LANDSCAPE MODELING FOR RED OAK BORER ENAPHALODES RUFULUS (HALDEMAN) (COLEOPTERA: CERAMBYCIDAE) USING GEOGRAPHIC INFORMATION SYSTEMS
LANDSCAPE MODELING FOR RED OAK BORER (ENAPHALODES RUFULUS) HALDEMAN (COLEOPTERA: CERAMBYCIDAE) USING GEOGRAPHIC INFORMATION SYSTEMS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

By

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Chapter 1: Literature Review
Introduction.

Red oak borer, *Enaphalodes rufulus* (Haldeman) (Coleoptera: Cerambycidae), is native to eastern North America (Donley 1980). Although it ranges from New England to Florida and from Minnesota to Texas, it has never been reported as a serious, tree-killing pest. In the past ten years, increasing populations of red oak borer have been implicated in contributing to oak decline in the Ozark Mountains of Arkansas, Oklahoma and Missouri (Stephen et al. 2001). In 2001, the USDA Forest Service estimated that oak decline affects over 400,000 hectares of forest in this area (Thompson 2002).

This study was designed to develop a model to predict the severity of red oak borer infestation in the Ozark National Forest. This was accomplished by screening a series of biotic and abiotic landscape variables to evaluate possible associations with higher populations of red oak borer. Abiotic factors included elevation, slope, aspect and many soils variables listed in Table 1. Biotic factors include stand variables from the Forest Service CISC database such as forest type, stand age and stand condition plus stand variables recorded at each plot such as percent oak, percent northern red oak, ft\(^2\)/acre total, ft\(^2\)/acre oak and number of northern red oak.

Large, concentrated areas of heavily damaged oaks suggest that one or more of these landscape factors may be contributing to larger insect infestations and ultimate tree death.

Oak decline.

Oak decline has been described by the USFS as an epidemic with many elements which, when brought together, promote tree degradation and susceptibility to disease.
These factors are classified as predisposing, which change the trees’ ability to react to their climate; inciting, which are short in duration; and contributing, which includes a collection of environmental factors and biotic agents such as fungi and insects (Manion 1991 Sinclair 1965). Predisposing factors such as stand age, prolonged drought and poor site quality over time can weaken trees increasing susceptibility to other decline factors. The Ozark National Forest in the last fifty years has experienced four major drought periods, each lasting from three to five years (Stephen 2001). The area soils are very shallow and rocky. The most prevalent of the inciting factors appears to be severe short-term droughts (Starkey 2000 Stephen 2001). Contributing factors are fungal root pathogens e.g., *Armillaria* spp. and canker fungi e.g., *Hypoxylon* spp. as well as insects like the red oak borer.

Oak decline has been occurring since the 1850s (Hopkins 1902) and it affects about 1.6 million hectares in the southeastern U.S. (Oak et al. 1996). In all these years and over all of this acreage, the red oak borer had never before been identified as a serious mortality factor in an oak decline event.

**Economic and Ecological Importance.**

Red oak borer is an economically important pest as holes bored into the heartwood degrade lumber value and reduce structural integrity of the wood. It causes a decrease in lumber quality; for example, it was estimated in 1980 that red oak borer caused a 40 percent loss of tree value (Donley 1980). The borer holes also serve as entry sites for fungi that may cause decay (Berry 1978). Further, many affected trees are near
roads and trails where winds can cause limbs or even whole trees to fall, blocking roads or placing people and property at risk.

The northern red oak is also a valuable tree for wildlife, timber and aesthetics. The hard mast produced by these trees is a major food source for wildlife. Many game species such as wild turkey (NRCS 1999), squirrels, deer (Auchmoody 1993), feral pigs and black bear as well as many non-game species such as pocket gophers, eastern woodrats, ringtails and raccoons (Sealander 1990) utilize acorns as a major dietary component.

**Cerambycidae Biology.**

Larvae of the family Cerambycidae are phytophagous with only a few species, like *E. rufulus*, attacking living trees. Most wood-feeding species prefer to feed under the bark of dead and decaying trees. Of those that do attack live trees, species of genera *Goes*, *Hammoderus*, and *Saperda* will die if the tree is cut before insect maturation (Linsley 1961).

Boring patterns and frass-type are both characteristic of certain Cerambycids and can be helpful in identification. Some species tunnel upward at an angle before turning sharply downward, others burrow in and continue upward. Tunnel length and depth are highly variable. Depending on the type of larval mandible, frass can be powdery, flaky or can be seen as long, fibrous shreds (Linsley 1961) like the frass of the red oak borer.

Cerambycid eggs often incubate in about 14 days, but some take as long as five weeks. Larval development in a few species is completed in as little as two to three months or as much as 20 or 30 years, but most require one to three years (Linsley 1961).
The primitive sub-families are generally more polyphagous than the more advanced sub-families. Although the wood being consumed is usually at some late stage of decomposition, sub-families such as Parandrinae, Prioninae and Lepturinae may utilize both conifers and hardwoods. The sub-family Cerambycinae, which includes red oak borer, is more advanced and therefore more specialized. Their diet is limited to angiosperms (Linsley 1961).

