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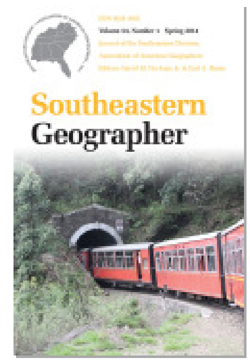

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Spatial Trends and Factors Associated with Hardwood Mortality in the Southeastern United States

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Hardwood species play an integral role in forested ecosystems in the southeastern United States. This necessitates an assessment of mortality patterns in these species as well as factors associated with them. This study assessed mortality patterns for hardwood species utilizing Forest Inventory Analysis (FIA) data from the United States Forest Service for two consecutive inventory cycles using kernels smoothing and Classification and Regression Tree (CART) modeling. The first inventory cycle (2000–2004) reveals a patterns and associated factors that can be associated with decline events that have recurred throughout the region while the second inventory cycle (2005–2009) exhibits a different pattern in mortality than cycle one. Mortality patterns and their associated factors should be monitored in the hope that methods can be developed to mitigate extreme impacts to these vitally important species.

*Las especies de madera dura juegan un papel fundamental en los ecosistemas forestales en el sureste de los Estados Unidos. Esto requiere una evaluación de las tendencias de la mortalidad en estas especies, así como los factores asociados a éstas. Este estudio evaluó las tendencias de mortalidad para las especies de madera dura utilizando análisis de inventario de bosque (*Forest Inventory Analysis*), datos del Servicio Forestal de los Estados Unidos durante dos ciclos consecutivos de inventario utilizando modelos* kernels smoothing *y* Classification and Regression Tree *(CART). El primer ciclo de inventario (2000–2004) revela una tendencia y factores asociados que pueden estar asociados con la disminución de eventos que se han repetido en toda la región, mientras que el segundo ciclo de inventario (2005–2009) exhibe una tendencia diferente en la mortalidad del ciclo uno. Estas diferencias podrían deberse a fenómenos meteorológicos extremos (como huracanes) que afectaron la región durante el segundo ciclo de inventario. Las tendencias de mortalidad y sus factores asociados deben ser monitoreadas con la esperanza de poder desarrollar métodos* *para mitigar los impactos extremos de estas especies de vital importancia.*

KEY WORDS: Oak Decline, Mortality, Kernel Smoothing, CART

PALABRAS CLAVE: Descenso de Robles, Mortalidad, Kernels Smoothing, CART

INTRODUCTION

Forests are an economically and ecologically important feature of the southeastern United States. Southern U.S. forests account for approximately 60 percent of timber harvested in the United States annually (Smith et al, 2009). Hardwood forests, which comprise approximately 55 percent of all forested areas in the southern United States, are of particular importance (Wear and Greis 2012). Hardwood species, particularly those belonging to the oak genus (*Quercus* spp.), provide materials for a variety of wood products ranging from pulp for paper production to veneers (Patterson 2004). Beyond their use for products, oak species provide habitat for a wide variety of wildlife species and provide food via acorn production for species such as the white-tailed deer (*Odocoileus virginianus*; Feldhamer 2002; Clark 2004).

Hardwood forests are impacted by a variety of events that may lead to high mortality rates. Oak decline events, attributed to a disease complex (Manion 1991), have impacted southeastern U.S. forests periodically in past decades (Oak et al. 2004). Decline events can be incited by drought, defoliating insects, frost, or stand disturbance that lead to widespread impacts on oak species, particularly those in the red oak group; these events can cause lead to crown dieback (loss of biomass in the crown of a tree) and in some instances lead to the death of over half of the live basal area (Spetich 2004; Johnson et al. 2009). Decline can be further exacerbated by contributing factors such canker fungi, boring insects, or root disease (Oak et al. 2004; Fan et al. 2008; Haavik et al. 2011). In addition to biotic factors leading to or exacerbating oak decline, abiotic factors such as drought, ice storms, hurricanes, and tornadoes that frequently impact various portions of the southeastern United States can also trigger or worsen decline events. Severe storms can have devastating impacts on forests due to wind throw (Greenberg et al. 2011) and lead to the release of large amounts of carbon into the atmosphere (Crosby et al. 2008). Further, canopy gaps that result from wind-thrown trees can provide initiation points for impact by invasive species; damage resulting from Hurricane Rita in 2005 is thought to have influenced the spread of Chinese tallow (*Triadica sebifera*) throughout portions of southeast Texas (Fan et al. 2012a). Drought can also serve as an inciting factor and lead to elevated levels of mortality. The Ozark Highlands were the focus of a study where drought served as the primary factor leading to increased rates of mortality for a variety of oak species (Fan et al. 2012b). The eastern U.S. has also been impacted by decline events and drought that have led to elevated mortality rates (Starkey et al. 1989; Klos et al. 2009).

