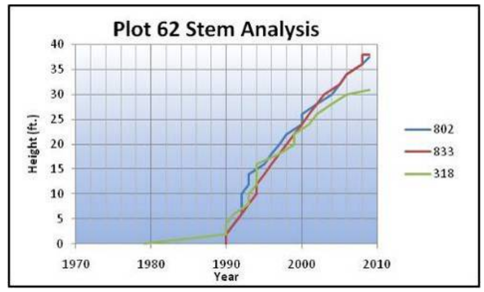




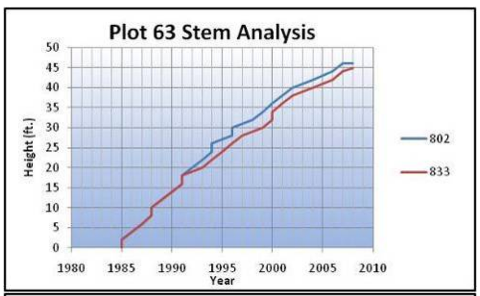


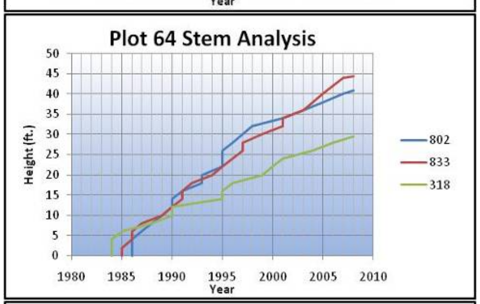


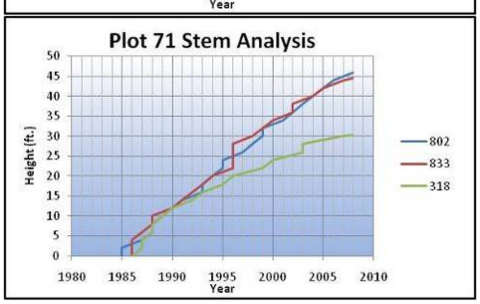


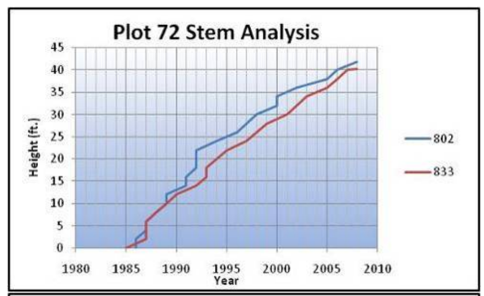


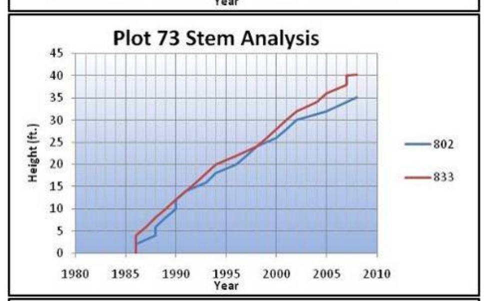
Little Lost Creek

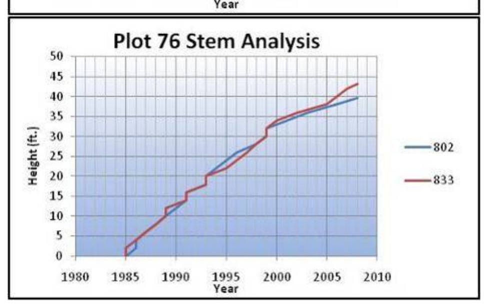


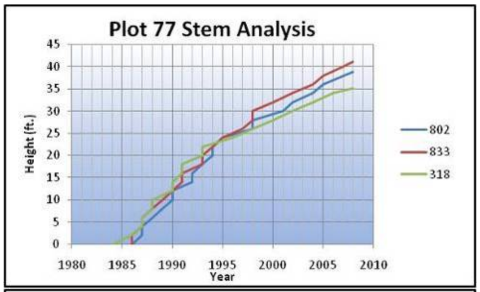








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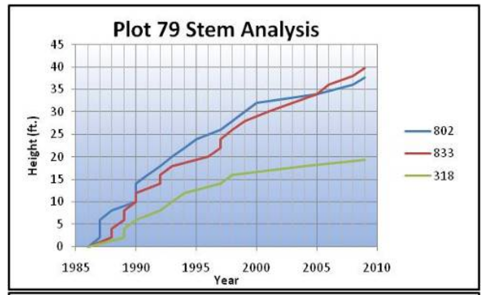
833
318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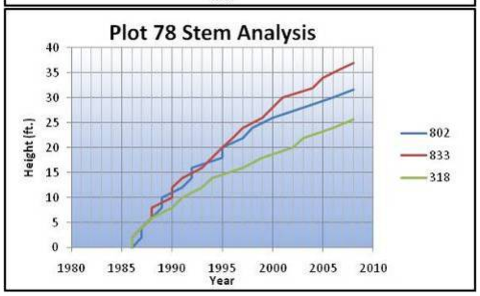
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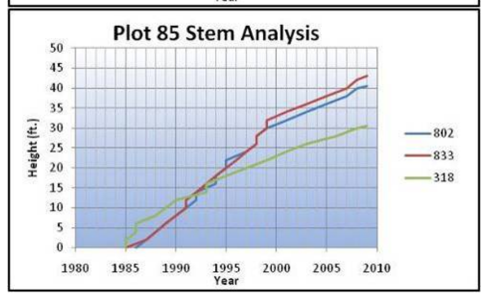
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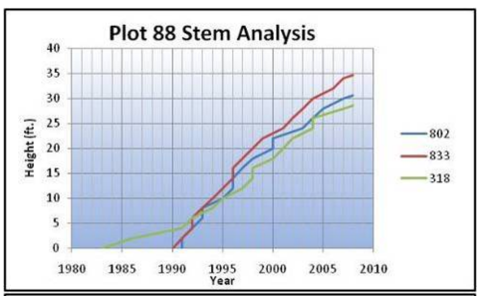
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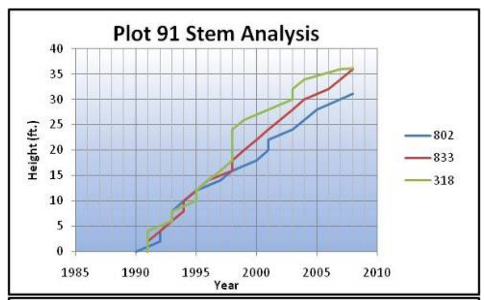
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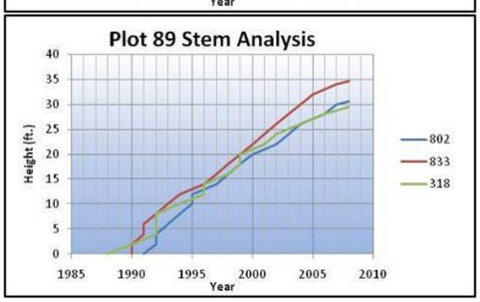
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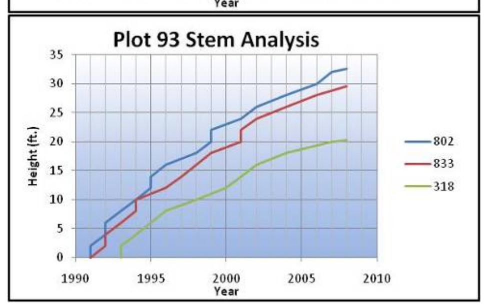
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Year
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833
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LITERATURE CITED

Abrams, M.D., 1990. Adaptations and response to drought in Quercus species of North America. Tree Phys. 7: 227-238.

Abrams, M.D. 1992. Fire and the development of oak forests. Bioscience. 42: 346-353.

Adams, D.E, and R.C. Anderson. 1980. Species response to a moisture gradient in central Illinois forests. Am. J. Bot. 67: 381-392.