**Red Oak Borer Biology.**

The adult red oak borer is approximately 23 to 33mm long with antennae about the same length as the body in females and twice the body length in males (Solomon 1995). The beetles have a two-year synchronous life cycle during which adult emergence occurs in Arkansas, in odd-numbered years. Emergence usually takes place at night from middle to late summer. The sex ratio is approximately 1:1 with copulation and oviposition occurring nocturnally on the host tree (Donley 1980) soon after adult emergence. Females oviposit in bark crevices or under lichens and moss. The eggs are attached with a water-soluble adhesive and as many as 95 percent of an average of 110 eggs may hatch (Donley 1980). In the Ozark National Forest, eggs hatch in late July through early August. The small larvae immediately begin burrowing through the bark into phloem tissue (Hay 1969) where they create galleries that are approximately 3.2 cm$^2$, where they remain for the first quiescent, over-wintering period (Kinney et al. unpublished). At this time some frass may be noticeable below entrance holes (Hay 1969). By the beginning of winter the larvae are well established in the phloem tissue. With the approach of spring and warmer weather attack sites may be more easily
recognized by sap ooze or by frass lodged in the entrance hole. By late spring, the beginning of the second active period, most attack sites begin oozing much more sap. Internally, the larvae begin to bore tunnels into the heartwood. In June the average tunnel is about three to four cm deep and the larvae have as much as quadrupled in size. In July, attacks are easily seen as considerable amounts of frass are extruded from the holes. In the following few months, larvae continue to create heartwood galleries, which run inward up to five centimeters before curving up to vertical for another ten centimeters. At this time large accumulations of frass can be seen around the tree base. These finished heartwood galleries run diagonally upward into the tree for ca. 5 cm before turning vertically upward for another 13 to 17 cm. The second winter and spring larvae experience another general period of inactivity, or quiescence. In April and May the larvae prepare pupal chambers by plugging the bottom of tunnels with frass and create frass cushions just beneath the top of the vertical tunnel where pupation occurs. The pupal stage lasts about three weeks, and in June and July callow adults can be found. Adult borers spend approximately two weeks in the tree before sexual maturity and finally, emergence (Hay 1979).

**Hosts.**

Red oak borers preferentially oviposit on red oaks (subgenus *Erythrobalanus*) but also attack white oak species (subgenus *Leucobalanus*) (Donley1980). Common oak species in the Ozark National Forest include northern red oak (*Quercus rubra*, L.), which is the most heavily attacked species when present, black oak (*Q. veluntina* Lamarck),
southern red oak (*Q. falcata* Michaux) white oak (*Q. alba* L.), and post oak (*Q. stellata* Wangenh.).

**Tree Health.**

There is a high degree of association between oak decline and several stand and site factors (Oak 1995). These associated factors include ‘site index,’ i.e., tree height to age ratio, ‘stand age,’ ‘forest type,’ i.e. classification regarding dominant species within the stand, and ‘condition class’ which is a classification of damage and maturity of a stand, i.e. ‘damaged poletimber,’ ‘low-quality sawtimber,’ or ‘seedling & sapling.’ These variables classify stands into categories of ‘decline-vulnerable,’ ‘decline-damaged,’ ‘unaffected,’ or ‘other damage.’ Vulnerable stands have a high proportion of oak, relatively low ratio of site index/age, which is a measure of physiological maturity, and lack limiting damage conditions. ‘Decline-damaged’ is the same as the vulnerable classification, but with limiting damage conditions (i.e. sparse stands, damaged stands, or low quality stands). Stands classified as ‘other damage,’ have the same conditions as ‘decline-damaged,’ except with a high site index/age ratio. ‘Unaffected’ stands lack damage conditions and have a relatively high site index/age ratio or are non-oak forests (Oak 1995).

Site index is a measurement that uses the height and age of a selected tree within a stand as an estimate of stand health (CISC 1993); better sites have higher site indices. Slope gradients from zero to ten percent have increasing site indices for increasing slope steepness (Graney 1977). For slopes that were greater than ten percent, steepness showed much less influence on site indices (Graney 1977).
The soils in which trees are growing greatly influence their health, and therefore their ability to resist borer attacks (Solomon 1977). Because of a shallow, marine deposition, much of the Ozark soils are very loamy sandstone, which are not recommended for growing oaks that are present in the area (Graney 1977).

Aspect, the direction a slope faces, seems to be predictive of decline. Fierke et al (unpublished) found that trees on ridge-tops incur greater mortality than trees on north, east, south or west-facing slopes based on percent of standing dead northern red oaks. West and south-facing slopes have more standing dead than either north or east. Graney (1977) also determined that north and east facing slopes are better sites for both white and red oaks while south and west facing slopes were not as suitable. This is due to the higher temperatures, greater rates of evapotranspiration and more rapid use of available soil moisture on the south and west-facing slopes (Graney 1977).

**Infestation Area Description.**

The red oak borer outbreak occurs across the Ozark Mountains of Arkansas, Oklahoma and Missouri (Figure 1). This area falls within the interior highlands, which can be further divided into three plateaus: the Salem plateau, Springfield Plateau and the Boston Mountains (Figure 2). These were domes formed by uplift in the Pennsylvanian Period of the Paleozoic era. The landscape has since become mountainous, as it has been chiseled by water erosion (Sealander 1990). Because of the shallow, marine deposition, the rocks are primarily limestone and sandstone. This type of soil allows for quick percolation of water, leaving little available for plant growth. The Ozark Mountains consist of mainly the upland oak-hickory forest type (CISC 1993). In the Pleasant Hills
Ranger District of the Ozark National Forest the species composition is 46% red oak, 28% white oak and 26% other hardwood and pine (Starkey et al. 2000). The Ozark Highlands of Missouri, Arkansas and Oklahoma along with the Boston Mountains of Arkansas and eastern Oklahoma have well over 15 million acres of timberland, 90 percent of which is oak or oak-pine dominated (Pell et al. 1999). Because there is so much oak, there is great potential for damage in this current epidemic. Many of the trees seem to be killed or attacked in large concentrated areas (Figure 3). The oak trees within these areas have experienced large numbers of borer emergence as evidenced by the obvious holes in their trunks (Figure 4).