Regardless of whether mortality is influenced by a decline-type event or results from large scale natural disturbance, it is important that mortality trends and potential explanatory factors be understood. The United States Department of Agriculture, Forest Service, Forest Inventory

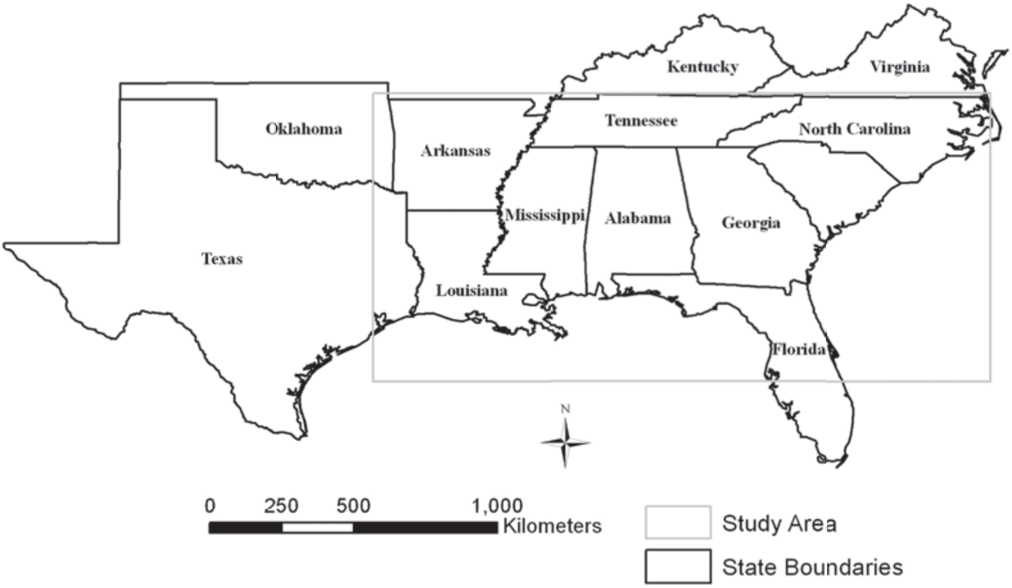

Figure 1. Study area in the southeastern United States.

and Analysis (FIA) program serves the nation by providing forest inventory data throughout the United States. FIA inventory plots measure a variety of variables including biometric data for all trees located on sample plots (e.g., diameter at breast height (dbh), height, etc.) as well as tree status (live vs. dead) and cause of mortality (see Bechtold and Patterson (2005) for details on FIA sampling program). The objectives of this study were to determine 1) the spatial pattern for mortality and 2) possible explanatory factors and differences between various species groups for two consecutive five-year FIA inventory cycles in the southeastern U.S. This study has implications for projections of future hardwood forest management through the determination of potential relationships between mortality and a number of easily obtained inventory variables.

METHODOLOGY

The study area encompasses portions of 10 states (Alabama, Arkansas, Florida, Georgia, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas; Figure 1) and covers a variety of forest cover and land uses. In an effort to assess factors related to oak mortality, FIA data were obtained for the states in the study area (http://apps.fs.fed.us/fiadb-downloads/datamart.html). The FIA database was queried to obtain plot locations (i.e., latitude and longitude) and a number of inventory variables (i.e., dbh, height, physiographic class, forest type, status (live or dead), species group and individual species found on plots). Basal area was then calculated for each plot (or for each species on each plot) and the percentage of dead basal area (dead trees counted in each inventory cycle) was calculated as a surrogate for mortality (Equation 1). After data extraction and basal area calculations, the data were divided by inventory cycle (Cycle 1, 2000–2004; Cycle 2, 2005–2009) and then into four groups consisting of 1) all hardwood species, 2) all oak species, 3) red oak species only, and 4) white oak species only. Calculations of dead basal area were then made for each group. This allowed for an assessment of changing mortality patterns and differences in significant factors associated with mortality between the two inventory cycles.

$$\%\text{ Dead Basal Area} = \frac{\text{Basal Area of Dead Trees}}{\text{Total Basal Area of All Trees}} \times 100 \quad (1)$$