Adams, C.M., and T.C. Hutchinson. 1992. Fine-root growth and chemical composition in declining Central Ontario sugar maple stands. Can. J. For. Res. 22: 1489-1503.

Aguilar, R., and R.W. Arnold. 1985. Soil-landscape relationships of a climax forest in the Alleghany High Plateau, Pennsylvania. Soil Sci. Soc. Am. J. 49: 695-701.

Allison, T.D., H.W. Art, F.E. Cunningham, and R. Teed. 2003. Forty-two years of succession following strip clearcutting in a northern hardwoods forest in northwestern Massachusetts. For. Ecol. Man. 285-301.

Anderson, D.R. Model Based Inference in the Life Sciences. New York, NY, Springer Science and Business Media, LLC. 2008.

Atwood, C.J., T.R. Fox, and D.L. Loftis. 2008. Stump sprouting of oak species in three silvicultural treatments in the southern Appalachians. *In*: Jacobs, Douglass F.; Michler, Charles H., eds. 2008. Proceedings, 16th Central Hardwood Forest Conference; 2008 April 8-9; West Lafayette, IN. Gen. Tech. Rep. NRS-P-24. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 2-7.

Bahari, Z.A., S.G. Pallardy, and W.C. Parker. 1985. Photosynthesis, water relations, and drought adaptation in six woody species of oak-hickory forests in central Missouri. Forest. Sci. 31: 557-569.

Bailey, S.W., S.B. Horsley, and R.P. Long. 2005. Thirty years of change in forest soils of the Allegheny Plateau, Pennsylvania. Soil Sci. Soc. Am. J. 69: 681-690.

Bailey, S. W., Horsley, S. B., Long, R. P., & Hallett, R. A. 2004. Influence of edaphic factors on sugar maple nutrition and health on the Allegheny plateau. Soil Sci. Soc. Am. J. 68:243-252.