**Sampling for Red Oak Borer.**

There are limited sampling options for adult red oak borers in forests. No pheromones have been discovered and host odors that have been tested on the borers have yielded no response. Research is currently being conducted on contact pheromones. Pheromone lures will probably not work from a distance. Adults can be caught in flight intercept traps or at black lights. Different instars can be collected any time of year by scraping logs for larvae in phloem galleries or by splitting infested trees for second-year larvae in heartwood galleries (Kinney et al. unpublished).

In 1974, Hay sampled over 1000 trees and found a maximum of 71 red oak borer attack sites in a single tree. Donley and Rast (1984) sampling over 400 trees, found 2.3 to 5.2 attack sites per tree. In 2003, through intensive sampling, we have found an average of 160 attack sites per m² of bark surface on 13 northern red oaks, and an average of 13 emergence holes per m² of bark surface on 24 trees (Fierke et al. unpublished).
To permit estimates of ROB density at the stand and landscape levels, Fierke et al. (unpublished) developed a non-destructive rapid estimation procedure (REP). The REP uses a percent crown condition index, which combines foliage transparency due to crown dieback and crown measurement outlines (USDA 2001) along with numbers of basal emergence-holes to estimate infestation history. Crown condition index has four categories, zero representing no crown dieback; one representing 1 to 33% dieback; two representing 34 to 66% dieback, and three representing 67 to 100% dieback. Basal emergence-hole index is a categorized count of red oak borer emergence holes on the lowest two meters of the tree bole. Zero represents no borer emergence holes; one represents 1 to 5 emergence holes; two represents 6 to 20 emergence holes and three represents more than 20 emergence holes. These two variables are summed to produce a single value, the rapid estimation index (REI) and is used as a ranking of infestation severity (Fierke et al. unpublished). A higher REI indicates increased borer numbers in the infested tree. The REP is non-destructive and is much less labor-intensive than previous methods which relied on cutting trees and mapping bark holes, then scraping bark to count phloem galleries or splitting the wood to count heartwood galleries (Fierke et al. unpublished). This means that more trees can be sampled in less time. Also, trees with lower REIs can be left standing with the possibility of survival.

GPS.

Global positioning systems (GPS) allow researchers to log specific points on the landscape into computer mapping programs as well as allowing other researchers to visit the same areas in the future. Both Garmin® and Trimble® hand-held GPS units were
used in this study to navigate to and record positions of plots. Accuracy of these units has been tested and is adequate for forestry applications (Oderwald et al. 2003). Using inexpensive consumer-grade GPS units without differential correction (correction for the difference in speed of signal due to the Earth’s atmosphere) is much more accurate than previous methods of navigation, such as compass and pace.

**Types of Mathematical Models.**

There are many types of models that can be used for risk ratings of forest pests. The simplest type, ordinal, yields a two-outcome answer, i.e. yes/no. Ordinal scales have also been used where more than two classes are developed. One class is most likely to become infested, while the next class is less likely, and so on, to the zero likelihood of infestation. While ordinal scales are appropriate for many models, the more useful models yield a continuous scale. These show differences between areas as well as the amount of variability (Stage 1980).

**Geographic Information Systems and Modeling.**

Geographic information systems (GIS) are computer programs that allow users to manipulate, analyze and present spatially referenced information. These systems have been in use since the 1960s when the earliest were developed by architects and city planners (Burough and McDonnell 1998). Today GIS are used by civil engineers planning new construction, police departments analyzing crime statistics, utility companies routing water and gas lines, and many other agencies. With aerial photography and satellite images, large tracks of land can be mapped and analyzed for
the varying needs of geologists, ecologists and other natural resource professionals (Burough and McDonnell 1998).

Vector-based data use points, lines and polygons to display spatial features. Vector data are ideal for discrete areas with defined boundaries, such as buildings and roads, but do not work as well for continuous data that vary over space such as weather, elevation or large, growing areas of insect infestation. These types of data are best represented with raster (Chang 2001). Raster-based data are often referred to as a grid, or raster maps. Raster grids display geographic features with cells, which are equal-sized square blocks (Wing et al. 2003). Using cells, a raster map can show points, lines and polygons like the vector data model by displaying single cells for points, sequences of cells for lines and areas of several adjacent cells for polygons. Every cell in a raster map has its own value for each attribute in question. This means that any one cell can have a value for every variable in question, i.e., elevation, aspect, soil type, distance to roads, red oak borer damage, etc.

GIS have been used extensively for habitat modeling in recent years. Previous studies using GIS to define animal habitat have included snakes, bears and insects such as gypsy moth and Douglas fir tussock moth. Analyses for modeling snake and bear dens used the Mahalanobis distance (\(D^2\)) statistic as outlined by Dunn and Duncan (2000). \(D^2\) begins its analysis at one cell in a raster and works its way outward in every direction from that cell computing a probability of habitat suitability. This was used because the data were points that each represented one snake or bear den. From these points, the statistic calculated the likelihood that a den could exit in the areas it spanned with the actual den representing 100 percent likelihood (Thatcher 2002 Browning 2000).
With this red oak borer project, each point on the map represents a variable-radius prism plot with an assigned index as to the extent of borer damage, rather than a presence/absence value. The area surrounding each of the points is likely to have the same infestation index, but because of plot boundaries, would not be included. For this reason, the distance statistic would not be as useful in determining the epicenter of borer infestations. Both vector and raster data were used in this project. Roads, streams, soils and stand data were all obtained in vector format. The digital elevation model, from which slope and aspect were derived, was acquired as a Raster. Vector data layers were initially converted to raster so that each ten-meter cell or pixel would have an assigned value for each data layer. All GPS coordinates were entered into the GIS and a data table was created to house data from all layers within a single table.

