Factors Influencing Upland Oak Advance Reproduction in the Missouri Ozarks

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by

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

Factors Influencing Upland Oak Advance Reproduction in the Missouri Ozarks

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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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DEDICATION

To my wife, Magda, I am forever greatful for your love, support, and encouragement.

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ABSTRACT

Successful oak stand regeneration requires an abundance of well developed advance reproduction. Past studies have found that oak reproduction varies on upland landscapes by inferred measures of nutrient and water supply such as site index, slope-aspect, and slope position. There is a need to relate oak reproduction to soil nutrient and water supply parameters to better understand variations in oak reproduction on upland landscapes. On the USDA Forest Service, Sinkin Experimental Forest, located in the Missouri Ozarks, we first examined the relationship between black oak site index and terrain shape measurement including terrain shape index (tsi), landform index (lfi), slope position and the slope-aspect using data collected in 120 experimental plots. The tsi and lfi were each significant ($P<0.05$) parameters in models predicting site index. including tsi, lfi, and slope aspect. Concave land forms had greater tsi and lfi values and higher site index values than the convex land forms. Overall, the tsi and lfi each appear to be useful for quantifying terrain shape and its influence on the productivity of upland hardwood stands in the Ozark Highlands.

Using reproduction data we examined regression models for estimating the advance reproduction density of red oaks, white oaks, and non-oaks. Parameters included site index (SI), an estimate of soil plant available water holding capacity

(AWC), soil base saturation (BS), Beers transformed aspect (Taspect), tsi, photosynthetically-active radiation (PAR), and Gingrich stocking. Significant ($P<0.01$) models were found for red oaks and non-oaks. The abundance of red oak advance reproduction was lesser on northeast-facing slopes and inversely related to AWC and BS suggesting a greater accumulation on sites having both a lesser water and nutrient supply. The abundance of non-oaks was greatest on northeast-facing slopes and positively related to site index and BS suggesting a greater accumulation on sites having a higher site quality and greater nutrient supply. There were no significant models relating these factors to the abundance of white oak advance reproduction however it was significantly ($P = 0.04$) correlated to the abundance of red oak advance reproduction. Modeling indicates that oak advance reproduction naturally accumulates on drier, nutrient-deficient sites with low competition. Unlike other oak regeneration studies, we measured soil properties related to water and nutrient supply rather than inferring them using surrogates such as slope position. The properties that were most related to the accumulation of red oak advance reproduction are also readily available in soil surveys and therefore readily available to forest managers. The relationships modeled in this study are useful to managers to understand where oak advance reproduction will naturally occur and where additional silvicultural prescriptions are needed to favor the accumulation of oak advance reproduction prior to harvesting the stand.

CHAPTER I:

INTRODUCTION & LITERATURE REVIEW

Oaks are a valuable component of hardwood and oak-pine mixed hardwood forests in the central hardwood region. Upland, mixed-oak (*Quercus spp.*) forests occupy over 50% of the forested land area in the central hardwood region of the United States. Therefore, oak trees play a pivotal role in forest ecology and economics of the region (Johnson et al., 2009).

The central hardwood region (CHR) covers approximately 600,000 square kilometers and is the largest contiguous area of deciduous tree species found anywhere in the world (Hicks, 1998). The region is located east of the Great Plains, south of the great lakes, and north and west of the southern pine forests of the Coastal Plain and Piedmont regions. The region is comprised of forests in the Ouachita/Ozark Mountains located in Missouri, Arkansas, Oklahoma extending east through the Appalachian Mountains, and in states such as Illinois, Indiana, Ohio, Pennsylvania, Kentucky, West Virginia, Virginia, North/South Carolina and Tennessee (Hicks, 1998). The upland hardwood forests in this region vary in terms of climatic, soil, and topographic conditions with varying species. Xeric site conditions exist in the western portion of the central hardwood region in states such as Missouri, Oklahoma and Arkansas and mesic site conditions tend to occur in the eastern side of the region through the Appalachian mountains (Johnson et al., 2009).

Regenerating oak stands on productive upland sites in the CHR has been noted to be a serious problem (Lorimer, 1993; Johnson et al., 2009). As productivity increases, the amount of light available at the forest floor decreases, and in deep shade, respiration often exceeds the photosynthetic rates of oak seedlings causing mortality (Hanson et al., 1987; Dey and Parker, 1996). Research has focused on developing shelterwood methods to encourage the development of large oak advance reproduction on mesic sites (Brose et al., 1999; Loftis, 1990). In application, these methods have brought a mixture of success and failure leaving scientists to search for more information.

Advance Reproduction: the Key to Stand Regeneration

Oak reproduction is comprised of seedlings (stem and roots of the same age), seedling sprouts (stem age younger then root age), and stump sprouts (Johnson, 1993). All three of these reproduction classes contribute to successful stand regeneration, but in different ways. Oak stump sprouts provide an important contribution to stand regeneration as they are the fastest-growing and most competitive source of oak reproduction (Johnson et al., 2009). However, stump sprouts cannot be solely relied on to regenerate a stand. The reason is that not all oak stems produce suitable sprouts that will successfully compete for growing space to become a dominant tree in the stand. As oak trees age, they become less likely to contribute stump sprouts to regeneration after overstory disturbance plus the probability of reaching maturity also declines with an increase in age and decrease in light levels (Johnson, 1993; Dey et al., 2008).

The key to successful natural stand regeneration therefore lies in having sufficient quantities of seedlings and seedling sprouts that have large root systems, are capable of rapid shoot growth, and can outcompete other species to capture growing space prior to overstory disturbance (Sander, 1971; Sander et al., 1984; Johnson et al., 2009). In most oak stands, seedlings will number in the range of 1000 to 2000 per acre before any treatment is conducted (Johnson et al., 2009). However, the seedlings must also be of great vigor and size after a disturbance opens the canopy in order to reach canopy dominance. Sander (1971) suggested that stands with large quantities of oak seedlings with basal diameters between 0.5 and 1.0 inch will have a great probability of successful regeneration. Productive stands are usually deficient in oak reproduction with most seedlings having basal diameters less than 0.2 inches and as a result have a small probability of successful stand regeneration (Loftis, 1988). As productivity increases, the amount of light available at the forest floor decreases, and in deep shade, respiration often exceeds the photosynthetic rates of oak seedlings causing poor vigor or great mortality rates (Hanson et al., 1987; Dey and Parker, 1996). However, with sufficient light levels, oak seedlings can develop large root systems and accumulate in the understory in greater quantities. If the advance reproduction in a stand is not of great enough size and vigor, then it can be favored by a light midstory removal and by fire that may kill competitors, increase light levels at the forest floor, and favor oaks (Loftis, 1990; Brose et al., 1999). The difficulty lies in determining which sites need additional silvicultural treatments since productivity varies on the landscape due to varying light, nutrient and moisture supplies.

Soil and Landform Influence Productivity

Since oak seedlings develop well on less productive upland sites it is important to consider the potential influences of site productivity. Site productivity depends on availability of light, water and more than a dozen vital soil elements (Fisher and Binkley, 2000). Soil is the primary source of water and nutrients for plants. Soils vary greatly on the landscape as a function of the climate, vegetation, parent materials, topography, and time of soil development (Schaetzl and Anderson, 2005). The variability of soils including landscape position therefore influences productivity and dynamics of forest vegetation. Many different physical and chemical soil properties contribute to the productivity of a forest stand.

Physical influence of soil on available water:

The amount of water available to plants is strongly related to forest growth rate and varies in a soil by the texture, amount of coarse fragments, organic matter, and the bulk density of soil (Brady and Weil, 2008). First, the volume of pore space as described by texture influences the amount of water available to plants by determining the volume of water a soil can hold without it draining out of the profile. Plant available water is the volume of soil water between the permanent wilting point and field capacity and is generally greater for loamy texture classes and less for clayey and sandy textures. (Brady and Weil, 2008). Coarse fragments (>2mm in diameter) retain little or no water and consequently decrease the amount of plant available water (Brady and Weil, 2008). The greater the coarse fragment content, or the shallower the depth to bedrock, the less capacity there is to store water for plant growth (Brady and Weil, 2008). Third, organic matter can also influence the amount of moisture available to plants in soil (Brady and Weil, 2008). The amount of water available for plant uptake can be greater when a soil contains organic matter, but organic matter is not as significant of a factor in determining water availability compared to the soil pore space (Brady and Weil, 2008). Finally, soil bulk density influences the amount of water available for plants. The soil bulk density is a measure of the mass of dry soil per unit of bulk volume. Usually, the greater the bulk density, the less pore space there is available to hold water for plant uptake. Bulk density can be very difficult to measure in the field as it requires extensive soil sampling equipment in order to collect samples to dry and weigh. As a result, often bulk density is not considered in estimating available water for plants, but can be a significant factor.

If there is a root restricting layer such as a fragipan present in the soil, it can be noted to estimate the total rooting volume of soil available to plants in the same way the presence of bedrock at shallow depths in the soil can be used.

<u>Influence of landform on available water:</u>

The supply of moisture in the soil largely determines the types of trees that can survive on a site and is also related to the landform (Fisher and Binkley, 2000). Variation in site index, species composition, and forest productivity, has long been attributed to changes in landform resulting from the influence on water movement, sunlight intensity, and temperature (Trimble and Weitzman, 1956; McNab, 1989; McNab 1993; Johnson et al., 2009). Landform influence results from the slope aspect, steepness, position, and shape of the slope. Slope aspect affects forest productivity due to its shading influence of solar radiation and microclimate, but aspect alone does not completely explain the variability in productivity across a landscape (Trimble and Weitzman, 1956; Trimble, 1964; Rosenberg et al., 1983; Fekedulegn et al., 2003). In eastern North America as well as most of the northern hemisphere, northeast facing slopes tend to be the most productive while southwest facing slopes tend to be the least productive (Trimble and Weitzman, 1956). Slope steepness magnifies the effect of aspect on site productivity by further influencing the amount of solar radiation a site receives and amount of water that is available (Johnson et al., 2009). Water availability is also influenced by slope shape. Soil scientists use slope shape in addition to slope position to infer water movement and subsequently to map the kinds of soils formed in different locations on the landscape (Ruhe, 1975; Hudson, 1990). Forest scientists have also noted the influence of slope shape on water movement and productivity and have documented relationships typically with inferred measures of productivity such as site index (Johnson et al., 2009). Despite documented relationships between slope shape and forest productivity, descriptions of slope shape are difficult to make and have largely remained qualitative. Land units are allocated into a slope position class such as summit, shoulder, backslope, footslope, or toeslope defined by their position along a hillslope and by the degree of concavity or convexity they exhibit in the down-slope direction (Ruhe, 1975). Slope positions are sometimes assigned an additional modifier describing the degree of concavity or convexity they exhibit along the contour (e.g., headslopes, noseslopes, or sideslopes) (Schoenenberger et al., 2002). In general it is assumed that convex features shed water, while concave features collect water. Given that assumption, the more concave a feature is, the more water there is available for plant growth.

In the southern Appalachians, McNab (1989 and 1993) developed methods for quantifying the geometric shape of the land surface with the land form index (lfi) and the terrain shape index (tsi). These metrics are determined in the field by making a few measurments with a clinometer and do not require the application of GIS terrain modeling techniques. Measurements are collected starting in the direction of the aspect and then rotating clockwise in 45 degree increments for a total of eight slope measurements which are averaged in a percent slope. For the tsi, the slope from the plot center to the plot perimeter is measured parallel to the land surface recording the surface shape of the landscape surrounding the sampling point. For the lfi, the slope from the plot center to the horizon is measured indicating the overall landform shape. Both the tsi and lfi along with slope position and aspect were found to be correlated to yellow-poplar (*Liriodendron tulipifera* L.) site index in the southern Appalachians and therefore useful for predicting site index in stands where suitable yellow-poplar site index trees were lacking. McNab's (1989 and 1993) success correlating simple terrain metrics with yellow-poplar site index suggested that this approach may be applicable to other forests. This method estimates the availability of water and light from the shape of the landsurface and estimates the impact on site productivity. These models are able to estimate the relationship of slope shape to site quality from the degree of convexity and concavity of the land surface. However, these measures only infer the supply of soil moisture and nutrients, and are not as accurate compared to actual measures from the soil (Johnson et al., 2009).