Beaudet, M, & C. Messier. 1998. Growth and morphological responses of yellow birch, sugar maple, and beech seedlings growing under a natural light gradient. Can. J. For. Res. 28: 1007-1015.

Bédard, S., and Z. Majcen. 2001. Ten-year response of sugar maple-yellow birch-beech stands to selection cutting in Québec. Nor. J. Appl. For. 18: 119-126.

Belden, A.C., and S.G. Pallardy. 2009. Successional trends and apparent *Acer saccharum* regeneration failure in an oak-hickory forest in central Missouri, USA. Plant Ecol. 204: 305-322.

Bicknell, S.H. 1982. Development of canopy stratification during early succession in northern hardwoods. For. Ecol. Manage. 4:41-51.

Bigelow, S.W., & C.D. Canham. 2002. Community organization of tree species along soil gradients in a north-eastern USA forest. J. Ecol. 90:188-200.

Boerner, R.E.J., and E.K. Sutherland. 1997. The chemical characteristics of soil in control and experimentally thinned plots in mesic oak forests along a historical deposition gradient. Applied Soil Ecology 7: 59-71.

Brady, N.C., & R.R. Weil. The Nature and Property of Soils. 13th ed. Upper Saddle River, NJ. Prentice Hall. 2002.

Brashears, M.B., M.A. Fajvan, and T.M. Schuler. 2004. An assessment of canopy stratification and tree species diversity following clearcutting in central Appalachian hardwoods. For. Sci. 50: 54-64.

Braun, E.L. 1985. *Deciduous forests of eastern North America*. Macmillan, New York.

Bretz, J.H. 1965. Geomorphic History of the Ozarks of Missouri. Vol. XLI, 2nd series. State of Missouri, Division of Geological Survey and Water Resources. Rolla, Missouri.

Buckley, D.S., T.L. Sharik, & J.G. Isebrands. 1998. Regeneration of northern red oak: positive and negative effects of competitor removal. Ecology. 79: 65-78.

Buol, S.W., R.J. Southard, R.C. Graham, and P.A. McDaniel. Soil Genesis and Classification. 5th ed. Ames, IA. Iowa State Press. 2003.

Burke, D.J., J.C. Lopez-Gutierrez, K.A. Semo, and C.R. Chan. 2009. Vegetation and soil environment influence the spatial distribution of root-associated fungi in a mature beech-maple forest. Appl. Environ. Microbiology. 75: 7639-7648.

Butler, B.J., and E.C. Leatherberry. 2004. America's family forest owners. J. For. 102:4-14.

Canham, C.D., and P.L. Marks. 1985. The response of woody plants to disturbance: patterns of establishment and growth. The Ecology and Natural Disturbance and Patch Dynamics. Eds. S.T.A. Pickett & P.S. White. pp. 197-216. Academic Press, Orlando, Fla.

Canham, C.D., A.R. Berkowitz, V.R. Kelly, G.M. Lovett, S.V. Ollinger, and J. Schnurr. 1996. Biomass allocation and multiple resource limitation in tree seedlings. Can. J. For. Res. 26: 1521-1530.

Casperson, J.P., and R.K. Kobe. 2001. Interspecific variation in sapling mortality in relation to growth and soil moisture. Oikos. 92: 160-168.

Christopher, S.F., B.D. Page, J.L. Campbell, and M.J. Mitchell. 2006. Contrasting stream water NO_3 and Ca^2 in two nearly adjacent catchments: the role of soil Ca and forest vegetation. Global Change Biology. 12: 364-381.

Cogliastro, A., D. Gagnon, S. Daigle, and A. Bouchard. 2003. Improving hardwood afforestation success: an analysis of the effects of soil properties in southwestern Quebec. For. Ecol. Man. 177: 347-359.

Collins, R.J., & W.P. Carson. 2004. The effects of environment and life stage on Quercus abundance in the eastern deciduous forest, USA: are sapling densities most responsive to environmental gradients. For. Ecol. Man. 201: 241-258.

Coughlan, A.P., Y. Dalpé, L. Lapointe, and Y. Piché. 2000. Soil pH-induced changes in root colonization, diversity, and reproduction of symbiotic arbuscular mycorrhizal fungi from healthy and declining maple forests. Can. J. For. Res. 30:1543-1554.

Cronan, C.S., and D.F. Grigal. 1995. Use of calcium/aluminum ratios as indicators of stress in forest ecosystems. J. Environ. Qual. 24:209-226.

Crow, T.R. 1992. Population dynamics and growth patterns for a cohort of northern red oak (*Quercus rubra*) seedlings. Oecologia. 91:192-200.

Cutter, B.E., and R.P. Guyette. 1994. Fire frequency on an oak-hickory ridgetop in the Missouri Ozarks. Am. Mid. Nat. 132:393-398.

Demchik M.C., and W.E. Sharpe. 2000. The effect of soil nutrition, soil acidity and drought on northern red oak (Quercus rubra L.) growth and nutrition on Pennsylvania sites with high and low red oak mortality. For. Ecol. Man. 136: 199-207.