Gypsy moth and tussock moth GIS research benefits from much previously collected data. Maps of both gypsy moth and tussock moth defoliation have been archived for many years (Elmes et al. 1993 Liebhold et al. 1993). These maps can be scanned into a GIS; based on yearly distribution, inferences can be made about defoliation frequency and the spread and damage most likely to occur. These studies, although not totally applicable, do have some similarities to the red oak borer study. Much of the data collected for gypsy moth have to do with tree susceptibility. Healthier trees grow on flatter, lower elevations. Oak trees, which are a favorite host of gypsy moth, are healthier in certain type of soil and on certain slopes and elevations (Elmes et al 1993).

Landscape modeling for southern pine beetle (*Dendroctonus frontalis*) has been done extensively. Hazard-rating models for pine stands are dated pre-1980. Southern
pine beetle outbreak risk can be assessed based on beetle numbers and stand resistance (Paine et al. 1985). Sampling for southern pine beetle is well documented. Beetle numbers are often used as indicators of infestation severity. With red oak borer, sampling is not done quite as easily, although new sampling techniques are in development.

Models used for mapping vulnerability of forests in the Pacific Northwest to western spruce budworm and Douglas-fir tussock moth (both defoliators) use several “vulnerability factors.” These include site quality, host abundance, canopy structure, stand density, host age, stand vigor and connectivity of host stands (Hessburg et al. 1999). The vulnerability factors in this study are similar to the ones used in current red oak borer modeling. Site quality in this red oak borer study is represented by soils attributes, aspect and slope. Host abundance, stand density and age are included in red oak borer models while stand vigor is only partially represented by stand condition. Measurements for canopy structure are not used due to lack of availability. Connectivity of host stands is not of issue in this red oak borer outbreak as nearly all stands within the Ozark National Forest contain some amount of northern red oak as well as other suitable host species.
Table 1. All variables tested, biotic and abiotic with descriptions. Biotic variables were field collected or obtained from USDA Forest Service’s CISC database. Abiotic variables were gathered from other sources of automated mapping data.

<table>
<thead>
<tr>
<th>Dependent Variable:</th>
<th>Average REI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq ft/acre NRO</td>
<td>Square feet per acre of northern red oak in each plot</td>
</tr>
<tr>
<td>Sq ft/acre oak</td>
<td>Square feet per acre of oak in each plot</td>
</tr>
<tr>
<td>Sq ft/acre total</td>
<td>Square feet per acre of all oaks in each plot</td>
</tr>
<tr>
<td>Percent NRO</td>
<td>Percent of northern red oak in each plot</td>
</tr>
<tr>
<td>Percent Oak</td>
<td>Percent of all oak except northern red oak in each plot</td>
</tr>
<tr>
<td>No. NRO</td>
<td>Number of northern red oak in each plot</td>
</tr>
<tr>
<td>Total sq ft/acre</td>
<td>Total square feet per acre of all trees in each plot</td>
</tr>
<tr>
<td>Land Class</td>
<td>Values assigned by USDA Forest Service to represent different types of land (lakes, public parks, wildlife openings, etc.)</td>
</tr>
<tr>
<td>Forest Type</td>
<td>Values assigned by the USDA Forest Service to represent the dominant tree species growing in each area (red oak-white oak-hickory, pine, etc.)</td>
</tr>
<tr>
<td>Stand Condition</td>
<td>Classes assigned by USDA Forest Service to represent types of trees growing in the area (damaged poletimber, forest pest infestation, seedling, sapling, etc.)</td>
</tr>
<tr>
<td>Age Year</td>
<td>Year a stand was last clear-cut</td>
</tr>
<tr>
<td>Management</td>
<td>Numbers assigned by the USDA Forest Service to represent the way the land is managed</td>
</tr>
<tr>
<td>Aspect</td>
<td>Direction a slope faces, ridges included as a separate aspect</td>
</tr>
<tr>
<td>Sine Aspect</td>
<td>Sine of the degree that a slope faces</td>
</tr>
<tr>
<td>Cosine Aspect</td>
<td>Cosine of the degree that a slope faces</td>
</tr>
<tr>
<td>Elevation</td>
<td>Elevation of each point, in meters</td>
</tr>
<tr>
<td>Slope</td>
<td>Degree of steepness of the slope</td>
</tr>
<tr>
<td>Available Water</td>
<td>Available water capacity, an average of high and low extremes from the soils database (expressed in inches per inch for the soil layer or horizon</td>
</tr>
<tr>
<td>Available Water</td>
<td>Capacity</td>
</tr>
<tr>
<td>Clay</td>
<td>Amount of clay in the soil (expressed as a percentage of the material less than 2mm in size)</td>
</tr>
<tr>
<td>Inch10 rock</td>
<td>Percent by weight of the rock fragments greater than ten inches in the soil layer</td>
</tr>
<tr>
<td>Inch 3 rock</td>
<td>Percent by weight of the rock fragments greater than three and less than 10 inches in the soil layer</td>
</tr>
<tr>
<td>Permeability</td>
<td>Average value for the range in permeability rate for the soil layer or horizon expressed as inches per hour</td>
</tr>
<tr>
<td>Horizon Depth</td>
<td>Horizon depth, the depth to the bottom of the lowest layer of soil (expressed in inches)</td>
</tr>
<tr>
<td>Texture</td>
<td>Soil texture, originally in letter symbols. Each letter symbol was replaced by a number</td>
</tr>
<tr>
<td>Roads</td>
<td>Straight-line distance to roads in meters</td>
</tr>
<tr>
<td>Streams</td>
<td>Straight-line distance to streams in meters</td>
</tr>
</tbody>
</table>
**Figure 1.** The National Forests of Arkansas, Southern Missouri and Western Oklahoma affected by red oak borer: Ozark National Forest of Northwest Arkansas highlighted in red.