Landforms and nutrient supply:

Soil nutrients such as nitrogen (N), phosphorus (P) and base cations, vary on upland landscapes and are important to plant growth and species composition (Schaetzl and Anderson, 2005). Availability of soil nutrients on upland landscapes are generally related to water availability since water affects weathering, movement, and deposition of soil and nutrients (Schaetzl and Anderson, 2005). Soil nutrient availability is often assumed to increase downslope and on protected aspects along with the availability of water, but field measurements often indicate great variation in nutrient availability on the landscape (Ruhe, 1975, Hairston and Grigal, 1994, Fisher and Binkley, 2000). Nutrient availability declines over time as soils weather (Brady and Weil, 2008). Upper slope positions generally have lesser base saturation and nutrient supply than lower slope positions, but many exceptions exist due to variations in the parent materials, deposition and weathering, and physical soil properties (Schaetzl and Anderson, 2005). The availability of macro nutrients such as calcium (Ca), magnesium (Mg), potassium (K), N and P available to plants is strongly correlated to pH (Brady and Weil, 2000). As pH decreases through weathering, nutrient availability also decreases. This relationship between pH and nutrient availability influences plant community composition by determining which species are more competitive on a site.

The biota present on a site also influence the development of soils, nutrient availability, and the rate of nutrient cycling. In forests, the main deposition of organic matter occurs by littering on the soil surface. As a result, the source of nutrient recycling occurs in the surface horizons and is influenced by the tree species present. Oaks have been noted as xerophytes in that they naturally promote slower nutrient recycling through slow rates of decomposition of their leaves (Johnson et al., 2009). Slower decomposition of leaves can also influence disturbance from fire. Since there is typically more fuel on the soil surface of oak forests compared to other eastern deciduous forest types, fire can burn more frequently and intensely. Oaks are more fire adapted than most other hardwood species and regeneration is encouraged on sites where fire and other disturbances frequently occurs (Brose et al., 2005).

Advance Reproduction Varies by Productivity and Landform

The accumulation of oak reproduction in the central hardwood region generally increases as site quality decreases (Johnson et al., 2009). Oak reproduction was found to be more abundant on drier sites with smaller nutrient supplies such as upper slope positions and southwest facing aspects (Trimble, 1973; Sander et al., 1984; Lorimer, 1989; Loftis, 1990; Walters, 1990; Larsen and Johnson, 1998; Johnson et al., 2009). Johnson et al. (2009) noticed variations in site productivity along with the abundance of oak reproduction and developed terminology to describe sites that naturally accumulate oak reproduction. They used the term *intrinsic accumulators* to refer to ecosystems that naturally accumulate oak reproduction over time and *recalcitrant accumulators* to describe sites where oak reproduction fails to accumulate. Sites that are intrinsic accumulators have smaller soil moisture and nutrient supplies, support lesser overstory densities, and have fewer competitors. Sites that are recalcitrant accumulators have higher soil moisture and nutrient supplies and have numerous competitors (Kabrick et al., 2008). In between recalcitrant and intrinsic accumulating sites exist ambivalent accumulators. Ambivalent accumulators exist somewhere between xeric and mesic ecosystems and can vary greatly in the density of oak advance reproduction (Johnson et al., 2009). The rates in accumulation of oak reproduction are strongly influenced by minor disturbances and are likely to be manipulated by silvicultural treatments (Brose et al., 1999). Despite their hypothesis, studies have only been able to link the accumulation of oak advance reproduction with inferred moisture and nutrient supplies. Studies typically use variables such as slope position, slope aspect, and site index to infer the supply of moisture and nutrients on the site.

Walters (1990) examined the abundance of oak reproduction on sites in southeastern Ohio both pre-treatment and 3 years after applying partial cuts, prescribed burns, and herbicide treatments. His results showed that oak reproduction density did not increase as a result of treatments and was therefore attributed largely to the pre-treatment density of advance reproduction. Oak reproduction was most abundant on south west facing slopes and density increased with increasing slope steepness. Differences also exist between oak species. In the Missouri Ozarks, Kabrick et al. (2008) examined the abundance of white oak (*Quercus* spp. L.; section Quercus) and red oak (*Quercus* spp. L.; section Lobatae) reproduction by ecological land types representing different soils and slope aspects and found a greater abundance of red oak reproduction, comprising black oak (*Q. velutina* Lam.) and scarlet oak (*Q. coccinea* Muenchh.) reproduction on south or southwest facing slope, but no significant relationship with the abundance of white oak, comprising white oak (*Quercus alba* L.) and post oak (*Quercus stellata* W.) reproduction. Red oak group species are usually found to vary significantly by drier landform conditions due to their lesser shade tolerance compared to white oaks (Kabrick et al., 2008). The main white oak species in Kabrick et al. (2008) suggested that white oak has greater shade tolerance which allows reproduction to persist in a greater range of site conditions than the red oaks (Rogers, 1990).

Models have been developed that utilze inferred soil and moisture supply variables such as site index, slope position and slope aspect to predict where oak reproduction will accumulate on the landscape. Sander et al. (1984) developed a model to evaluate advance reproduction in the Missouri Ozarks. They generated values resulting from the height of the regeneration sampled, the slope aspect, slope position, and site index that can be used in a regression model they developed to predict the regeneration success for stands in the Missouri Ozarks. They tested the model and successfully predicted the density of oak advance reproduction in 5 out of 6 stands indicating the usefulness of the model. As a result, site index, slope position, and slope aspect are essential variables that infer the contribution of soil moisture and nutrients to site quality, and they can be used to make stand regeneration predictions in upland ecosystems (Dey, 1991; Dey et al., 1996)

The location of recalcitrant upland sites can therefore be predicted using physiographic info, but they will still be successionally displaced by non-oaks if management practices are not implemented to control competing species in the mid and understory while allowing oak reproduction to accumulate (Trimble, 1973; Johnson et al., 2009). Generally shelterwood methods have been developed to favor oak reproduction with mixed results. Loftis (1990) developed a shelterwood treatment for use in the Appalachians that uses an herbicide application to remove 25-30% of the basal area from the midstory in a stand without creating canopy gaps. The shelterwood was retained for approximately 10 years to allow oak reproduction that existed before treatment to mature. Loftis (1990) indicated that shelterwoods enhance the size of the advance reproduction that existed prior to shelterwood implementation, but did not enable establishment of additional oak reproduction prior to shelterwood removal. Brose et al. (1999) developed a shelterwood method, but included a prescribed burn to favor oak reproduction over reproduction of competing species such as yellow poplar (*Liriodendron tulipifera* L.). Basal area was reduced to about 50% and a prescribed burn was implemented between initial shelterwood establishment and overstory removal. Brose et al. (1999) indicated that establishment of oak reproduction was favored by more intense burns implemented between the shelterwood establishment and removal cuts. Both Loftis (1990) and Brose et al. (1999) had mixed success regenerating upland oak stands. Loftis (1990) indicated that oak reproduction densities could not be increased by a shelterwood, but only could be enhanced, while Brose et al. (1999) indicated that oak reproduction could be favored over competitors by combining a shelterwood and a prescribed burn. These differences indicate that further research is warranted to better understand regeneration dynamics between oak reproduction and competing species in upland ecosystems.

Objectives

The first objective of this research was to determine what landform metrics are significant in predicting black oak site index in the Missouri Ozarks. Terrain shape index (tsi), landform index (lfi), slope position and aspect will be used in models to predict black oak site index in the Missouri Ozarks. This will help determine which metrics are most suitable to estimate the influence of landform on site productivity in those complex forested ecosystems.

The second objective of this research is to then evaluate Johnson et al. (2009) terminology describing sites that naturally accumulate advance reproduction in the Missouri Ozarks. Our hypothesis is that moisture and nutrient deficient sites will have higher densities of oak advance reproduction and lower densities of advance reproduction of competing species. This hypothesis will be evaluated using metrics for site quality (site index), landform (aspect, tsi), soil nutrient and moisture supply (base saturation (BS), pH, and plant available water capacity (AWC), and stand density (PAR and stocking) to predict the density of oak reproduction as well as competitors of oak advance reproduction. Since past studies have not related actual measures of soil nutrients and moisture to the abundance of oak reproduction on the landscape, measures for soil nutrients and moisture will be included in models predicting the abundance of oak reproduction on the landscape.

CHAPTER II:

LANDFORM AND TERRAIN SHAPE INDICES ARE RELATED TO OAK SITE INDEX IN THE MISSOURI OZARKS

INTRODUCTION

Site index remains the most commonly used measure of site quality by practicing foresters. In the Central Hardwood Region, it is used to determine suitable species to manage and to predict oak regeneration potential and stand development patterns (Johnson et al., 2002). Timber volume equations often include site index along with diameter to estimate stand volume (Hahn and Hansen 1991). Despite its utility and common use, site index cannot be determined unless suitable trees are present. Suitable site index trees are those that have remained as canopy dominant or codominants and are relatively free of disease, pests, or other health problems, ideally growing in even-aged stands that are near the index age (McQuilkin and Rogers 1978). Field estimates of site index are problematic when adequate site index trees cannot be found because of past disturbances, past pest or disease problems, or in stands where the age of the trees greatly exceeds those used to develop site index relationships (Monserud 1984, Berguson et al., 1994). Therefore, equations have been developed to estimate site index from soil, topographic, and other site factors. Although some of these equations account for 70-85 percent of the observed variation in site index, application of these equations can sometimes be difficult to apply because they require detailed site-specific information about soil characteristics (Johnson et al., 2009).

In the eastern United States, variation in site index, species composition, and forest productivity, has long been attributed to variations in topography (Trimble and Weitzman 1956, McNab 1989 and 1993, Johnson et al., 2009). Slope aspect also affects forest productivity from shading of solar radiation and influence on microclimate, but aspect alone does not completely explain the variability in productivity across a landscape (Trimble and Weitzman 1956, Trimble 1964, Rosenberg et al., 1983, Fekedulegn et al., 2003). Soil scientists use slope shape in addition to slope position to infer water movement and subsequently to map the kinds of soils formed in different locations on the landscape (Ruhe 1975, Hudson 1990). Forest scientists have also noted the relationship between slope shape and water movement, and have developed methods to correlate those relationships with measures of forest productivity such as stand site index (Johnson et al., 2009).

Despite documented relationships between slope shape and forest productivity, descriptions of slope shape have largely remained qualitative. Landform units are allocated into a hillslopes such as summit, shoulder, backslope, footslope, or toeslope defined by their position along a hillslope and by the degree of concavity or convexity they exhibit in the down-slope direction. Slope positions are sometimes assigned an additional modifier to described the degree of concavity or convexity they exhibit along the contour (e.g., headslopes, noseslopes, or sideslopes) (Schoenenberger et al., 2002) In the southern Appalachians, McNab (1989 and 1993) developed methods for quantifying the geometric shape of the land surface with the land form index (lfi) and the terrain shape index (tsi). These metrics are determined in the field by collecting a few measurments with a clinometer and do not require the application of GIS terrain modeling techniques. Each of these indices was found to be correlated to yellow-poplar (Liriodendron tulipifera L.) site index in the southern Appalachians and were useful for predicting site index in stands where suitable yellow-poplar site index trees were lacking. Because suitable site index trees frequently are not available in oak stands in the Missouri Ozarks due to high grading or other past land use, a simple but reliable means for predicting site index would be helpful for forest management planning in this region. McNab's (1989 and 1993) success correlating simple terrain metrics with yellow-poplar site index suggested that this approach may be applicable to the Missouri Ozarks. However, these metrics have not been evaluated in drier oak-hickory (Quercus L.-Carya Nutt.) forests where relationships between site quality and terrain characteristics potentially differ from those of the southern Appalachians. In this region, site index for most oak species is commonly converted to and expressed on a black oak species basis for comparing stand site quality. Our objective was to examine relationships between the tsi and lfi and black oak site index in the Missouri Ozarks.