Dey, D.C., R.G. Jensen, and M.J. Wallendorf. 2008. Single-tree harvesting reduces survival and growth of oak stump sprouts in the Missouri Ozark highlands. *In*: Jacobs, Douglass F.; Michler, Charles H., eds. 2008. Proceedings, 16th Central Hardwood Forest Conference; 2008 April 8-9; West Lafayette, IN. Gen. Tech. Rep. NRS-P-24. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station: 2-7.

Dijkstra, F.A., and M.M. Smits. 2002. Tree species effects on calcium cycling: the role of calcium uptake in deep soils. Ecosystems. 5:385-398.

Duchesne, L., R. Ouimet, and D. Houle. 2002. Basal area growth of sugar maple in relation to acid deposition, stand health, and soil nutrients. J. Environ. Qual. 31: 1676-1683.

Duchesne, L., R. Ouimet, J.-D. Moore, and R. Paquin. 2005. Changes in structure and composition of maple-beech stands following sugar maple decline in Quebec, Canada. For. Ecol. Man. 208:223-236.

Ellsworth, D.S., and P.B. Reich. 1992*a*. Leaf mass per area, nitrogen content and photosynthetic carbon gain in *Acer saccharum* seedlings in contrasting forest light environments. Functional Ecology. 6: 423-435.

Ellsworth, D.S., and P.B. Reich. 1992*b*. Water relations and gas exchange of Acer saccharum seedlings in contrasting natural light and water regimes. Tree Phys. 10: 1-20.

Finzi, A.C., C.D. Canham, and N. Van Breemen. 1998. Canopy tree-soil interactions within temperate forests: species effects on pH and cations. Eco. Applications. 8: 447-454.

Forest Inventory & Analysis Staff, US Forest Service, FIA VALIDator online tool. Available online at http://www.fia.fs.fed.us/tools-data/other/default.asp/ accessed February 5, 2011.

Foster, N.W., M.J. Mitchell, I.K. Morrison, and J.P. Shepard. 1992. Cycling of acid and base cations in deciduous stands of Huntington Forest, New York, and Turkey Lakes, Ontario. Can. J. For. Res. 22: 167-174.

Fralish, J.S. 1976. Forest site-community relationships in the Shawnee Hills region , southern Illinois. In: Proceedings of the 1st Central Hardwoods Forest Conf., Southern IL Univ., Carbondale, IL. p. 65-87.

Fralish, J.S. 1988. Predicting potential stand composition from site characteristics in the Shawnee Hills forest of Illinois. Am. Midl. Nat. 120: 79-101.

Fralish, J.S. 1994. The effect of site environment on forest productivity in the Illinois Shawnee Hills. Ecol. Appl. 4: 134-143.

Frey, B.R., M.S. Ashton, J.J. McKenna, D. Ellum, and A. Finkral. 2007. Topographic and temporal patterns in tree seedling establishment, growth, and survival among masting species of southern New England mixed deciduous forests. For. Ecol. Man. 245: 54-63.

Fujinuma, R., J. Bockheim, and N. Balster. 2005. Base-cation cycling by individual tree species in old-growth forests of Upper Michigan, USA. Biogeochemistry. 74:357-376.

Gilbert, A.M. 1965. Stand differentiation ability in northern hardwoods. USDA Forest Service Res. Paper NE-37, Northeastern For. Exp. Stat. Upper Darby, PA. 34 p.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the central states. For. Sci. 13: 38-53.

Godman, R. M. 1969. Culture of Young Stands. *In* Proceedings-Sugar Maple Conference, August 1969, Houghton, MI p. 15-19. Michigan Tech. University and USDA For. Ser.

Godman, R.M., Yawney, H.W., and Tubbs, C.H. 1990. Sugar maple: *Acer saccharum* Marsh. P. 784-791 *in* Silvics of North America. Vol. 2. Hardwoods. Edited by R.M. Burns and B.H. Honkala. USDA For. Serv. Handb. No. 654.

Guldin, J.M. and C.G. Lorimer. 1985. Crown differentiation in even-aged northern hardwood forest of the Great Lakes region, U.S.A. For. Ecol. Man. 10:65-86.

Hallet, R.A., and J.W. Hornbeck. 1997. Foliar and soil nutrient relationships in red oak and white pine forests. Can. J. For. Res. 27: 1233-1244.

Heiligmann, R.B., E.R. Norland, and D.E. Hilt. 1985. 28-year-old reproduction on five cutting practices in upland oak. North. J. Appl. For. 2: 17-22.

Hilt, D.E. 1985. Species composition of young central hardwood stands that develop after clearcutting. In: J.O. Dawson and K.A. Majerus (Eds.) Proceedings of the Central Hardwoods Forest Conference V. University of IL, Urbana-Champaign, IL. p. 11-14.