**Figure 2.** Three plateaus eroded by water to carve out the Ozark Mountains in Northwest Arkansas.

**Figure 3.** Aerial photo of North Central Arkansas (Clarksville area) from USDA Forest Service taken October 3, 2000, illustrates large concentrated areas of tree damage.

**Figure 4.** Red oak tree bole illustrates holes resulting from emergence of adult red oak borer. Holes encircled in yellow. Each is approximately 1.5-3.0 cm in diameter.
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Natural resources conservation service. Wildlife habitat management institute. 


CHAPTER 2: Comparison of landscape attributes with the level of tree damage determined by a rapid estimation procedure for red oak borer *Enaphalodes rufulus* (Haldeman)
Abstract.

The objective of this research was to assess red oak borer distribution and relate red oak borer occurrence to landscape features across the Ozark National Forest using a rapid estimation procedure developed by the Forest Entomology Lab at the University of Arkansas. This non-destructive procedure is used to determine the infestation history of northern red oaks in a stand. Twenty-six variables, both biotic and abiotic, were analyzed for possible inclusion in a model to predict rapid estimation indices for stands containing northern red oak in the Ozark National Forest. Three hundred thirty-nine plots were evaluated and a model was generated using the significant variables: percent oak, basal area of northern red oak and sine of aspect (north vs. south). This model is a first step in generating a more precise and detailed model for determining susceptibility of forest stands to red oak borer outbreaks.

Introduction.

Red oak borer, *Enaphalodes rufulus* Haldeman (Coleoptera: Cerambycidae), is native to eastern North America (Donley 1980) and ranges from New England to Florida and from Minnesota to Texas. In the past ten years, increasing populations of red oak borer have been implicated as contributing to oak mortality in an oak decline event in Arkansas, Oklahoma and Missouri (Stephen et al. 2001). In 2001, the United States Forest Service estimated that oak decline affects over 1 million acres of forest in this area (Thompson 2002).
The study area is the Ozark National Forest in Northwest Arkansas (Figure 1, chapter 1), which is in The Ozark Mountains. These mountains were formed from three plateaus (Figure 2, chapter 1), which were chiseled by water erosion to create a steep landscape (Sealander 1990). The Ozark Highlands of Missouri, Arkansas and Oklahoma along with the Boston Mountains of Arkansas and eastern Oklahoma have well over 15 million acres of timberland, 90 percent of which is oak or oak-pine dominated (Pell et al. 1999). Because there is so much oak (Figure 1), there is great potential for damage in this current epidemic. Many of the attacked trees die in large concentrated areas while other areas seem to have much less damage as seen from aerial photos from the USDA Forest Service (Figure 2). These areas of dead oaks suggest that there may be one or more landscape factors contributing to stress and ultimate death of the trees.

In separate, previous studies, aspect, soils and slope have all been shown to greatly affect tree health. Ridge-tops and south-facing slopes incur greater mortality of northern red oaks than north-facing slopes based on numbers of standing dead northern red oaks (Fierke et al. unpublished). Because of higher temperatures, greater rates of evapotranspiration and more rapid use of available soil moisture on south and west-facing slopes, Graney (1977) determined that north and east facing slopes were better sites for both white and red oaks. Despite the presence of oak as a dominant component of Ozark forests, many of the area soils are very loamy sandstone, which results in xeric conditions that are not ideal for oak growth (Graney 1977). Site indices, which are estimates of stand health, increase with steepness in slopes having gradients of zero to ten percent (Graney 1977).
Red oak borer is economically important as larval galleries in heartwood degrade lumber value and reduce structural integrity of the wood. It was estimated in 1980 that red oak borer reduced lumber value by as much as 40 percent (Donley 1980). Also, many affected trees are near roads and trails where winds can cause limbs or even whole trees to fall blocking roads or potentially putting people and property at risk.

Red oak borer has a 2-year life cycle, with synchronous adult emergence from middle to late summer in odd-numbered years (Hay 1969). Adults are 2 to 3.5 cm in length with antennae the same as the body length in females and twice the body length in males (Solomon 1995). The sex ratio is approximately 1:1 with copulation and oviposition occurring nocturnally on the host tree (Donley 1980) soon after adult emergence. Females oviposit in bark crevices or under lichens or moss. Upon hatching, in late July through early August, the small larvae begin burrowing through the bark into phloem tissue (Hay 1969) where they create small galleries (surface area about 3.2 cm²) to spend the first quiescent, over-wintering period (Kinney et al. unpublished). The second active period, (summer of even-numbered years), larvae begin boring into the heartwood. The tunnels run diagonally upward into the tree for ca. 5 cm before turning vertically upward for another 13 to 17 cm. Larvae spend the second quiescent period in this heartwood gallery, which also serves as a pupation chamber. Pupation to adult emergence spans approximately three weeks (Hay 1969).

Red oak borers preferentially oviposit on red oaks, (subgenus Erythrobalanus) but are also known to successfully attack white oak species, (subgenus Leucobalanus) (Donley 1980). Common oak species in the Ozark National Forest include northern red
oak, black oak, southern red oak (Q. falcata Michaux) white oak (Q. alba L.), and post oak (Q. stellata Wangenh.).