To determine the spatial patterns for mortality and the factor associated with mortality in the various groups between the two inventory cycles, R statistical software was utilized. Specifically, the "stats" package was utilized to perform kernel smoothing (R Core Development Team, 2012) and Classification and Regression Tree (CART) analysis was accomplished via the "rpart" package (Therneau et al. 2012). Gaussian kernel smoothing was utilized to visualize spatial patterns in mortality by a local averaging of data by using a non-parametric "weighted moving average of the kernel" (Wand and Jones 1995) that serves to estimate the density of a variable. The estimate at some location, x, is given by the kernel density estimator

$$K(x) = \prod_{i=1}^{n} \frac{1}{h\sqrt{2\pi}} e^{\frac{(x-x_i)^2}{2h^2}} \quad (2)$$

where K is the kernel function, h is the smoothing parameter (bandwidth), x_i is the relative mortality, and e is the base of the natural logarithm. Kernel smoothing provides an appropriate, robust method for assessing mortality patterns utilizing FIA data (Fan et al, 2012b; Fan et al. 2013) by providing mortality estimates in areas where there are no current inventory plot locations. CART models are utilized to assess the impact on the response variable (i.e., percent dead basal area) of numerous explanatory variables (e.g., height, dbh, forest type, species, etc.; De'ath and Fabricius 2000). Each group was analyzed in each inventory cycle beginning with the whole dataset. The data were then partitioned based on the homogeneity of splits in the data (Steinberg and Colla 1997). Trees produced are then pruned by measuring the level of accuracy enhancement contributed by a split to the regression tree (i.e., cost-complexity parameter, see Steinberg and Colla 1997). A more easily understandable tree is then produced, in which significant relationships between the response variable, percent dead basal area, and the factors of interest can be assessed. For this study, we present the variables associated with the greatest amount of mortality for each group as a table.

RESULTS AND DISCUSSION

Cycle 1

In cycle one (2000–2004), the greatest amount of dead basal area for all hardwoods occurred across portions of north Alabama, central South Carolina, and western/central North Carolina. The mortality patterns indicated for hardwood species shows greater mortality throughout Alabama, northern Georgia, eastern Tennessee, and the Carolinas (Figure 2a). The results of the CART model provide more detailed estimates of mortality and

Figure 2. Mortality pattern for all hardwood species (a), all oak species (b), red oak species (c), and white oak species (d) in the southeastern United States for the years 2000–2004.

the associated variables than can be ascertained from the patterns found via kernel density. The highest percent dead basal area (19.2%) occurred in hardwood species between 12.7 cm (5 in) and 23.1 cm (9.1 in) dbh for 48 species, most notably a variety of maples (*Acer* spp.), hickories (*Carya* spp.), green ash (*Fraxinus pennsylvanica*), yellow poplar (*Liriodendron tulipifera*), scarlet oak (*Quercus coccinea*), southern red oak (*Quercus falcata*), chestnut oak (*Quercus prinus*), and northern red oak (*Quercus rubra*) (Table 1). There was also a host of noncommercial species (e.g., flowering dogwood (*Cornus florida*), American holly (*Ilex opaca*), etc.) contributing to the greatest level of mortality among all hardwoods.

The spatial pattern of the oak species group (*Quercus* spp.) is similar to that of all hardwoods (Figure 2b), with the greatest amount of dead basal area being found in trees greater than 24.1 cm (9.5 in) dbh, and height greater than 17.1 m (56 ft), and species found primarily in pine and oak/hickory forest types (Table 1). An area encompassing northern Alabama and Georgia, eastern Tennessee and west/central portions of North and South Carolina have the greatest levels of mortality. This is an area of concern as the southern and eastern portions of the U.S. are impacted by large-scale oak decline events (Oak 2004). The factors associated with the greatest percentage of mortality (dbh greater than 24.1 cm and height greater than 17.1 m) indicates that larger, likely older, trees are being lost. Various wildlife species depend upon oak mast for sustenance; widespread loss of oaks can significantly impact mast yields (Oak et al. 1988) and have implications for wildlife populations such as black bear (*Ursus americanus*) and white-tailed deer in the southeastern United States (Feldhamer, 2002; Clark 2004).

Species in the red oak group generally follow a pattern similar to that of all oaks (Figure 2c). Factors contributing to the greatest percentage of dead basal area are dbh greater than 33.3 cm (13.1 in), average height of at least 17.6 m (57.8 ft), and species found primarily in pine, oak/pine, and oak/hickory forest types (Table 1).

Table 1. CART results showing factors associated with greatest mortality amounts in cycle 1.