STUDY SITE

The study was conducted in the Sinkin Experimental Forest located approximately 30 miles south of Salem, MO, within the Current River Hills Subsection of the Ozark Highlands (Keys et al., 1995). This region has narrow ridges and steep side slopes with a relief of 200 ft and soils formed from Ordovician and Cambrian dolomite and sandstone (Nigh and Schroeder 2002). Information accessable through the Missouri Cooperative Soil Survey (www.soilsurvey.org) indicate that the soils on the ridge tops and upper hillsides are developed in parent materials derived from Roubidoux and upper Gasconade formations and are highly weathered, droughty, strongly acid, and contain a large percentage of rock fragments. Common soil series on ridge tops and upper slopes included Coulstone and Clarksville (both Typic Paleudults), Hobson (Oxyaquic Fragiudalfs), Lebanon (Typic Fragiudults), and Nixa (Glossic Fragiudults). Soils on the lower hillsides developed in parent materials derived from the lower Gasconade or Eminence formations generally are less weathered. Some of these soils are influenced by the underlying dolomite and consequently contain clayey residuum that has a greater cation exchange capacity, fewer rock fragments, and a greater water holding capacity. The soil series on lower hillsides included Clarksville and Doniphan (both Typic Paleudults), and Moko (Lithic Hapludolls). Outcrops of dolomite occur with some of the Moko soils.

The relationships between topographic variables and site index in the Missouri Ozarks were examined as part of a comprehensive oak regeneration study named the Regional Oak Study (ROS). The ROS is a regional, multi-disciplinary research program being implemented by both the USDA Forest Service Northern and Southern Research Stations at sites located in North Carolina, Tennessee, and Missouri (Greenberg et al., 2007). The study consists of 20-rectangular-12-acre treatment units that were each established across a moisture gradient from ridge top to footslope. Each treatment unit has six circular, 0.12-acre sampling plots positioned evenly within the twenty 12-acre treatment units providing a total of 120 sample locations. The treatment units are in oak-pine and mixed oak forests with an average stand age of 82 years for the overstory. Inventories in these plots revealed that oaks were the dominant species contributing 59 percent of the basal area. Of the oak species present, white oak (Quercus alba L.) contributes 22 percent of the basal area, black oak (Q. velutina Lam.) 21 percent, scarlet oak (Q. coccinea Muenchh.) 12 percent, and northern red oak (Q. rubra L.) 4 percent. Shortleaf pine (Pinus echinata Mill.) comprises 22 percent of the basal area. Other species by basal area include hickory species (Carya spp.) (7 percent), slippery elm (Ulmus rubra Muhl.) (2 percent), flowering dogwood (Cornus florida L.) (2 percent), blackgum (Nyssa sylvatica Marsch.) (2 percent), black walnut (Juglans nigra L.) (2 percent), and red maple (Acer rubrum L.) (1 percent).

METHODS

Measurements at each of the 120 sampling plots included site index, aspect, slope position, tsi, and lfi. Site index was determined using a representative dominant or co-dominant tree within each plot. Site index trees included red oaks (Quercus spp. L.; section Lobatae), white oaks (Quercus spp. L.; section Quercus), and shortleaf pine. The height of each site index tree was measured to the nearest foot using an Impulse™ 200 laser. A core was removed at breast height using an increment borer and rings were counted with the aid of a hand lens. Site index in feet was calculated for each species using relationships developed by McQuilkin (1974 and 1978) for oaks and Nash (1963) for shortleaf pine. All site index values were converted to black oak site index basis using the relationships developed by McQuilkin (1976) in order to accurately compare site index between sites.

Aspect was measured from plot center using a handheld compass and taken in the direction of the steepest down-slope direction. Slope position was also recorded in each plot and given a categorical value of shoulder, backslope, or footslope following the definitions originally proposed by Ruhe (1975) now routinely used in soil mapping (Schoeneberger et al., 2002). As mentioned earlier, shoulders occur on upper slopes and generally are convex in profile. Backslopes occur mid-slope and are nearly linear in profile but can vary in shape along the contour and include sideslopes (linear along the contour), noseslopes (concave along the contour), and headslopes (convex along the contour). Footslopes occur on lower slopes and generally are concave in profile.

The tsi and lfi was measured from the center of each plot using a hand-held Suunto clinometer. At each plot, measurements were taken starting in the direction of the aspect and then rotating clockwise in 45 degree increments for a total of eight slope measurements. For the tsi, the slope from the plot center to the plot perimeter (41 ft) measured parallel to the land surface was recorded. For lfi, the slope from the plot center to the horizon was measured. Slopes were recorded as a percent, with down-slope measurements being recorded as negative values and up-slope measurements as positive values. All eight measurements were then averaged to determine the tsi or lfi value.

McNab (1989 and 1993) found that estimates of tsi or lfi almost always stabilized when measuring four directions and changed little when eight or more measurements were taken.

Data Analysis:

An Information-Theoretic approach (Burnham and Anderson 1998) was used to compare the models predicting black oak site index (response variable) and the lfi, tsi, and other measures of terrain including slope position and aspect (explanatory variables). As per the Burnham and Anderson’s (1998) approach, a series of candidate models was developed for estimating site index by including the lfi or tsi singly or in combination with the slope position and aspect. These models were used to evaluate the hypotheses that including the lfi or tsi improves predictions of site index compared to using only the traditional descriptive measures of slope position and/or slope aspect. Models were compared using Akaike’s information criterion (or AIC). The $AIC = n\ln(RSS/n)+2k$, where n is the sample size, ln is the natural log, RSS is the residual sums of squares, and k is the number of parameters in the model. Smaller AIC scores indicate a better modeled vs. observed fit. Models having AIC scores more than two units apart are generally considered significantly different from each other (Burnham and Anderson 1998). We applied the correction for small sample size (creating an AICC score) by adding $2k(k+1)/(n-k-1)$ to the AIC score as per the recommendations of Burnham and Anderson (1998).

The MIXED procedure in SAS™ statistical software (SAS version 9.1, SAS Institute, Inc. Cary, NC, USA) was used to estimate model parameters and to generate AICC scores for each model. The mixed procedure was used to accommodate models that included categorical and continuous data and to account for both fixed effects (i.e., terrain variables) and random effects (i.e., 12-acre treatment units). The model form was Y= βo + B1X1 + B2X2 + …+ BnXn where Y was the black oak site index in feet, βo was the intercept, and subsequent parameters were for the lfi or tsi, slope position, and/or slope aspect. Prior to analyses, the distribution of site index was examined and found to be normally distributed so there was no need for transformation. During analyses, the slope position was included as a categorical variable (i.e., shoulders, backslopes, and footslopes) and the slope aspect was included as a continuous variable after it was transformed to a linear value ranging from 0 (azimuth of 225 degrees) to 2 (azimuth of 45 degrees) following the model by Beers et al. (1966) where the Transformed aspect = cos(45-Aspect) + 1.

The Information-theoretic approach for model selection was used because the AICC score accounted for the number of parameters in models. Thus, the method discriminated against models having more parameters and thereby reduced the risk of over fitting the models. Thus, the approach offered an advantage over the stepwise regression procedure where over fitting generally increases the apparent goodness of fit. However, one disadvantage of the method is that typical measures of goodness of fit (e.g., R-values) are not provided. To remedy this, models using the glm procedure (SAS version 9.1, SAS Institute, Inc. Cary, NC, USA) were used. The glm procedure produced model parameters that were similar in magnitude to those produced by the mixed procedure (they were not exactly the same because glm cannot account for random effects) and provided R values as an additional estimate of goodness of fit.

RESULTS

Both the terrain shape index (tsi) and landform index (lfi) were related to the slope position with a few outliers (fig. 1). Generally, the tsi and lfi were each positive and larger in magnitude on footslopes indicating a more concave land surface shape and were smaller in magnitude or negative in value on backslopes and shoulders indicating a linear or slightly convex shape. The lfi was generally greater in magnitude and more positive than the tsi. This is reasonable since the lfi is determined by measuring the slope angle to the surrounding horizon which usually appears at the surrounding ridge tops. Consequently, slope measurements made from below a ridge top are very likely to have large and positive values. There also were differences in the magnitude of the variation between the lfi and tsi. The lfi was most variable on backslopes while the tsi was most variable on footslopes.

The tsi and lfi were each significant ($P<0.05$) parameters in models predicting site index (table 1). The AICC scores indicated that the best models included parameters for the slope position and aspect along with the tsi (model 2), the lfi (model 3), or both the lfi and tsi together (model 1). However, the AICC scores also indicated that models including either the tsi or lfi along with slope position and aspect were statistically indistinguishable from each other. Also, models including both the slope position and aspect in addition to the tsi or lfi were better than those that did not include slope position and aspect.

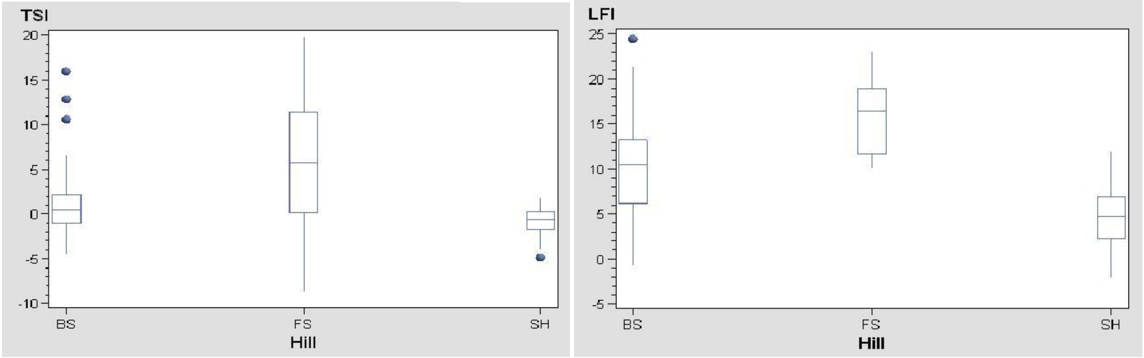


Figure 1. - Box-and-whisker diagrams displaying terrain shape index (tsi) and landform index (lfi) values by slope position. Note: BS denotes back slope, FS denotes foot slope, and SH denotes shoulder slope. Both tsi and lfi values are in percent gradient

Table 1. - Site index models with effects for slope position (including shoulder, backslope, or footslope), Beers-transformed aspect (taspect), terrain shape index (tsi), and land form index (lfi).

Model[1]	AICC	Delta AICC[2]	R
1. Slopeposition* + taspect* + tsi + lfi	861	0	0.36
2. Slopeposition + taspect + tsi***	862	1	0.32
3. Slopeposition* + taspect** + lfi***	862	1	0.33
4. Slopeposition + taspect	867	6	0.22
5. Slopeposition* + tsi**	867	6	0.29
6. Slopeposition* + lfi**	867	6	0.27
7. Taspect* + tsi**	874	13	0.25
8. Taspect* + lfi**	874	13	0.24
9. Tsi**	878	17	0.20
10.Lfi**	880	19	0.17

[1] Model form $Y = \beta o + B1X1 + B2X2 + \ldots + BnXn$

[2] Change in AICC score from the least. Smaller AICC scores indicate better models and a change in AICC score greater than 2 indicates a model is statistically different from other models.