**Objectives.**

This study was designed to screen a series of biotic and abiotic landscape variables to determine if they could be used to predict areas where high oak mortality from red oak borer would occur. Abiotic factors included elevation, slope, aspect and a series of soils variables; all listed in Table 1. Biotic factors include stand variables from the Forest Service CISC database such as forest type, stand age and stand condition plus stand variables recorded at each plot including percent oak, percent northern red oak, ft²/acre total, ft²/acre oak and number of northern red oak.

**Methods.**

**Variable Selection.**

The attributes chosen for analysis were elevation and its derivatives, slope and aspect; soil and associated attributes; distance to roads; distance to water; percent oak; percent northern red oak; basal area of all oaks, and of northern red oak and total basal area. These features were chosen based on the idea that they may be biologically important. Better soils, better slope position and preferable aspects can yield healthier stands with trees that may be able to better defend themselves from red oak borer attack.

Soils data were obtained from the Natural Resources Conservation Service (NRCS). Aerial photographs were used as the map base and data were recorded by surveyors using transverses and transects along delineation boundaries. Soils map scales
range from 1:12000 to 1:63000 (SSURGO 1995). Slope and aspect were created from the 10-meter digital elevation model (DEM) from the USDA Forest Service. These variables were included in analyses because ridges, or tops of slopes, tend to have shallower soils than sides of hills or valleys. Shallow soils hold less moisture and fewer nutrients, so there is not as much available for plant growth. Because aspect is a circular variable (0 and 360 degrees are both north), both sine (for north and south) and cosine (for east and west) were used for analysis rather than aspect itself. A separate categorical variable was also created to divide aspect into five classes. This was the best available method to analyze ridge-tops as a separate category from the 360-degree aspects. The classes were: north, 315-45 degrees; east, 45-135 degrees; south, 135-225 degrees; west, 225-315 degrees and ridge-tops. Ridge-top plots were visually selected in Environmental Systems Research Institute’s (ESRI’s) ArcMap 8.2 using the aspect layer as well as two hillshade layers with opposing light sources. If a plot looked as if it were on a ridge-top in the east-lit (light source at 45°) hillshade (Figure 3a), the reverse hillshade, light source west (315°) (Figure 3b), would confirm the ridge-top status of the plot by its remaining in the light. If it were not actually on a ridge-top, the plot would be shaded in the second view. Road and stream data, dated 1999, were originally from the Arkansas Highway and Transportation Department, but were obtained from the University of Arkansas’ Center for Advanced Spatial Technology (CAST) website, Geostor. Distance layers for each were created in ArcMap. The ground in the study area is usually dry in the summer months. Distance to streams was used as a layer because above ground water sources are generally considered to be areas of more vigorous plant growth, although this layer
includes ephemeral streams. Distance to roads was analyzed because of the possibility of roads facilitating borer migration though a normally dense forest.

ROB Assessment.

A sampling method to quickly assess red oak borer density and infestation history was developed by the University of Arkansas forest entomology lab (Fierke et al. unpublished). This procedure uses a percent crown condition index, which combines foliage transparency due to crown dieback and crown measurement outlines (USDA 2001) along with a basal emergence-hole index to estimate infestation history. Crown condition index has four categories, zero representing no crown dieback; one representing 1 to 33% dieback; two representing 34 to 66% dieback, and three representing 67 to 100% dieback. Basal emergence-hole index is a categorized count of red oak borer emergence holes on the lowest two meters of the tree bole. Zero represents no borer emergence holes; one represents 1 to 5 emergence holes; two represents 6 to 20 emergence holes and three represents more than 20 emergence holes. These two variables are summed to produce a single value, the rapid estimation index (REI) (Fierke et al. unpublished). Borer holes and crown conditions were counted for each tree within every plot. Plot REIs were determined by averaging REIs of all trees within each plot.

Plot Selection.

Prism plots were selected in two ways, randomly and purposefully. I established 85 non-random prism plots from June through August of 2003. Seventy of these were recorded at 0.5-mile intervals using off-highway vehicle (OHV) trails in several regions
of the Ozark National Forest. Trails were chosen for variability in elevation, distance to roads and distance to streams. Fifteen plots were located along the Ozark Highlands Trail, which is accessible only to hikers. These 15 plots were separated by ten to fifteen minutes of walking, which was estimated to be approximately 0.5 miles. Forest Service employees established 467 prism plots from May to August 2003 to assess borer activity across the Ozark National Forest. These plots were located at coordinates randomly generated using Environmental Systems Research Institute’s (ESRI’s) ArcView GIS 3.2. Global positioning systems, (GPS) were used to either navigate to the previously determined coordinates or to record newly collected coordinates as plots were actively being established. All coordinates were transferred from GPS units to GIS and used to relate plots according to spatial distribution in all analyses. Prisms used by each group had basal area factors (BAF) of ten square feet per acre. For each plot, GPS coordinates, species of all trees within the plots, all northern red oak diameters at breast height (DBH) and information to rank insect infestation history using the Rapid Estimation Procedure (REP) were recorded. Sites were classified as high, medium or low level infestations based on the average REP value of the trees in the plot (Figure 4).

Of the 552 plots, only 328 contained northern red oak, which is required for the REP. All other plots were eliminated from the study. Once all areas were ranked, they were added to the GIS for comparison of all data layers at each plot.