Hinckley,T.M., P.M. Dougherty, J.P. Lassoie, J.E. Roberts, & R.O. Teskey. 1979. A severe drought: impact on tree growth, phenology, net photosynthetic rate and water relations. Am. Mid. Nat. 102: 307-316.

Hinckley, T.M., R.G. Aslin, R.R. Aubuchon, C.L. Metcalfe, & J.E. Roberts. 1978. Leaf conductance and photosynthesis in four species of the oak-hickory forest type. For. Sci. 24: 73-84.

Hix, D.M., and C.G. Lorimer. 1990. Growth-competition relationships in young hardwood stands on two contrasting sites in southwestern Wisconsin. For. Sci. 36: 1032-1049.

Honeycutt, C.W., R.L. Blevins and R.F. Wittwer. 1982. Growth of white oak (Quercus alba L.) in relation to soil and site properties in eastern Kentucky. In Proc. Fourth Central Hardwood Forest Conference. Eds. R. N. Muller. University of Kentucky Press. pp 193–206.

Horsley, S. B., Long, R. P., Bailey, S. W., Halett, R. A., and Hall, T. 2000. Factors associated with decline disease of sugar maple on the Allegheny Plateau. Can. J. For. Res. 30:1365-1378.

Host, G.E., K.S. Pregitzer, C.W. Ramm, J.B. Hart, and D.T. Cleland. 1987. Landform-mediated differences in successional pathways among upland forest ecosystems in northwestern lower Michigan. For. Sci. 33: 445-457.

Howell, D. L., & Kucera, C. L. 1956. Composition of pre-settlement forests in three counties of Missouri. Bull. Tor. Bot. Club. 83(3):207-217.

Huggett, B.A., P.G. Schaberg, G.J. Hawley, and C. Eager. 2007. Long-term calcium addition increases growth release, wound closure, and health of sugar maple (Acer saccharum) trees at the Hubbard Brook Experimental Forest. Can. J. For. Res. 37: 1692-1700.

Iverson, L.R., M.E. Dale, C.T. Scott, and A. Prasad. 1997. A GIS-derived integrated moisture index to predict forest composition and productivity of Ohio forests (U.S.A.). Landscape Ecol. 12: 331-348.

Jacobs, R.D. 1965. Seasonal height growth patterns of sugar maple, yellow birch, and red maple seedlings in Upper Michigan. USDA Forest Service Res. Note LS-57, Lake States For. Exp. Stat. St. Paul, MN. 4 p.

Jenkins, M.A., and G.R. Parker. 1989. Composition and diversity of woody vegetation in silvicultural openings of southern Indiana forests. For. Ecol. Man. 109: 57-74.

Jensen, R.G., and J.M. Kabrick. 2008. Comparing single-tree selection, group selection, and clearcutting for regenerating oaks and pines in the Missouri Ozarks. P. 28-49 in Proc. of the 16th Central Hardwoods Forest Conf., Jacobs, D.R>, and C.H. Michler (eds.). US For. Serv. Gen. Tech. Rep. NRS-P-24, Newtown Square, PA.

Johnson, P. S. 1979. Shoot elongation of black oak and white oak sprouts. Can. J. For. Res. 9(4):489-494.

Johnson, P.S., S.R. Shifley, and R. Rogers. 2009. The ecology and silviculture of oaks. 2nd ed. Cambridge MA, CABI

Jones, T.A., S.C. Thomas. 2004. The time course of diameter increment responses to selection harvests in *Acer saccharum*. Can. J. For. Res. 34: 1525-1533.

Juice, S.M., T.J. Fahey, T.G. Siccama, C.T. Driscoll, E.G. Denny, C. Eager, N.L. Cleavitt, R. Minocha, and A.D. Richardson. 2006. Response of sugar maple to calcium addition to northern hardwood forest. Ecology. 87: 1267-1280.

Kabrick, J.M., E.K. Zenner, D.C. Dey, D. Gwaze, and R.G. Jensen. 2008. Using ecological land types to examine landscape-scale oak regeneration dynamics. 255: 3051-3062.

Kabrick, J.M., K.W. Goyne, Z. Fan, and D. Meinert. 2011. Landscape determinants of exchangeable calcium and magnesium in forest and woodland soils of the Missouri Ozark Highlands. Soil Sci. Soc. Am. J. 75:164-180.

King, D.B.; Roberts, E.V.; Winters, R.K. 1949. Forest Resources and Industries of Missouri. Central States For. Exp. Sta. Res. Bull. 452. 89 p.

Kittredge, D.B. 1988. The influence of species composition on the growth of individual red oaks in mixed stands in southern New England. Can. J. For. Res. 18:1550-1555.

Kobe, R.K., G.E. Likens, and C. Eager. 2002. Tree seedling growth and mortality responses to manipulations of calcium and aluminum in northern hardwood forest. Can. J. For. Res. 32:954-966.