* effect significance $P \leq 0.10$

** effect significance $P \leq 0.05$

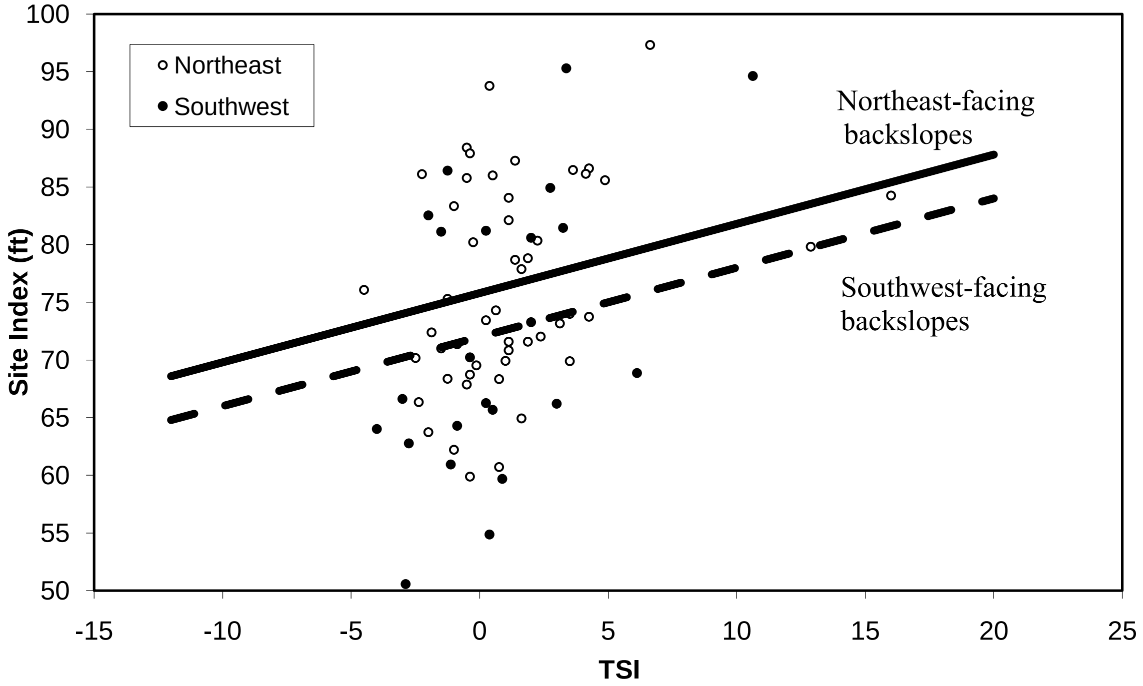
*** effect significance $P \leq 0.01$

The parameters for models that included the slope position, aspect, and the tsi (model 2) or the lfi (model 3) shown in table 2 were used to illustrate relationships between them and the black oak site (figs 2 and 3). The best models indicated that northeast-facing slopes generally had greater site index values than southwest-facing slopes and that shoulder and backslopes had greater site index values than did footslopes. They also indicated that for a given slope position or aspect, increasing the tsi or the lfi (i.e., increasing the concavity) generally increased the site index estimate. However, the wide scatter in the actual data plotted in figures 2 and 3 and low R values for the models (Table 1) indicated considerable variation in the site index data.

Table 2. - Parameters for site index models 2 and 3 in Table 1 for estimating black oak site index in feet.

Effect	Estimate	Standard error	P-value
Model 2—TSI			
Intercept	70.60	2.35	<0.01
Slope position			
Backslope	1.41	1.92	0.47
Footslope	-4.72	3.42	0.17
Shoulder	--	--	--
Transformed aspect	1.93	1.27	0.13
TSI	0.57	0.23	0.01
Model 3—LFI			
Intercept	67.40	2.60	<0.01
Slope position			
Backslope	-0.19	2.14	0.93
Footslope	-7.02	3.82	0.07
Shoulder	--	--	--
Transformed aspect	2.27	1.28	0.08
LFI	0.50	0.20	0.01

a) Slope aspect



b) Slope position

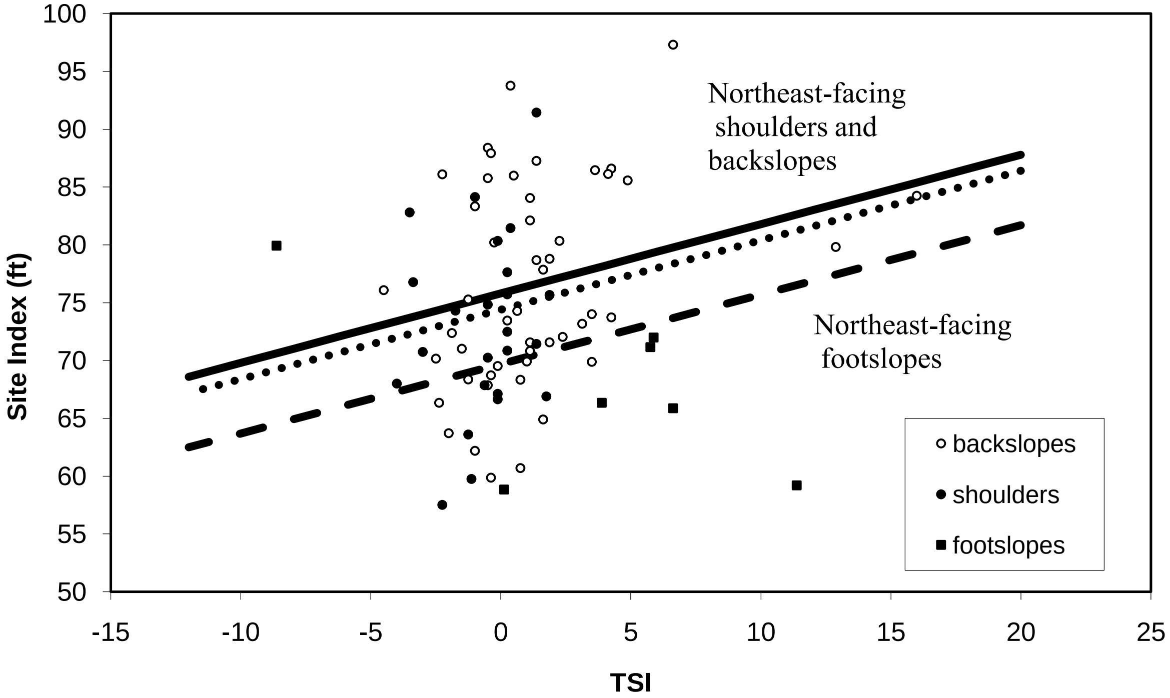
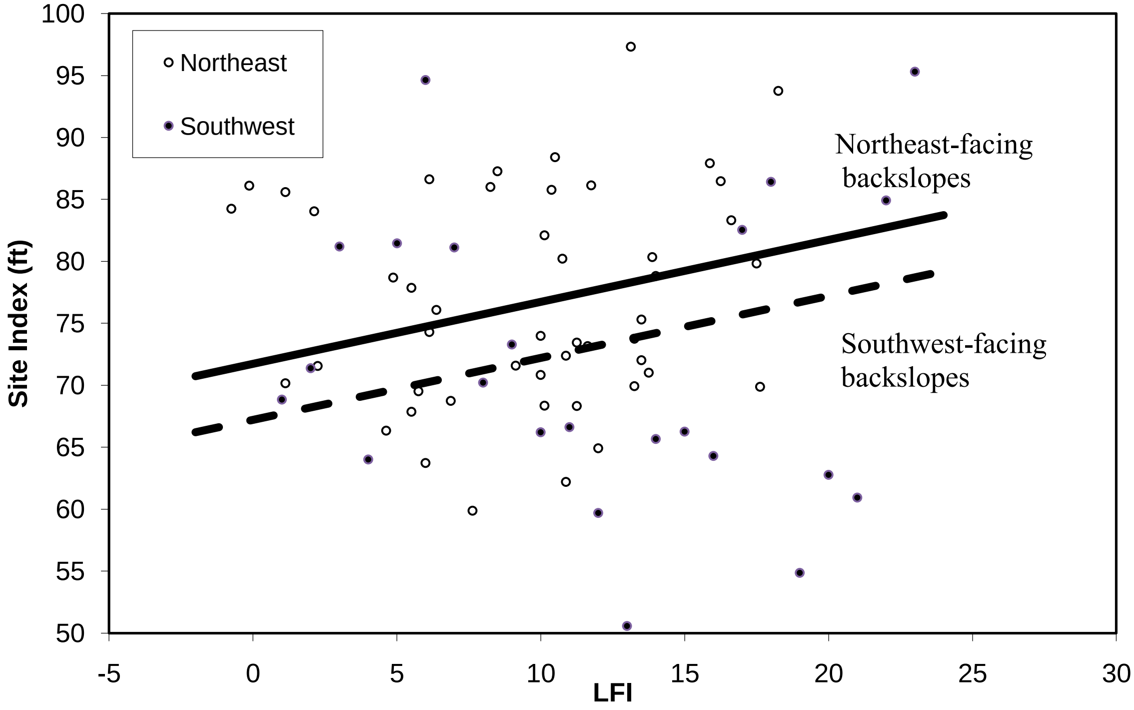


Figure 2. - (a) and (b) Black oak site index and terrain shape index (tsi) by a) slope aspect, and b) slope position.

a) Slope aspect



b) Slope position

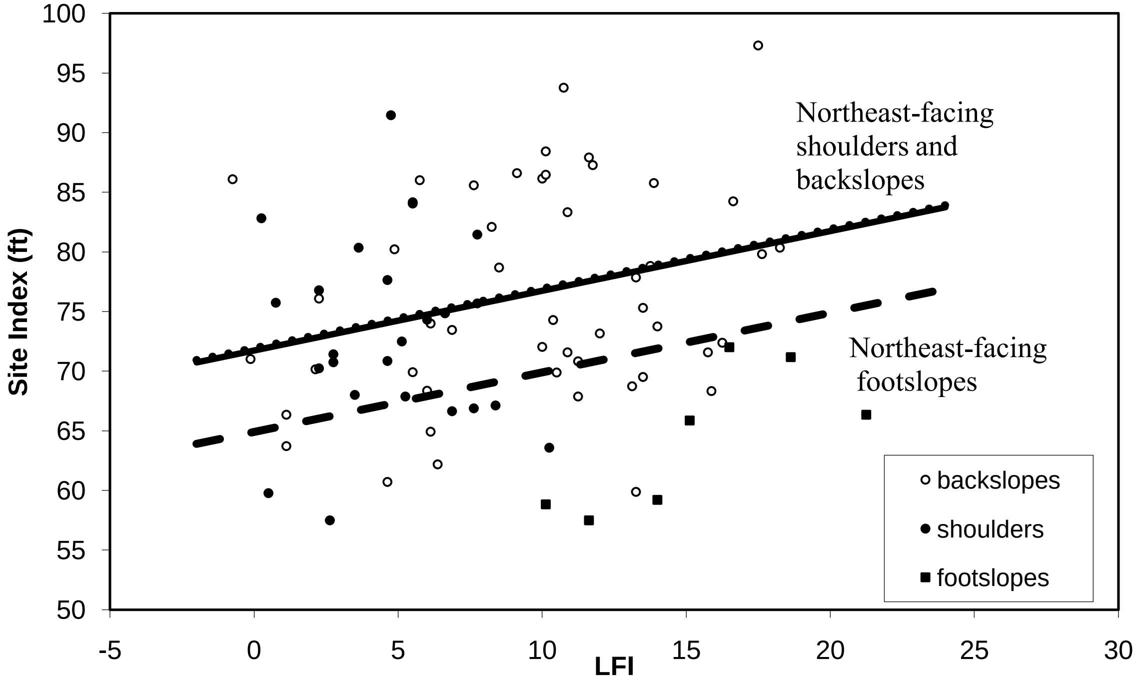


Figure 3.- (a) and (b) Black oak site index and land form index (lfi) by a) slope aspect, and b) slope position.

DISCUSSION

Much has been written about the effects of slope variability on the height growth or site index of trees (Carmean 1967, Hannah 1968, Hartung and Lloyd 1969, Auchmoody and Smith 1979, McNab 1989). Most previous studies indicated that height growth or site index is generally greater on lower slopes or in concave “cove” positions where the soil’s ability to supply nutrients and particularly water is generally greater (White 1958, Fralish 1994). Despite the influence of terrain on site productivity, few scientists have developed approaches for quantifying terrain shape to accompany other more descriptive assessments of topography for predicting site index. McNab (1989 and 1993) developed a method for quantifying terrain shape by averaging the slopes in four or more directions from a plot center to its perimeter parallel to the land surface (tsi) or to the horizon (lfi). When applied in the mesophytic forests of the southern Appalachians, there were significant correlations between yellow-poplar site index and tsi (McNab 1989) and lfi (McNab 1993). Similar to McNab (1989,1993), we found significant relationships between black oak site index and tsi and lfi. Our three most significant models for explaining variation in black oak site index included parameters for slope position, Beers-transformed aspect, and tsi, lfi or both. These three models were statistically indistinguishable from each other, suggesting any of the three were equally useful for predicting site index. However, foresters are more likely to measure a single index and our findings suggest that tsi and lfi work equally well. Slope position and aspect were also important parameters in these models and our analysis suggested that both should be included with either tsi or lfi to render the best estimates of site index in similar landscapes of the Missouri Ozarks.

Despite the statistical significance of the parameters, the R values for our data were generally quite small indicating considerable variation not accounted for with the models that we developed. McNab (1989 and 1993) generally found stronger relationships between the yellow-poplar site index and the lfi (R between 0.45 and 0.65) and the tsi (R=0.71) in the southern Appalachians. This may be due to the wider range in site index values and in the tsi and lfi values encountered in the Appalachian region compared to the Missouri Ozarks where the terrain is gentler. In the Missouri Ozarks, greater correlations may have occurred had we accounted for variation in soil properties related to water and nutrient supply.