Another 15 vegetation-monitoring plots were then added to bring the total number of plots to 343. These 30 x 100 meter plots are measured yearly by the forest entomology crew at the University of Arkansas for a temporally based evaluation of changing REP classes. These plots were selected using ArcView GIS to find areas at specific elevations
with certain aspects or ridges. All plot variables were converted to per acre measurements to avoid differences associated with non-uniformity of plot size. All prism plots contained between one and 13 northern red oaks, while vegetation monitoring plots had between 22 and 157.

Analysis.

An initial regression model relating average REI to the biotic and abiotic variables (Table 1) was used in the analysis. The model took into account potential spatial correlation by adding a spatial error structure to the model statement, i.e., the program was written specifying that the points are correlated because of their proximity to each other (Cressie 1991). Backward elimination was then used to remove variables that did not have a significant effect on average REI. The removal criteria was p=0.05. The adequacy of the final model was decided by plotting residuals versus predicted values and using standard diagnostic statistics. All analyses were carried out using SAS Proc Mixed (SAS version 8.2, SAS Institute, Inc. Cary, NC).

Results.

Once all variables with non-significant p-values were removed, percent oak, basal area of northern red oak and sine of aspect remained (Table 2). These three variables now yield a model estimating an expected Rapid Estimation Index for any forested area in the Ozarks:
Average $\text{REI} = 0.9541 + 0.0166B + 0.0049C - 0.2203D$

where:

$B$  = observed percent oak  
$C$  = observed basal area of northern red oak  
$D$  = observed sine of aspect

When the initial analysis was completed on the dataset, residuals (the difference between the observed values and predicted values) greater than 4.0 in absolute value were treated as potential outliers and were examined individually. Eighty-eight of the prism plots in the dataset contain only one northern red oak. Four of these were found to have high rapid estimation indices. Because of the variable size of prism plots, the size of and distance between stems limits the number of trees within the actual plot. There could be numerous northern red oaks in an area, with only one or even none included in the prism plot. Many of these plots were field-checked to ensure that the surrounding area contained sufficient numbers of northern red oak so that damage estimates would not be based on the only northern red oak in an area. Because all checked plots did have surrounding northern red oaks with borer damage estimates comparable to the actual plotted trees, the plots with one northern red oak were left in the analysis. Since all plots were not checked, we cannot be certain that every plot had surrounding northern red oaks. For this reason, four outliers with residual values greater than four and containing only one northern red oak were removed from the final analysis leaving 339 plots to fit the model.

In a plot of residuals against the predicted values a random scatter of points about the horizontal axis indicates that the data are randomly scattered about the fitted curve (Figure 5). The downward sloping sequences of points in the graph are due to repeated
observed values in the data. The empty area in the lower left corner delineated by the lowest cluster of points results from the restriction that negative observed REIs are impossible. The line itself represents prism plots with an REI of zero. For every increase in percent oak, the average REI increases by .0166 if the other variables remain unchanged. In a similar manner to percent oak, an increase in square feet per acre (basal area) of northern red oak increases the REI. Because the prism used was 10 BAF, every $10^2$ feet per acre increase, raises the REI by .0049. Sine of aspect is not a linear function of aspect and depends on the slope face it represents. When aspect is facing northward, between 270 (due west) and 90 (due east) degrees, the sine function is positive so average REI decreases. When aspect is south-facing, between 90-270 degrees, sine is negative, so average REI increases. Because sine is not linear, a change near the top (north) or bottom (south) of the sine curve will have less an effect on the model than would a change mid-wave (east or west).

Discussion

Most of the tested variables were not statistically significant. Three variables that are not in the model show significance in a general linear model without consideration of the spatial correlation of the plots. Distance to roads, distance to water and categorized aspect with ridges as a separate category, show significance when run in SAS (SAS Institute Inc. 1999) or JMP (SAS Institute Inc. 2003). When a spatial error structure is added to the model these same variables lose their significance.

The difference between ridges and directional slopes should be very important because the soils on ridges are much thinner and rockier and there is less water and
organic matter available. It is evident that the trees in these areas are less vigorous. Trees on these ridges are much smaller than their same-age counterparts on different slopes. There are also more standing dead oaks with high numbers of borer emergence holes on ridge-tops than on any of the 360-degree aspects (Fierke personal communication).

The soils data could be significant if it were collected and recorded on a larger scale. The largest-scale soils data available, SSURGO, are 1:24,000. These are taken using some field-recorded data, aerial photographs and topographic maps. They may not distinguish differences at a large enough scale to show ridges and the different aspects as having different values for each soil variable.

The model resulting from this project is not the best model possible. It is, however the best model possible with the available data. Improvements can be made if more plots are added. New plots should be sure to represent more equally, each possible outcome of every variable to be used. For example, instead of a totally random design, a certain number of plots could be generated randomly for north-facing or other slopes as well as for ridges. Soils data should be taken at each plot rather than relying on relatively small-scale data to accurately assess the organic content, depth to bedrock and available moisture.

Within the Ozark National Forest, the best way to determine general susceptibility of a particular parcel of land to red oak borer outbreaks is to know how much northern red oak is available to the insects. If the percentage of oak trees is high as well as the amount of northern red oak, it is likely that infestation could occur. If the trees are healthy, it is much less likely that the borers can damage them to the point of death.
**Table 1.** All variables tested, biotic and abiotic with descriptions. Biotic variables were field collected or obtained from USDA Forest Service’s CISC database. Abiotic variables were gathered from other sources of automated mapping data.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Average REI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sq ft/acre NRO</td>
<td>Square feet per acre of northern red oak in each plot</td>
</tr>
<tr>
<td>Sq ft/acre oak</td>
<td>Square feet per acre of oak in each plot</td>
</tr>
<tr>
<td>Sq ft/acre total</td>
<td>Square feet per acre of all oaks in each plot</td>
</tr>
<tr>
<td>Percent NRO</td>
<td>Percent of northern red oak in each plot</td>
</tr>
<tr>
<td>Percent Oak</td>
<td>Percent of all oak except northern red oak in each plot</td>
</tr>
<tr>
<td>No. NRO</td>
<td>Number of northern red oak in each plot</td>
</tr>
<tr>
<td>Total sq ft/acre</td>
<td>Total square feet per acre of all trees in each plot</td>
</tr>
</tbody>
</table>