Kogelmann, W.J., and W.E. Sharpe. 2006. Soil acidity and manganese in declining and nondeclining sugar maple stands in Pennsylvania. J. Environ. Qual. 35:433-441.

Kucera, C. L., & McDermott, R. E. 1955. Sugar Maple-Basswood studies in the forest-prairie transition of central Missouri. Am. Midl. Nat. 54(2):495-503.

Larsen, D.R., M.A. Metzger, and P.S. Johnson. 1997. Oak regeneration and overstory density in the Missouri Ozarks. Can. J. For. Res. 27: 869-875.

Leitner, L.A., and M.T. Jackson. 1981. Presettlement forest of the unglaciated portion of southern Illinois. Am. Mid. Nat. 105: 290-304.

Liptzin, D., & Ashton, P.M.S. 1999. Early-successional dynamics of single-aged mixed hardwood stands in a southern New England forest, USA. For. Ecol. and Manage. 116:141-150.

Liu, X., Tyree, M.T. 1997. Root carbohydrate reserves, mineral nutrient concentrations and biomass in a healthy and a declining sugar maple (*Acer saccharum*) stand. Tree Phys. 17:179-185.

Liu, X, D.S. Ellsworth, and M.T. Tyree. 1997. Leaf nutrition and photosynthetic performance of sugar maple (Acer saccharum) in stands with contrasting health conditions. Tree Phys. 17: 169-178.

Long, M.A., and J.W. Groninger. 2010. Pre- and post-clearcut tree species distribution in two physiographic regions of the Shawnee National Forest, Illinois. Stanturf, J.A. ed. Proceedings of the 14th biennial southern silvicultural research conference. Gen. Tech. Rep. SRS-121. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 614 p.

Long, R.P., S.B. Horsley, and P.R. Lilja. 1997. Impact of forest liming on growth and crown vigor of sugar maple and associated hardwoods. Can. J. For. Res. 27:1560-1573.

Long, R.P., S.B. Horsley, R.A. Hallett, and S.W. Bailey. 2009. Sugar maple growth in relation to nutrition and stress in the northeastern United States. Ecol. App. 19:1454-1466.

Long, R.P., S.B. Horsley, and T.J. Hall. 2011. Long-term impact of liming on growth and vigor of northern hardwoods. Can. J. For. Res. 41:1295-1307.

Lorimer, C.G., J.W. Chapman, and W.D. Lambert. 1994. Tall understory vegetation as a factor in the poor development of oak seedlings beneath mature stands. J. Ecol. 82:227-237.

Marks, P.L. 1975. On the relation between extension growth and successional status of deciduous trees of the northeastern United States. Bull. Torr. Bot. Club. 102: 172-177.

Marks, P.L., and S. Gardescu. 1998. A case study of sugar maple (*Acer saccharum*) as a forest seedling bank species. J. Torr. Bot. Soc. 125: 287-296.

McClure, J.W., T.D. Lee, and W.B. Leak. 2000. Gap capture in northern hardwoods: patterns of establishment and height growth of four species. For. Ecol. Man. 127: 181-189.

McClurkin, D. C. 1963. Soil-site index predictions for white oak in northern Mississippi and west Tennessee. For. Sci. 9(1):108-113.

McLaughlin, S.B., and R Wimmer. 1999. Tansley review no. 104 calcium physiology and terrestrial ecosystem processes. New Phyt. 142: 373-417.

McNab, W.H. 2010. Effects of landform on site index for two mesophytic tree species in the Appalachian mountains of North Carolina, USA. Intl. J. For. Res. 2010: 1-7.

McGill, D.W., R. Rogers, A.J. Martin, and P.S. Johnson. 1999. Measuring stocking in northern red oak stands in Wisconsin. Northern J. Appl. For. 16: 144-150.

McQuilken, R. A. 1975. Growth of four types of white oak reproduction after clearcutting in the Missouri Ozarks. USDA FS, Res. Pap. NC-116. NC For. Exp. Stat., St. Paul, MN. 5 p.

McWilliams, W.H., R. White, S.L. Arner, C.A. Nowak, and S.L. Stout. 1996. Characteristics of declining forest stands on the Allegheny National Forest. Research Note NE-360. USDA. For. Ser. NE For. Res. Exp. Sta. 9 p.

Moore, J.-D., and R. Ouimet. 2006. Ten-year effect of dolomitic lime on the nutrition, crown vigor, and growth of sugar maple. Can. J. For. Res. 36: 1834-1841.

Moore, J.-D., L. Duchesne, and R. Ouimet. 2008. Soil properties and maple-beech regeneration a decade after liming in a northern hardwood stand. For. Eco. Man. 225: 3460-3468.

Moore, J.-D., C. Camire, and R. Ouimet. 2000. Effects of liming on the nutrition, vigor, and growth of sugar maple at the Lake Clair Watershed, Quebec, Canada. Can. J. For. Res. 30: 725-732.