The models that we developed have utility for estimating black oak site index in the Missouri Ozarks for stands lacking suitable site index trees. For each inventory plot, the slope position and aspect is recorded and the tsi or lfi is determined as described in the methods section of this paper and applied to the models in Table 2. For example, for shoulder slopes having an azimuth of 83 degrees (Beers transformed = 1.79) and a tsi = 2.1, the black oak site index = 75 feet. For backslopes having an azimuth of 180 degrees (Beers transformed = 0.29) and a lfi = 10.7, the black oak site index = 73 feet.

Although the tsi and lfi are determined in the field, the increasing availability of high resolution terrain information and GIS software has provided alternatives for estimating these and other metrics of slope shape. Some of these terrain metrics have been used along with other remotely-sensed data and to estimate site index elsewhere in the Central Hardwood Region. For example, Iverson et al. (1997) used GIS software to develop a moisture index model based on soil water holding capacity, topographic shape, and slope-aspect for the Vinton Experimental Forest in southern Ohio. This moisture index was highly correlated ($R > 0.79$) to the oak site index, particularly with terrain models derived from fine-resolution (<1:24,000 scale) source data.

Predicting site index is not limited to the need for estimating potential merchantable volume or biomass production of a stand. In the Central Hardwood Region, site index is also important for identifying where future oak regeneration problems may occur. Further research is needed to determine if measures of terrain shape such as the tsi or lfi do provide an additional metric for identifying where oak regeneration problems are likely to occur, particularly where suitable site index information is lacking.

CHAPTER III:

FACTORS AFFECTING THE ACCUMULATION OF OAK ADVANCE REPRODUCTION IN UPLAND OZARK FORESTS.

INTRODUCTION

Regenerating oaks (*Quercus* spp. L.) on productive upland sites in eastern North American hardwood forests has long been a problem (Lorimer, 1993). The problem has largely been attributed to the failure to accumulate sufficient quantities of oak advance reproduction having large root systems capable of rapid shoot growth that can compete with other species to capture growing space following a canopy disturbance (Sander, 1971; Sander et al., 1984; Johnson et al., 2009). Studies showed that a site's ability to accumulate oak advance reproduction is related to site quality usually indicated by site index (Trimble, 1973; Sander et al., 1984; Lorimer, 1989; Loftis, 1990). As site quality increases, the amount of light available at the forest floor decreases, and in deep shade, respiration often exceeds the photosynthetic rates of oak seedlings causing mortality (Hanson et al., 1987; Dey and Parker, 1996). Site quality varies across upland landscapes and is related to slope steepness, slope position, aspect and other site factors such as the availability of light, water, and nutrients (White, 1958; McNab, 1989; Johnson et al., 2009). Site quality is generally greatest on lower slope positions of northeast-facing aspects and least on upper slope positions of southwest-facing aspects (Carmean, 1965; Hannah, 1968; Hartung and Lloyd, 1969; Auchmoody and Smith, 1979).

Johnson et al. (2009) recognized that a site's ability to accumulate oak advance reproduction was related to site quality and used the term *intrinsic accumulators* to refer to ecosystems that naturally accumulate oak reproduction over time and *recalcitrant accumulators* to describe sites where oak reproduction fails to accumulate. Sites that are intrinsic accumulators generally have smaller soil moisture and nutrient supplies and consequently support fewer oak competitors. Sites that are recalcitrant accumulators generally have greater soil moisture and nutrient supplies, and support more oak competitors.

Despite the terminology, there has been little evidence linking physical soil water and nutrient supply to the abundance of oak reproduction on the landscape. In most oak regeneration studies, moisture or nutrient supply gradients have been inferred by using slope position, slope-aspect, or other surrogates (Sander et al., 1984; Walters, 1990; Dey, 1991; Dey et al., 1996; Kabrick et al., 2008). The objective of this study was to evaluate the hypothesis that the accumulation of oak advance reproduction is related to the soil's ability to supply water and nutrients in addition to other measured variables including the amount of photosynthetically active radiation reaching the ground, measures of stand density, and competition. This work was conducted in the Ozark Highlands where oak advance reproduction generally accumulates and persists in the understory for long periods of time but there is still considerable variation that appears to be related to site quality (Sander et al., 1984; Dey, 1991; Kabrick et al., 2008).

STUDY SITE

The study was conducted in the Sinkin Experimental Forest located in Southeastern Dent County, Missouri, within the Current River Hills Subsection of the Ozark Highlands (Nigh and Schroeder 2002). This region has narrow ridges and steep side slopes with a relief of around 60 m and soils formed from Ordovician and Cambrian dolomites and sandstones. The soils on the ridge tops and upper hillsides developed in parent materials derived from the Roubidoux and upper Gasconade formations and are highly weathered, droughty, strongly acid, and contain a high percentage of rock fragments. Information obtained from the Missouri Cooperative Soil Survey (www.soilsurvey.org; verified 25 Feb. 2011) indicated that common soil series on ridge tops and upper slopes include Coulstone and Clarksville (both Typic Paleudults), Hobson (Oxyaquic Fragiudalfs), Lebanon (Typic Fragiudults), and Nixa (Glossic Fragiudults). Soils on the lower hillsides developed in parent materials derived from the lower Gasconade or Eminence formations and generally are less weathered. Some of these soils are influenced by the underlying dolomite and consequently contain clayey residuum that has a greater cation exchange capacity, fewer rock fragments, and a greater water holding capacity then in higher landscape positions. The most common soils series on lower hillsides include Clarksville and Doniphan (both Typic Paleudults), and Moko (Lithic Hapludolls). Outcrops of dolomite occur with some of the Moko soils.

The abundance of oak regeneration was examined as part of a comprehensive oak regeneration and wildlife habitat study hereafter referred to as the Regional Oak Study (ROS). The ROS is a regional, multi-disciplinary research project comparing the effects of different shelterwood methods and prescribed fire on oak regeneration dynamics and focal wildlife populations and is being implemented by both the USDA Forest Service Northern and Southern Research Stations at sites located in North Carolina, Tennessee, and Missouri (Greenberg et al., 2007). The study consists of 20-rectangular-5-hectare treatment units that are each established across an inferred upland moisture gradient from ridge top to footslope. Each treatment unit has six circular, 0.05-hectare overstory sampling plots positioned evenly within the twenty 5-hectare treatment units providing a total of 120 sample locations. Within each overstory plot is a 0.004-hectare reproduction plot. The plots are in oak-pine mixed forests having an average age of 82 years for the overstory. Inventories in these plots revealed that oaks were the dominant species contributing 59 percent of the basal area. Of the oak species present, white oak (*Quercus alba* L.) contributes 22 percent of the basal area, black oak (*Q. velutina* Lam.) 21 percent, scarlet oak (*Q. coccinea* Muenchh.) 12 percent, and northern red oak (*Q. rubra* L.) 4 percent. Shortleaf pine (*Pinus echinata* Mill.) comprises 22 percent of the basal area. Other species by basal area include hickory species (*Carya spp.*) (7 percent), slippery elm (*Ulmus rubra* Muhl.) (2 percent), flowering dogwood (*Cornus florida* L.) (2 percent), blackgum (*Nyssa sylvatica* Marsh.) (2 percent), black walnut (*Juglans nigra* L.) (2 percent), red maple (*Acer rubrum* L.) (1 percent) and sugar maple (*Acer saccharum* Marsh.) (<1 percent). In the understory there was spice bush (*Lindera benzoin* (L.) Blume) and Carolina buckthorn (*Frangula caroliniana* (Walter) A. Gray) present.

METHODS

Data was collected at each site to determine the influence of site productivity, landform, stand density, and soils on oak advance reproduction. Site index was used to estimate the productivity at each site and was determined on a representative dominant or co-dominant tree within each circular 0.05-ha plot. Preferred site index trees were red oak species (*Quercus* spp. L.; section Lobatae), followed by white oaks (*Quercus* spp. L.; section Quercus), and shortleaf pine. The height of each site index tree was measured to the nearest 0.1 m using an Impulse™ 200 laser. A core was removed at breast height using an increment borer and rings were counted with the aid of a hand lens. Site index in feet was calculated for each species using relationships developed for oaks and shortleaf pine in Missouri (Nash, 1963; McQuilkin, 1974; McQuilkin, 1978). All site index values were then converted to black oak site index basis for comparison (McQuilkin, 1976).

Landform measurements were collected using the aspect and the shape of the land surface at each site via terrain shape index (tsi) (McNab, 1989). Aspect was measured from plot center in the direction of the steepest slope using a hand-held compass and Suunto clinometer. Aspect was transformed to a linear value ranging from 0 (azimuth of 225 degrees) to 2 (azimuth of 45 degrees) following the model developed by Beers et al. (1966) where the Transformed aspect = cos(45-Aspect) + 1 (Beers et al., 1966). The tsi was measured as described by McNab (1989) from the center of each plot using a hand-held clinometer. At each plot center, measurements were made starting in the direction of the aspect and then rotating clockwise in 45 degree increments for a total of eight slope measurements. The slope from the plot center to the plot perimeter (12.6m) measured parallel to the land surface was recorded. Slopes were recorded as percent, with down-slope measurements recorded as negative values and up-slope measurements as positive values. All eight measurements were summed and divided by eight to obtain an average tsi value.

Stand density was determined by calculating the stocking (Gingrich 1967) from a stand inventory and measuring the photosynthetically active radiation (PAR) at each 0.05-ha circular overstory plot. In the stand inventory, trees >25cm dbh were recorded within the entire 0.05-ha plot. Trees 5 to 25 cm dbh were measured within a concentrically nested 0.01-ha plot. Trees < 5 cm dbh were inventoried within a 0.004-ha circular plot located 8m from the center of the 0.05-ha overstory plot at a 45 degree azimuth. For some analyses, species were allocated into the species groups red oaks (primarily black oak and scarlet oak), white oaks (primarily white oak and some post oak), and non-oaks. Trees 5-25cm dbh were considered to be in the midstory and trees < 3.8 cm dbh were considered advance reproduction following the convention of Sanders et al. (1984). Basal area was then calculated and a percent stocking was estimated using equations from Gingrich (1967) for hardwoods and from Rogers (1983) for shortleaf pine in Missouri.

Photosynthetically active radiation (PAR) was measured using Smart Sensors using a HOBO® Micro Station (Onset Computer Corp., Bourne, MA, USA). PAR sensors were mounted on a camera tripod and leveled at a height of 0.9 m, approximately the height at or just above the seedlings. During the months of July and August, a single PAR sensor was located at the center of each regeneration plot and PAR was logged every hour for a 24hr period. Values were expressed relative to those in full sunlight by dividing the PAR values logged in the vegetation plots by PAR values logged over the same 24hr period nearby but in the open.

Soils were sampled in a single 1-m-deep excavation within each 0.05-ha overstory plot adjacent to the 0.004-ha reproduction plot. In each pit, soil horizons were identified and described, the percent volume of coarse fragments >2mm diameter in each horizon were ocularly estimated, and samples from each horizon were collected for laboratory analysis. Soil samples were air dried, crushed and analyzed for particle size determination by the pipet method, pH (H_2O and $CaCl_2$), exchangeable base cations including calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K) and the exchangeable acidity by titration. All methods were completed according to the Soil Survey Laboratory Methods Manual (2004). Percent base saturation (BS) was calculated for each horizon by summing extractable bases (Ca, Mg, Na, K) and dividing by the sum of the extractable bases and the exchangeable acidity. Base saturation was expressed on a profile basis by weighting the base saturation of individual horizons proportionally by their thickness. Lab measurements for pH were generated using a 1:1 ratio of soil to water and a 1:2 ratio of soil to $CaCl_2$ solution. Both a water pH (H_2O) and a salt pH ($CaCl_2$) were converted to a hydrogen ion concentration basis and expressed on a profile basis using the same weighting procedure as used for the base saturation. An estimate for soil plant available water capacity (AWC) was then calculated using the laboratory-determined particle size distribution to identify the texture class for each horizon.