**Biotic Variables**

<table>
<thead>
<tr>
<th>Land Class</th>
<th>Values assigned by USDA Forest Service to represent different types of land (lakes, public parks, wildlife openings, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest Type</td>
<td>Values assigned by the USDA Forest Service to represent the dominant tree species growing in each area (red oak-white oak-hickory, pine, etc.)</td>
</tr>
<tr>
<td>Stand Condition</td>
<td>Classes assigned by USDA Forest Service to represent types of trees growing in the area (damaged poletimber, forest pest infestation, seedling, sapling, etc.)</td>
</tr>
<tr>
<td>Age Year</td>
<td>Year a stand was last clear-cut</td>
</tr>
<tr>
<td>Management</td>
<td>Numbers assigned by the USDA Forest Service to represent the way the land is managed</td>
</tr>
</tbody>
</table>

**Abiotic Variables**

<table>
<thead>
<tr>
<th>Aspect</th>
<th>Direction a slope faces, ridges included as a separate aspect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine Aspect</td>
<td>Sine of the degree that a slope faces</td>
</tr>
<tr>
<td>Cosine Aspect</td>
<td>Cosine of the degree that a slope faces</td>
</tr>
<tr>
<td>Elevation</td>
<td>Elevation of each point, in meters</td>
</tr>
<tr>
<td>Slope</td>
<td>Degree of steepness of the slope</td>
</tr>
<tr>
<td>Available Water Capacity</td>
<td>Available water capacity, an average of high and low extremes from the soils database (expressed in inches per inch for the soil layer or horizon</td>
</tr>
<tr>
<td>Clay</td>
<td>Amount of clay in the soil (expressed as a percentage of the material less than 2mm in size)</td>
</tr>
<tr>
<td>Inch10 rock</td>
<td>Percent by weight of the rock fragments greater than ten inches in the soil layer</td>
</tr>
<tr>
<td>Inch 3 rock</td>
<td>Percent by weight of the rock fragments greater than three and less than 10 inches in the soil layer</td>
</tr>
<tr>
<td>Permeability</td>
<td>Average value for the range in permeability rate for the soil layer or horizon expressed as inches per hour</td>
</tr>
<tr>
<td>Horizon Depth</td>
<td>Horizon depth, the depth to the bottom of the lowest layer of soil (expressed in inches)</td>
</tr>
<tr>
<td>Texture</td>
<td>Soil texture, originally in letter symbols. Each letter symbol was replaced by a number</td>
</tr>
<tr>
<td>Roads</td>
<td>Straight-line distance to roads in meters</td>
</tr>
<tr>
<td>Streams</td>
<td>Straight-line distance to streams in meters</td>
</tr>
</tbody>
</table>
Table 2. Significant variables resulting from analysis to predict red oak borer infestations with accompanying standard errors, t-values, predicted values and confidence intervals.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Estimate</th>
<th>Error</th>
<th>t-value*</th>
<th>p-value</th>
<th>Lower C.I.</th>
<th>Upper C.I.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>.9541</td>
<td>.1055</td>
<td>9.05</td>
<td>&lt;.0001</td>
<td>.7466</td>
<td>1.1616</td>
</tr>
<tr>
<td>Percent Oak</td>
<td>.0166</td>
<td>.0025</td>
<td>6.51</td>
<td>&lt;.0001</td>
<td>.0116</td>
<td>.0216</td>
</tr>
<tr>
<td>Ba. Area NRO</td>
<td>.0049</td>
<td>.0020</td>
<td>2.42</td>
<td>.0160</td>
<td>.0009</td>
<td>.0089</td>
</tr>
<tr>
<td>Sine Aspect</td>
<td>-.2203</td>
<td>.1015</td>
<td>-2.17</td>
<td>.0306</td>
<td>-.4199</td>
<td>-.0207</td>
</tr>
</tbody>
</table>

*t-value is testing the hypothesis that the estimate is zero
Figure 1. Continuous Inventory of Stand Conditions (CISC) data from U.S.D.A. Forest Service shows the number of different oak-hardwood type stands. Also illustrates the large amount of oak in the Ozark National Forest, particularly the white oak-red oak-hickory forest type shown in brown.

Figure 2. Aerial photo from USDA Forest Service of North-central Arkansas taken October 3, 2000, illustrates large concentrated areas of tree damage due to oak-decline.

Figure 3a. Hillshade example with light source in the east (45°). This was used in conjunction with Figure 5b, west-lit hillshade for determination of ridge-top plots.

Figure 3b. Hillshade example with light source in the west (315°). This was used in conjunction with Figure 5a, east-lit hillshade for determination of ridge-top plots.

Figure 4. All prism plots obtained from the USDA Forest Service as well as the UA forest entomology lab, with categorized rapid estimation values showing damage levels for each plot. More borer holes in the lower two meters of the tree bole and a higher percentage of crown dieback results in a higher rapid estimation index, meaning the area has sustained more damage from red oak borer.

Figure 5. Residual plot: predicted values vs. difference in observed and predicted. The plot indicates the values are randomly scattered about the fitted curve. The downward-sloping point sequences are due to repeated observed values.