Morrissey, R.C., D.F. Jacobs, J.R. Seifert, B.C. Fischer, and J.A. Kershaw. 2008. Competitive success of natural oak regeneration in clearcuts during the stem exclusion stage. Can. J. For. Res. 38: 1419-1430.

Moser, W. Keith; Treiman, Thomas; Moltzan, Bruce; Lawrence, Robert; Brand, Gary J. 2005. Missouri's Forest Resources in 2003. Resour. Bull. NC-243. St. Paul, MN: U.S. Dept. Ag., For. Ser., NC Res. Sta. 42 p.

Muller, R. N. 1982. Vegetation patterns in the mixed mesophytic forest of eastern Kentucky. Ecology, 63:1901-1917.

Nelson, P. W. 2005. The Terrestrial Natural Communities of Missouri. Rev. Ed. Missouri Natural Areas Committee.

Nigh, T. A., Pallardy, S. G., & Garrett, H. E. 1985. Sugar Maple-Environment Relationships in the River Hills and Central Ozark Mountains of Missouri. Am. Midl. Nat. 114(2):235-251.

Nigh, T.A., and W.A. Schroeder. 2002. Atlas of Missouri Ecoregions. Missouri Department of Conservation, Jefferson City, Missouri.

Norland, E.R., and D.M. Hix. 1996. Composition and structure of a chronosequence of young, mixed-species forests in southeastern Ohio, USA. Vegetatio. 125: 11-30.

Nowacki, G.J. & Abrams, M.D. (2008) The demise of fire and ''mesophication'' of the eastern United States. BioScience, 58, 123–128

Nyland, R.D., D.G. Ray, R.D. Yanai, R.D. Briggs, L. Zhang, R.J. Cymbala, and M.J. Twery. 2000. Early cohort development following even-aged reproduction method cuttings in New York northern hardwoods. Can. J. For. Res. 30: 67-75.

Nyland, R.D., Ray, D.G., & Yanai, R.D. 2004. Height development of upper-canopy trees within even-aged Adirondack northern hardwood stands. North. J. Appl. For. 21(3):117-122.

Oliver, C.D. 1980. Even-aged development of mixed-species stands. J. For. 78: 201-203.

Oliver, C.D., and B.C. Larsen. 1996. Forest stand dynamics: update edition. John Wiley and Sons. NY, p. 520.

Pallardy, S. G., Nigh T. A., & Garrett, H. E. 1988. Changes in Forest Composition in Central Missouri: 198-1982. Am. Midl. Nat. 120(2):380-390.

Palik, B.J., and K.S. Pregitzer. 1993. The vertical development of early successional forests in northern Michigan, USA. J. of Ecol. 81:271-285.

Park, B.B, and R.D. Yanai. 2009. Nutrient concentrations in roots, leaves and wood of seedling and mature sugar male and American beech at two contrasting sites. For Eco. Man. 258: 1153-1160.

Park, B.B, R.D. Yanai, T.J. Fahey, S.W. Bailey, T.G. Siccama, J.B. Shanley, and N.L. Cleavitt. 2008. Fine root dynamics and forest production across a calcium gradient in northern hardwood and conifer ecosystems. Ecosystems. 11: 325-341.

Peet, R.K., and O.L. Loucks. 1977. A gradient analysis of southern Wisconsin forests. Ecology, 58: 485-499.

Phelps, J.E., J.L. Chambers, & T.M. Hinckley. 1976. Some morphological, ecological, and physiological traits of four Ozark forest species. *In* Proc 1st Central Hardwood For. Conf., Southern Illinois Univ-Carbondale (Fralish, J.S., G.T. Weaver, and R.C. Schlesinger, eds.), p. 231-243.

Pommerening, A. 2002. Approaches to quantifying forest structures. Forestry. 75: 305-324.

Racine, C.H. 1971. Reproduction of three species of oak in relation to vegetational and environmental gradients in the southern blue ridge. 98: 297-310.

Read, R.A. 1952. Tree species occurrence as influenced by geology and soil on an Ozark north slope. Ecology. 33: 239-246.

Reich, P.B., R.O. Teskey, P.S. Johnson, and T. M. Hinckley. 1980. Periodic root and shoot growth in oak. For. Sci.. 26(4):590-598.

Roach, B.A., and S.F. Gingrich. 1968. Even-aged silviculture for upland central hardwoods. USDA. For. Serv. Agric. Handb.

Rochow, J.J. 1972. A vegetational description of a mid-Missouri forest using gradient analysis techniques. Am. Midl. Nat., 87: 37-396.

Rochow, J.J. 1975. Mineral nutrient pool and cycling in a Missouri forest. J. Ecol. 63: 985-994.

Rogers, R. 1990. *Quercus alba* L. White Oak. *In* Silvics of North America. Vol. 2. Hardwoods. pp. 605-613. Edited by R.M. Burns and B.H. Honkala. U.S. Dep. Agric. Agriculture Handbook 654, Washington D.C. 877 pp.

Ruhe, R.V. *Geomorphology*. Houghton Mifflin, Boston, MA, 1975: 246 pp.