Estimates of a AWC were assigned to each horizon based on soil texture using numeric values for similar soils in Missouri reported in the Cooperative Soil Survey. Values used were 0.1 cm/cm for a sandy loam, 0.14 cm/cm for a sandy clay loam, 0.15 cm/cm for clay and silty clay, 0.18 cm/cm for a silt loam, 0.19 cm/cm for clay loam, loam and silty clay loam. Each horizon was then calculated by removing the coarse fragments from the horizon and using the formula for each horizon AWC(horizon) = (horizon thickness x AWC (texture estimate) x %fine earth). For horizons with fragipans, the AWC was reduced by 50% if roots were noted within the fragipan. If the fragipan and horizons underlying the fragipan did not have roots present, an AWC of 0 was assigned. A profile-level AWC was then generated by summing up all AWC(horizon) in a profile.

Data analysis:

Linear regression was used to evaluate relationships between the abundance of reproduction of red oaks, white oaks, and non-oaks and measures of site productivity, topography, stand density, light levels, and soil water and nutrient supply. Plot data were averaged by sampling unit (n = 20) prior to analysis and is displayed in table 3. The regression procedure in SAS™ statistical software (Proc Reg, SAS version 9.1, SAS Institute, Inc. Cary, NC, USA) was used to estimate model parameters. The model form was $Y= \beta o + B1X1 + B2X2 + \ldots + BnXn$ where Y was the abundance of reproduction per hectare, βo was the intercept, and subsequent parameters were for the tsi, aspect, black oak site index, PAR, stocking, AWC, and $BS^{0.5}$. Correlations among the abundances of individual tree species were examined using the correlation procedure in SAS™ (Proc Corr, SAS version 9.1, SAS Institute, Inc. Cary, NC, USA).

Table 3. Statistics for data used in models predicting the abundance of advance reproduction.

Variables[1]	**Average**	**standard deviation**	**minimum**	**maximum**	**sample size (n)**
SI	73	5	63	84	20
AWC	8.8	1.3	5.6	10.7	20
BS	0.27	0.08	0.15	0.41	20
pH (H_20)	5.4	0.2	5.0	5.7	20
pH ($CaCl_2$)	4.5	0.2	4.2	4.9	20
Taspect	1.1	0.6	0.1	1.9	20
TSI	0.99	1.96	-1.88	6.40	20
PAR	0.10	0.04	0.05	0.25	20
Totalstock	95	12	78	118	20
Midstock	38	13	17	71	20
Overstock	58	10	39	71	20
reproduction densities per hectare					
red oak	3398	1489	1125	6500	20
white oak	1735	1172	292	4417	20
non oak	17008	5170	10250	28250	20

[1] Variables are SI = site index; AWC = plant available water holding capacity (cm); BS = base saturation (decimal form); pH (H_20) = water pH; pH ($CaCl_2$) = salt pH; Taspect = Beers-transformed aspect; TSI = terrain shape index; PAR = photosynthetically-active radiation (percent of full sunlight, decimal form); Totalstock = Gingrich stocking level (percent); Overstock = Gingrich stocking level for trees only part of the canopy (percent); Midstock = Gingrich stocking level only for trees in the mid-story (percent); Red oaks comprise primarily of scarlet oak (*Quercus coccinea* Munchh.) and black oak (*Quercus velutina* Lam.). White oaks comprise primarily of white oak (*Quercus alba* L.). Non-oaks comprise primarily of blackgum (*Nyssa sylvatica* Marsh.), flowering dogwood (*Cornus florida* L.), sassafras (*Sassafras albidum* (Nutt.) Nees), red maple (Acer *rubrum* L.), spice bush (*Lindera benzoin* (L.) Blume), and carolina buckthorn (*Frangula caroliniana* (Walter) A. Gray).

To compare alternative models with surrogate measures for BS or stocking, the Information-Theoretic approach (Burnham and Anderson, 1998) was used. As per the Information-Theoretic approach, a series of candidate models were developed that included tsi, aspect, black oak site index, PAR, stocking (either midstory stocking, overstory stocking or total stocking), AWC, and soil nutrient supply ($BS^{0.5}$, BS, pH (H_2O) or pH ($CaCl_2$)). These models were used to determine if surrogate measures for base saturation or if midstory or overstory stocking were better for predicting the abundance of red oak reproduction on the landscape. Models were compared using Akaike's information criterion (or AIC). The AIC = nln(RSS/n)+2k, where n is the sample size, ln is the natural log, RSS is the residual sums of squares, and k is the number of parameters in the model. Smaller AIC scores indicate a better modeled vs. observed fit. Models having AIC scores more than two units apart are generally considered significantly different from each other (Burnham and Anderson 1998). We applied the correction for small sample size (creating an AICC score) by adding 2k(k+1)/(n-k-1) to the AIC score as per the recommendations of Burnham and Anderson (1998). The mixed procedure in SAS™ statistical software was used to generate AICC scores using the same model format as the prior regression models (Proc Mixed, SAS version 9.1, SAS Institute, Inc. Cary, NC, USA). Akaike weights (W) were generated according to Burnham and Anderson (1998) and indicate the relative likelihood a model is the best. To generate W, the following formula was used:

$$W_i = \frac{\exp\left(-\frac{1}{2}\Delta i\right)}{\sum_{r=1}^{R} \exp\left(-\frac{1}{2}\Delta r\right)}$$

where W_i is the weight of the *i*th model, Δi is the difference between the lowest AICC score and the AICC score of the *i*th model, and R is equal to the total number of models compared.

RESULTS

The parameters for the three models predicting the advance reproduction abundance of red oaks, white oaks and non-oaks are shown in table 4. The model for predicting the abundance of red oak advance reproduction was significant ($P<0.01$, $R^2 =0.85$).Significant parameters in the model were the intercept ($P=0.01$), soil plant available water capacity (AWC) ($P=0.01$), the square root of the soil base saturation ($BS^{0.5}$) ($P=0.01$), and the aspect (taspect) ($P=0.02$). The model indicated that the abundance of red oak advance reproduction increased with decreasing BS and decreasing AWC (Fig. 4). Aspect also had a significant influence on the abundance of red oak advance reproduction. Northeast-facing aspects had less red oak reproduction than drier Southwest-facing aspects (Fig. 5). To ensure the abundance of red oak advance reproduction was not influenced by an abundant acorn crop or some other factor related to the abundance of red oaks in the overstory, the correlation between the abundance of red oak advance reproduction and the percent stocking of red oak in the overstory was examined finding the correlation to be insignificant ($P = 0.10$, $R = 0.37$). The model for predicting the abundance of white oak advance reproduction reproduction was not significant ($P = 0.62$). However, we found that the abundance of red oak advance reproduction was significantly correlated ($R = 0.47$, $P = 0.04$) to the abundance of white oak advance reproduction indicating that white oak reproduction is typically present where red oak reproduction is present (Fig. 6). The model for predicting the abundance

Table 4. Model parameters for estimating stems per hectare of either red oak, white oak, or non oak reproduction.

Effect[1]	**Estimate**	**Error**	**DF**	**t Value**	**Pr > |t|**
1. Model parameters for estimating red oak[2] advance reproduction (R^2 = 0.85, P < 0.01)					
Intercept	16492	4482	1	3.68	0.01
SI	-37	35	1	-1.05	0.31
AWC	-520	124	1	-4.19	0.01
$BS^{0.5}$	-10246	2093	1	-4.89	0.01
Taspect	-692	256	1	-2.71	0.02
TSI	-152	90	1	-1.70	0.12
PAR	1947	5090	1	0.38	0.71
totalstock	1	16	1	0.08	0.94
2. Model for white oak[3] advance reproduction (R^2 = -0.09, P = 0.616) (not significant)					
Intercept	13026	9622	1	1.35	0.20
SI	-63	76	1	-0.83	0.42
AWC	-123	267	1	-0.46	0.65
$BS^{0.5}$	-5095	4493	1	-1.13	0.28
Taspect	-634	549	1	-1.16	0.27
TSI	45	192	1	0.23	0.82
PAR	-7718	10926	1	-0.71	0.49
Totalstock	-17	34	1	-0.50	0.63
3. Model parameters for estimating non oak[4] reproduction (R^2 = 0.54, P = 0.01)					
Intercept	-69988	27507	1	-2.54	0.03
SI	639	216	1	2.96	0.01
AWC	-356	762	1	-0.47	0.66
$BS^{0.5}$	31342	12845	1	2.44	0.03
Taspect	6041	1568	1	3.85	0.01
TSI	92	550	1	0.17	0.87
PAR	58637	31234	1	1.88	0.09
Totalstock	157	97	1	1.62	0.13

[1] Effects are SI = site index; AWC = plant available water holding capacity (cm); BS = base saturation (decimal form); Taspect = Beers-transformed aspect; TSI = terrain shape index; PAR = photosynthetically-active radiation (decimal form); Totalstock = Gingrich stocking level (percent). Model form is $Y = \beta o + B1X1 + B2X2 + \ldots + BnXn$; denominator df = 1.

[2] Red oaks comprise primarily of scarlet oak (*Quercus coccinea* Munchh.) and black oak (*Quercus velutina* Lam.).

[3] White oaks comprise primarily of white oak (*Quercus alba* L.).

[4] Non-oaks comprise primarily of blackgum (*Nyssa sylvatica* Marsh.), flowering dogwood (*Cornus florida* L.), sassafras (*Sassafras albidum* (Nutt.) Nees), red maple (Acer *rubrum* L.), spice bush (*Lindera benzoin* (L.) Blume), and carolina buckthorn (*Frangula caroliniana* (Walter) A. Gray).

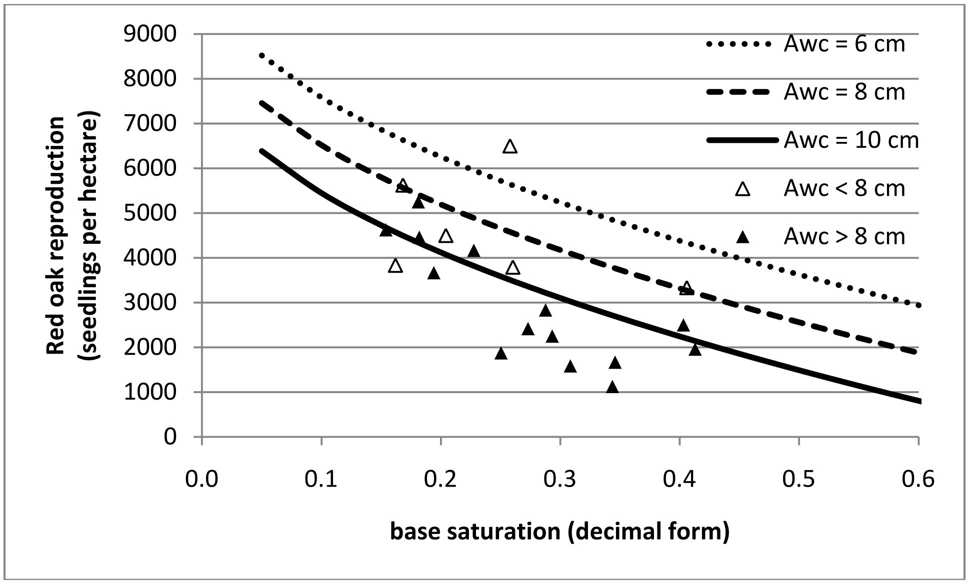


Figure 4. Red oak advance reproduction (all size classes) as a function of plant available water holding capacity (AWC) and soil base saturation (profile basis).

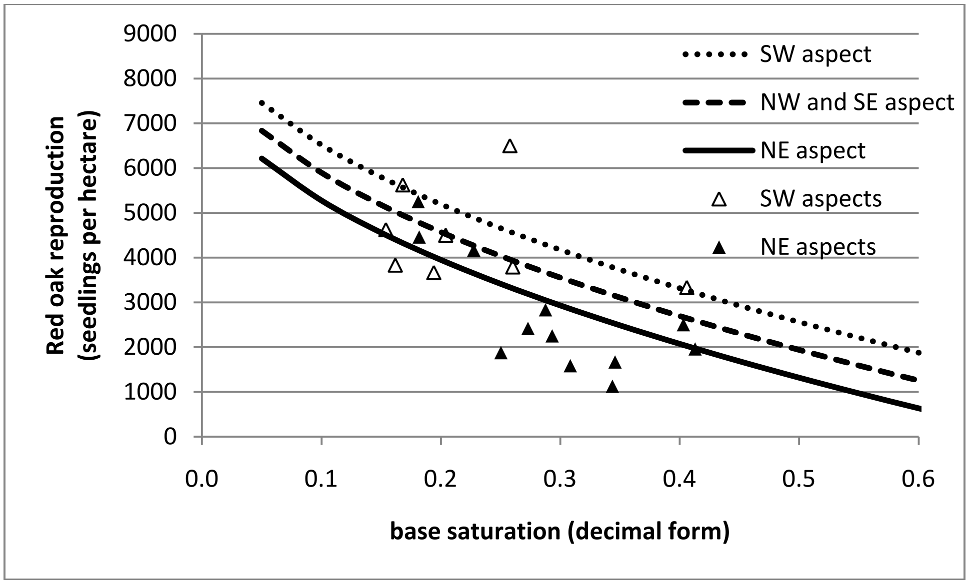


Figure 5. Red oak advance reproduction (all size classes) as a function of aspect and soil base saturation (profile basis).

of non-oak advance reproduction was significant ($P=0.01$, $R^2=0.54$). Significant parameters in the model were the intercept ($P=0.03$), black oak site index (SI) ($P=0.01$), the square root of the soil base saturation ($BS^{0.5}$) ($P=0.03$), and the aspect (taspect) ($P=0.01$). The model indicated that the abundance of non oaks increased as soil base saturation increases and as the aspect becomes more northeasterly (Fig. 7). The abundance of non oaks also increased with increase Black oak site index (Fig. 8).

Models for predicting the advance reproduction of competing species to oak were also examined. The models used the same form as those used for oak reproduction. None of the models successfully predicted the abundance of reproduction of individual competitors of oaks (table 5). However, the abundances of some of the oak competitors was correlated to the abundance of red oak advance reproduction (table 6). For example, the abundance of sassafras advance reproduction was significantly and positively correlated ($P<0.01$, $R = 0.79$) to the abundance of red oak advance reproduction (Fig.6, Fig.9). Also, the combined abundance of spice bush and Carolina buckthorn was significantly negatively correlated ($P<0.01$, $R = -0.63$) to the abundance of red oak advance reproduction (Fig. 10). These correlations indicated that sassafras reproduction occurs on sites where oak reproduction is abundant, while spice bush and Carolina buckthorn is more abundant where oak advance reproduction is not abundant or not present.

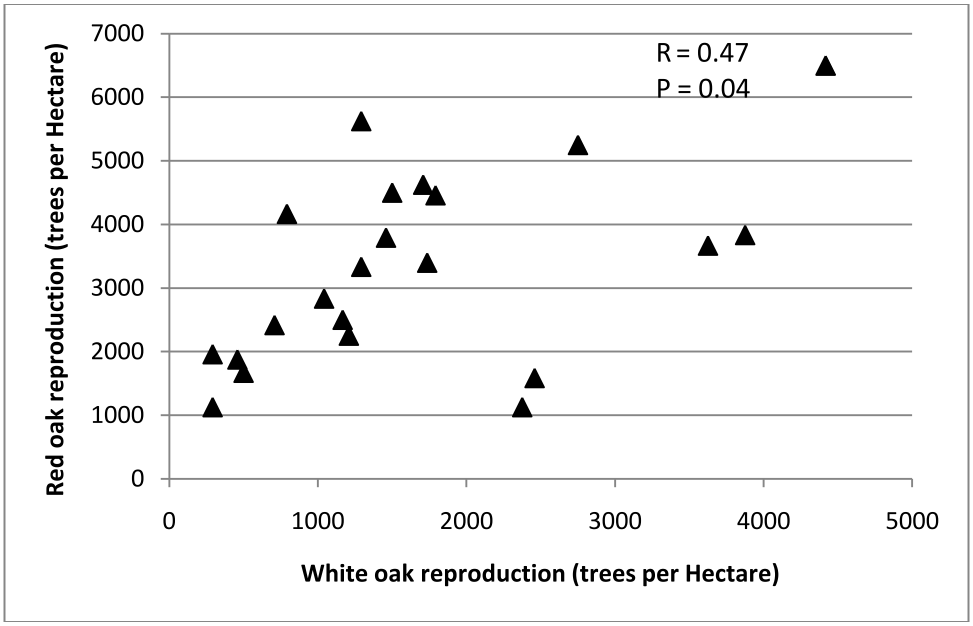


Figure 6. Correlation between white oak and red oak advance reproduction.

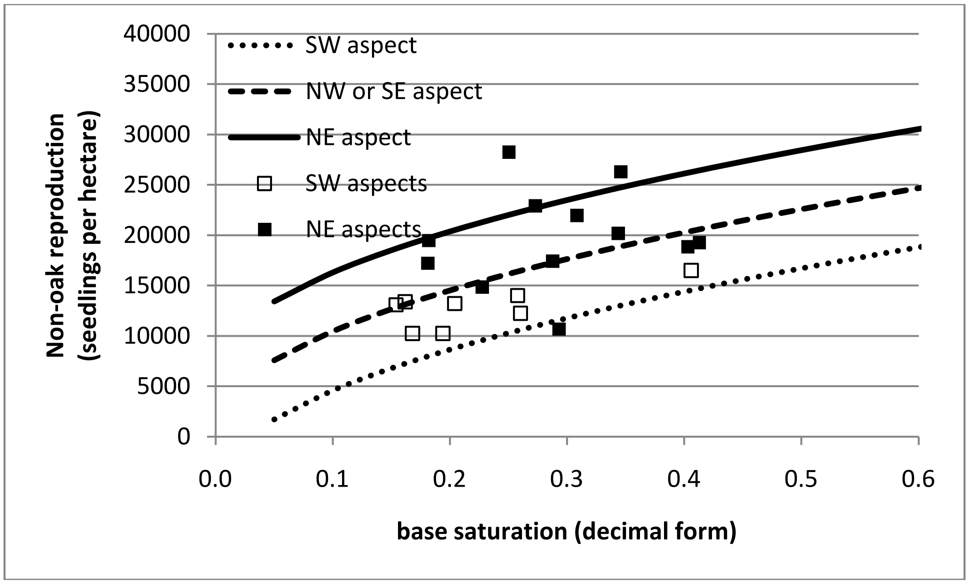


Figure 7. Non-oak advance reproduction as a function of aspect and soil base saturation (profile basis).

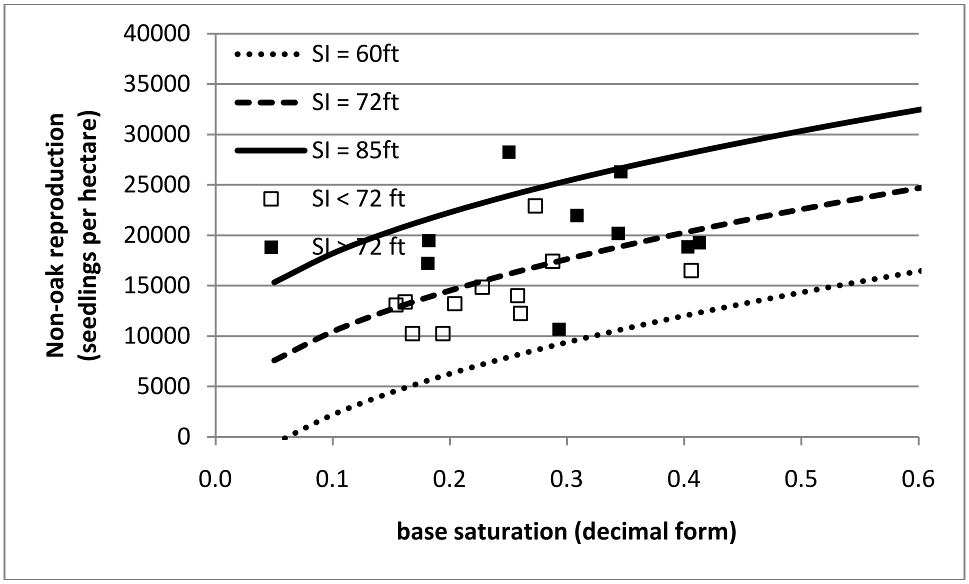


Figure 8. Non-oak advance reproduction as a function of black oak site index (in feet) and soil base saturation (profile basis).

Table 5. Models predicting the quantity of reproduction for various oak competitors.

Dependent variable (Y)[1]	F-value	P	R^2
maple (*Acer*)[2]	1.70	0.20	0.20
flowering dogwood (*Cornus florida* L.)	0.47	0.84	-0.24
sassafras (*Sassafras albidum* (Nutt.) Nees)	2.44	0.08	0.35
blackgum (*Nyssa sylvatica* Marsh.)	1.09	0.42	0.03
oak competitors[3]	0.63	0.72	-0.16
spice bush (*Lindera benzoin* (L.) Blume) + carolina buckthorn (*Frangula caroliniana* (Walter) A. Gray)	1.98	0.14	0.27

[1] model form Y = SI + AWC + $BS^{0.5}$ + Taspect + TSI + PAR + totalstock where SI = site index; AWC = available water holding capacity (cm); BS = base saturation (decimal form); Taspect = Beers-transformed aspect; TSI = terrain shape index; PAR = photosynthetically-active radiation (decimal form); Totalstock = Gingrich stocking level (percent).

[2] maple (*Acer*) is comprised primarily of red maple (Acer *rubrum* L.) along with sugar maple (*Acer saccharum* Marsh.)

[3] oak competitors is comprised of maple (*Acer*) + flowering dogwood (*Cornus florida* L.) + sassafras (*Sassafras albidum* (Nutt.) Nees) + black gum (*Nyssa sylvatica* Marsh.)

Table 6. Correlation for quantity of reproduction per hectare between red oaks and competing species. Correlation values are R values. Significant correlations (P<0.05) are shown in bold.

species[1]	red oaks	white oaks	maples	flowering dogwood	sassafras	blackgum	spicebush + carolina buckthorn
red oaks	1	**0.47** **(P = 0.04)**	0.04 (P = 0.87)	0.13 (P = 0.60)	**0.79** **(P < 0.01)**	0.23 (P = 0.33)	**-0.63** **(P < 0.01)**
white oaks		1	0.06 (P = 0.82)	0.11 (P = 0.66)	**0.59** **(P = 0.01)**	-0.01 (P = 0.97)	**-0.44** **(P = 0.05)**
maples			1	0.12 (P = 0.61)	0.24 (P = 0.32)	0.12 (P = 0.62)	-0.11 (P = 0.63)
flowering dogwood				1	0.37 (P = 0.11)	0.09 (P = 0.72)	-0.16 (P = 0.50)
sassafras					1	0.27 (P = 0.25)	**-0.5** **(P = 0.02)**
blackgum						1	-0.27 (P = 0.26)
spicebush + carolina buckthorn							1

[1] species are red oaks = scarlet oak (*Quercus coccinea* Munchh.) + black oak (*Quercus velutina* Lam.) + northern red oak (*Quercus rubra* L.); maple = red maple (*Acer rubrum* L.) + sugar maple (*Acer saccharum* Marsh.); fldogwood = flowering dogwood (*Cornus florida* L.); sassafras (*Sassafras albidum* (Nutt.) Nees); blackgum (*Nyssa sylvatica* Marsh.); spice bush (*Lindera benzoin* (L.) Blume); carolina buckthorn (*Frangula caroliniana* (Walter) A. Gray).

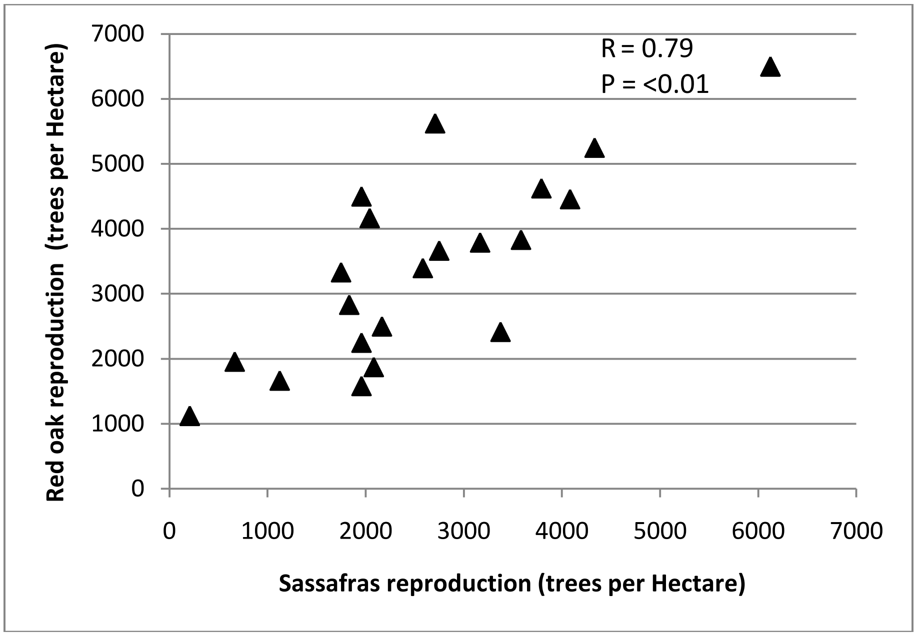


Figure 9. Correlation between red oak and sassafras advance reproduction.