Schaberg, P.G., J.W. Tilley, G.J. Hawley, D.H. DeHayes, and S.W. Bailey. 2006. Associations of calcium and aluminum with the growth and health of sugar maple trees in Vermont. For. Ecol. Man. 223:159-169.

Schlesinger, R. C. 1976. Sixteen Years of Selection Silviculture in Upland Hardwood Stands. USDAFS, Res. Pap. NC-125. NC For. Res. Exp. Stat., St. Paul, MN. 6 p.

Schmoldt, D.L., G.L. Martin, and J.G. Bockheim. 1985. Yield-based measures of northern hardwood site quality and their correlation with soil-site factors. For. Sci. 31:209-219.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., and Broderson, W.D. 1998. Field book for describing and sampling soils. Natural Resources Conservation Service, USDA, National Soil Survey Center, Lincoln, NE.

Schreeg, L.A., R.K. Kobe, and M.B. Walters. 2005. Tree seedling growth, survival, and morphology in response to landscape-level variation in soil resource availability in northern Michigan. Can. J. For. Res. 35: 263-273.

Showalter, J.M., J.A. Burger, C.E. Zipper, J.M. Galbraith, and P.F. Donovan. 2007. Influence of mine soil properties on white oak seedling growth: a proposed mine soil classification model. South. J. Appl. For. 31: 99-107.

Soil Survey Division Staff. 1993. Soil survey manual. Soil Conservation Service. U.S. Department of Agriculture Handbook 18.

Soil Survey Staff, 1996. Soil Survey Laboratory Methods Manual. Soil Survey Investigations Report No. 42, version 3.0, USDA-NRCS National Soil Survey Center, Washington, D.C.

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. Available online at http://websoilsurvey.nrcs.usda.gov/ accessed February 5, 2011.

St. Clair, S.B., J.E. Carlson, and J.P. Lynch. 2005. Evidence for oxidative stress in sugar maple stands growing on acidic, nutrient imbalanced forest soils. Oecologia. 145: 258-269.

Thompson, T.L. 1995. The Stratigraphic Succession in Missouri. Revised Ed. Missouri Dept. of Natural Resources. Rolla, Missouri. 188 p.

Tubbs, C.H. 1968. The influence of residual stand densities on regeneration in sugar maple stands. USDA For. Serv., Res. Note NC-47. North Central For. Exp. Sta., St. Paul, MN. 4 p.

Tubbs, C.H., & Metzger, F.T. 1969. Regeneration of northern hardwoods under shelterwood cutting. 1969. For. Chron. October, 333-337.

Van Breeman, N., Finzi, A.C., & Canham, C. D. 1997. Canopy Tree-Soil Interaction within Temperate Forests: Effects of Soil Elemental Composition and Texture on Species Distributions. Can. J. For. Res. 27, 1110-1116.

Villwock, J.L. 2011. Factors influencing upland oak advance reproduction in the Missouri Ozarks. Thesis. University of Missouri-Columbia.

Walters, M.B., and P.B. Reich. 1997. Growth of *Acer saccharum* seedlings in deeply shaded understories of northern Wisconsin: effects of nitrogen and water availability. Can. J. For. Res. 27: 237-247.

Ward, J.S., and G.R. Stephens. 1994. Crown class transition rates of maturing northern red oak (*Quercus rubra* L.). For. Sci. 40: 221-237.

Ware, S., P.L. Redfearn, Jr., G.L. Pyrah, and W.R. Weber. 1992. Soil pH, topography and forest vegetation in the central Ozarks. Am. Midl. Nat. 128: 40-52.

Whitney, G.G. 1991. Relation of plant species to substrate, landscape position, and aspect in north central Massachusetts. Can. J. For. Res. 21: 1245-1252.

Wilmot, T.R., D.S. Ellsworth, and T.T. Tyree. 1996. Base cation fertilization and liming effects on nutrition and growth of Vermont sugar maple stands. For. Ecol. and Man. 84: 123-134.

Wuenscher, J. E., & Valiunas, A. J. 1967. Presettlement forest composition of the river hills region of Missouri. Am. Midl. Nat. 78(2):487-495.

Wuenscher, J.E., & T.T. Kozlowski. 1971. Relationship of gas-exchange resistance to tree-seedling ecology. Ecology. 52: 1016-1023.

Yanai, R.D., T.G. Siccama, M.A. Arthur, C.A. Federer, and A.J. Friedland. 1999. Accumulation and depletion of base cations in forest floors of the northeastern United States. Ecology. 80:2774-2787.

Zeide, B. 2005. How to measure stand density. Trees – Structure and Function. 19: 1-14.

Zhang, L., B.P. Oswald, T.H. Green, and S.L. Stout. 1995. Relative density measurement and species composition in the mixed upland hardwood forests of North Alabama. USDA Forest Service General Technical Report SRS-1. USDA Forest Service, Southern Research Station, Asheville, North Carolina, pp. 467-472.