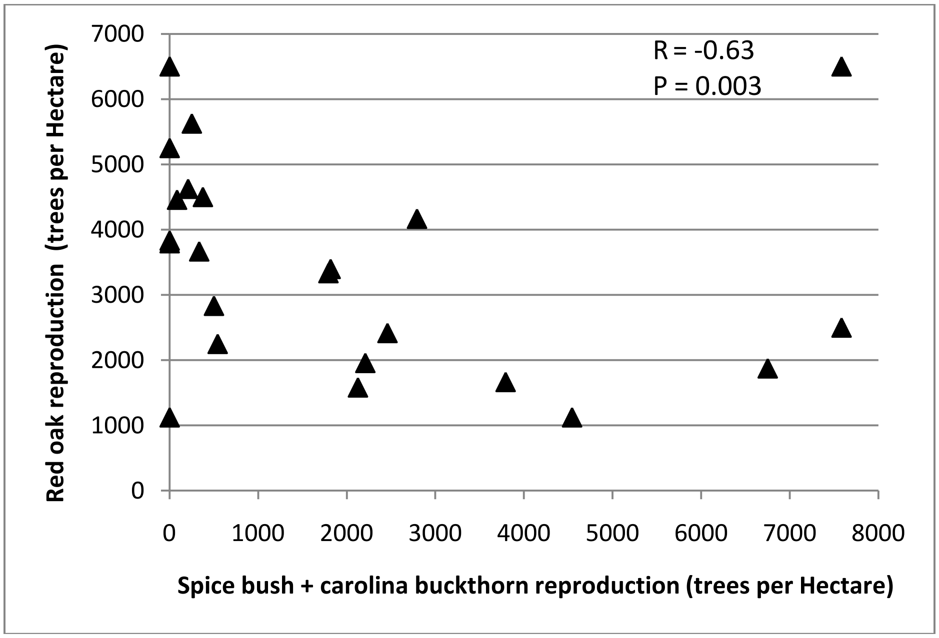


Figure 10. Correlation between red oak and spice bush + carolina buckthorn.

Alternative models that predict the abundance of red oak advance reproduction were examined to find the best model (table 7). Models 2-4 substitute in subsequent order base saturation (BS), water pH (H_20), and salt pH (CaCl) for the parameter for the square root of the base saturation ($BS^{0.5}$) in model 1. The AICC scores indicated that model 1 which uses the square root of the base saturation is better than models 3 and 4 which uses pH measurements but is statistically the same as model 2 which uses base saturation. However, model 1 has an R^2 of 0.85 and a W_i of 0.62 compared to model 2 which has an R^2 of 0.85 and a W_i of 0.38 indicating that model 1 using the square root of the base saturation is approximately twice as likely as model 2 to be the best model. Models 5 and 6 substitute either midstory stocking or overstory stocking for the parameter for total stocking in model 1. The AICC scores indicate that there is not a significant difference between any of these models and any one of these measures of stocking is sufficient.

Table 7. Models comparing alternative explanatory variables for base saturation and stocking using Akaike's information criterion scores corrected for small sample size (AICC).

Model[1]	AICC[2]	W_i[3]	R^2
1. SI + AWC** + $BS^{0.5}$** + Taspect* + TSI + PAR + totalstock	208	0.62	0.85
2. SI + AWC** + BS** + Taspect* + TSI + PAR + totalstock	209	0.38	0.85
3. SI + AWC** + pH (H20)* + Taspect + TSI + PAR + totalstock	221	0.00	0.75
4. SI + AWC** + pH ($CaCl_2$)** + Taspect + TSI + PAR + totalstock	224	0.00	0.77

1. SI + AWC** + $BS^{0.5}$** + Taspect* + TSI + PAR + totalstock	208	0.33	0.85
5. SI + AWC** + $BS^{0.5}$** + Taspect + TSI + PAR + overstock	208	0.33	0.85
6. SI + AWC** + $BS^{0.5}$** + Taspect + TSI + PAR + midstock	208	0.33	0.86

[1] Effects are SI = site index; AWC = plant available water holding capacity (cm); BS = base saturation (decimal form); pH (H_20) = water pH; pH ($CaCl_2$) = salt pH; Taspect = Beers-transformed aspect; TSI = terrain shape index; PAR = photosynthetically-active radiation (decimal form); Totalstock = Gingrich stocking level for all overstory trees(percent); Overstock = Gingrich stocking level for trees only part of the canopy (percent); Midstock = Gingrich stocking level only for trees in the mid-story (percent). Model form $Y = \beta o + B1X1 + B2X2 + \ldots + BnXn$; denominator df = 1

[2] Lower AICC scores indicate better models

[3] Akaike weights indicating the relative likelihood the model is the best.

*effect significance $P \leq 0.05$

** effect significance $P \leq 0.01$

DISCUSSION

The results of this work supported our hypothesis that in the Missouri Ozarks, oak advance reproduction will increase with decreasing nutrient and water supply. Our results suggest that greater quantities of red oak reproduction occur on soils with lesser plant available water capacity and base cation supply in the Missouri Ozarks (Figures 4 and 5). Aspect was an important physiographic determinant of oak advance reproduction with southwest facing aspects having greater quantities of red oak reproduction than northeast facing aspects (Figure 5). Measures of site index, light intensity, terrain shape, and stocking were not significant parameters in our model, but they were components of the best model predicting the abundance of red oak reproduction. Results indicated that physical measures of soil nutrient and water supply including a measure for aspect are most important in predicting where red oak advance reproduction will occur on the landscape.

We could not predict the abundance of white oak advance reproduction using our measures of soil water, nutrient supply, landform measurements, light intensity, and stocking. The abundance of white oak advance reproduction is significantly correlated to the abundance of red oak advance reproduction indicating that white oaks tend to occupy sites where red oaks are more abundant. These findings are similar to that of Kabrick et al. (2008) who examined the abundance of white oak and red oak advance reproduction in the Missouri Ozarks by ecological land type (ELT) and found a greater abundance of red oak advance reproduction on south- and southwest-facing ELTs, but no significant relationship with the abundance of white oak advance reproduction. White oak (*Q. alba*) which is generally more shade tolerant than the red oak group species in this study (primarily black oak and scarlet oak) and is tolerant of a wide range of site conditions (Rogers, 1990). These differences in shade and site quality tolerances may allow white oak reproduction to persist under a greater range of site conditions than do the red oaks identified in this study. PAR was expected to be a significant factor related to the abundance of oak advance reproduction, especially for red oaks. Considering that PAR, which ranged from about 5 to 25% of full sunlight, was not a significant factor in any of the models suggests that light availability may be less important than other factors in undisturbed stands. Rather, it may be that other factors such as the amount of available growing space for oak advance reproduction in the understory is more important.

Perhaps a good indication of the growing space available for oak advance reproduction can be inferred by examining the abundance of non oaks. Results of data analyses indicated that the abundance of non-oak advance reproduction was nearly the inverse of the red oak advance reproduction; non oaks were more abundant on sites with greater black oak site indices and base cation supply and on northeast-facing aspects. This suggests that non oak advance reproduction may have a much greater capacity to accumulate in the understory of un-harvested stands preventing the retention or accumulation of oaks, particularly those of the red oak group. Although statistical analysis failed to identify any single species or group of species as the principal oak competitors, the correlation analysis indicated that spice bush and Carolina buckthorn are likely candidates. These two shade-tolerant understory species are capable of persisting in the understory and perhaps preventing the retention of oak seedlings.

This study goes further than previous studies and supports Johnson et al. (2009) terminology describing sites that are moisture and nutrient deficient as accumulators of advance oak reproduction. Through the use of physical measures of soil base saturation the models indicate that red oak advance reproduction increases with decreasing base saturation, but as base saturation increases, the competitors of oak increase in abundance as the red oaks decrease. The physical measures of soil moisture and base saturation were more important parameters in models explaining the abundance of red oak reproduction than inferred measures such as tsi, PAR, stocking, and site index. Soil pH, when substituted for base saturation also created a significant model predicting the abundance of red oak reproduction, but base saturation is a preferred parameter over soil pH as the model using base saturation was statistically better than models using soil pH when comparing AICC scores. Soil base saturation, plant available water capacity from texture, and soil pH ranges are all available from a soil survey and should be used to model oak reproduction on the landscape.

CHAPTER IV:

SUMMARY AND CONCLUSIONS

This study evaluated the relationships between site productivity and landform as well as the abundance of oak reproduction with light availability, soil nutrient and moisture supply, vegetation density, and landform characteristics in the Missouri Ozarks. Data were collected on sample plots in mature oak-pine stands on the south end of the Sinkin experimental forest without any applied silvicultural treatments. The goal of this study was to determine how nutrient and moisture availability influences the productivity of stands as well as the abundance of reproduction for oaks and various competing species.

Landform has a significant influence on how soils develop and the supply of moisture and nutrients to plants. Landform therefore influences the productivity of forest stands which can be inferred by measurements such as site index, slope position, and slope aspect. The most significant models for estimating site index included parameters for slope position, aspect, and either tsi or lfi. Slope position and aspect were important parameters in these models and our analysis suggested that both should be included with either tsi or lfi to render the best estimates of site index in similar landscapes of the Missouri Ozarks. Models that use topographic information including slope position, aspect, and topographic shape measurements such as tsi and lfi provide reliable site index estimates when suitable site index trees are lacking. These models indicated that site index is typically greater on northeast facing aspects and lower slope positions. Measures such as tsi and lfi are suitable to estimate the influence of slope shape on stand productivity and therefore can be useful parameters along with slope aspect to estimate the overall influence of landform.

Landform along with soils has an influence on oak reproduction in upland ecosystems. Greater quantities of red oak reproduction occur on soils with less plant available water and base cation supply in the Missouri Ozarks. Aspect was also significant with southwest facing aspects having greater quantities of red oak reproduction than northeast facing aspects. Data suggested that physical measures of soil nutrient and plant available water capacity including a measure for aspect are more important than inferred measures such as site index, terrain shape, and stocking. The abundance of white oak reproduction on our sites was not able to be predicted, however the abundance of white oak reproduction was present on sites where red oak reproduction was also abundant. The reproduction abundance of individual competitors to oak could not be modeled, but the sum of all competitors grouped as non-oaks could be modeled. Non-oaks were greater on sites with higher site indices, base saturation, and generally on northeast facing aspects. The model for non-oaks was the inverse of the model for the red oaks indicating that competition is occurring between species. This data strongly supports our hypothesis that moisture and nutrient deficient sites which generally occur on southwest facing aspects and upper slope position do accumulate greater densities of oak advance reproduction.

The soil parameters of base saturation and plant available water capacity can be obtained from a soil survey by looking at ranges for base saturation and texture for individual soil series for a region. It is then possible to estimate the abundance of oak reproduction on the landscape using soil parameters in conjunction with landform variables such as aspect. This could possibly be done using GIS software. For example, Iverson et al. (1997) used GIS software to develop a moisture index model based on soil water holding capacity, topographic shape, and slope-aspect for the Vinton Experimental Forest in southern Ohio. This moisture index was highly correlated ($R > 0.79$) to the oak site index, particularly with terrain models derived from fine-resolution (<1:24,000 scale) source data. Additional research would be required, but a similar model could estimate the abundance of oak reproduction on the landscape in order to target upland hardwood stands where additional silvicultural treatments are required to control competitors and favor oak reproduction.

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