Group	Factors Associated with Highest Mortality	Mortality (%)
All Hardwoods	12.7 cm ≤ Average dbh < 23.1 cm	19.2
	Species (48 individual species)	
All Oaks	Average dbh > 24.1 cm	20.2
	Average height ≥ 17.2 m	
	Forest Type	
	Average dbh ≥ 33.3 cm	
Red Oak Species	Average height ≥ 17.6 m	20.4
	Forest Type	
White Oak Species	Average dbh ≥ 7.4 cm	20.8
	Forest Type	

These trees are approaching sawtimber size, and increased mortality could impact the availability of quality lumber, veneers, and other products derived from these species. Most upland areas through Arkansas, Georgia, Tennessee, and the Carolinas have mortality rates above 15 percent. Also, greater levels of mortality were detected in the Ozark Highlands area in northern Arkansas where mortality rates are three to five times higher than average mortality of approximately one percent annually (or five percent over a five year period). This aligns with findings of previous studies focusing on red oak species in this area (Shifley et al. 2006; Fan et al. 2012b). Greenberg et al. (2011) reported approximately 24 percent of species in the red oak species group were dead in an area of western North Carolina during the period from 1991–2006. There have been multiple oak decline events that seem to impact red oak species to a greater degree than other species, particularly white oak species. This study does not address the cause of mortality. However, decline events and wind throw typically impact larger, older trees to a greater degree than smaller trees (Greenberg et al. 2011). It is also possible for a variety of stress factors (e.g., drought and/or insects) to lead to large-scale mortality.

White oak species mortality is highest in eastern Texas, east-central Mississippi, and northern Alabama (Figure 2d). DBH of at least 7.4 cm (2.9 in) in shortleaf pine or oak/hickory forest types are the factors associated with the greatest mortality (Table 1). In comparison with red oak species, species in the white oak group have less mortality in the Ozark Highlands area of Arkansas and western North Carolina as reported previously (Greenberg et al. 2011; Fan et al. 2012). The smaller dbh included in the CART model could indicate that seedlings are contributing to greater mortality within the forest types listed. The reasons for the differences in red oak and white oak species are thought to be related to red oak species susceptibility to oak borer attack (Fan et al. 2008) and drought (Fan et al. 2012b) as well as ecological land type (Kabrick et al. 2007).

Cycle 2

The spatial patterns and significant variables differ greatly for cycle two (2005–2009) than those seen in cycle one. For all hardwood species, the spatial pattern shows mortality greater than 10 percent across large portions of northern Georgia and western North and South Carolina (Figure 3a). There is also a large swath of southern Mississippi that has greater levels of mortality. When considering all oak species, the area exhibiting greater than 15 percent mortality expands into most of Tennessee, central Mississippi, and central and northern Arkansas, covering the Ozark Highlands (Figure 3b). The highest mortality levels for red oaks species (Figure 3c) are concentrated in areas of the Appalachians and Ozark Highlands with several pockets of mortality above 25 percent in Mississippi. White oak mortality patterns differ from red oak species slightly (Figure 3d) by having a larger area of mortality in portions of Alabama and less expansive areas across the upland areas in the Ozarks and Appalachians.

The variables related to the greatest amount of mortality are the same for all groups considered, that is dbh greater than 12.7 cm (5 in) with an average mortality ranging between 15.5 and 15.9

Figure 3. Mortality pattern for all hardwood species (a), all oak species (b), red oak species (c), and white oak species (d) in the southeastern United States for the years 2005–2009.

Table 2. CART results showing factors associated with greatest mortality amounts in cycle 2.

Group	Factors Associated with Highest Mortality	Mortality (%)
All Hardwoods	Average dbh ≥ 12.7 cm	15.9
All Oaks	Average dbh ≥ 12.7 cm	15.6
Red Oak Species	Average dbh ≥ 12.7 cm	15.5
White Oak Species	Average dbh ≥ 12.7 cm	15.8

percent (Table 2). The spatial patterns indicate that elevation may play a role, considering the areas of greater mortality in the Ozark and Appalachian mountains for oak species. The analysis could also be confounded by significant droughts that impacted the regions prior to and during the two inventory cycles, particularly in the Ozark Highlands. The areas of relatively greater damage across portions of Mississippi and eastern Texas/western Louisiana are likely attributable to hurricanes Katrina and Rita that impacted these areas in 2005.

POTENTIAL CAUSAL FACTORS RELATED TO MORTALITY

The mortality patterns and associated factors observed in cycle one show that larger trees (i.e., those that are taller and/or have larger dbh) exhibited higher levels of mortality. It is suspected that drought could lead to such a region-wide pattern in mortality. Previous studies in the Ozark Highlands as well as areas in the eastern United States indicate that mortality increases area associated with periods of drought (Klos et al. 2009; Fan et al. 2012). A temporal lag of 2–5 years exists between the onset of drought and the impacts seen in (particularly) hardwood species mortality (Wargo et al. 1983) with subsequent drought periods further exacerbating mortality (Fan et al., 2012). The Ozark Highlands saw significantly higher levels of mortality, particularly for red oak species, following periods of drought (Fan et al., 2012b) and the eastern U.S. greater mortality rates related to drought severity, slope, and density (Klos et al. 2009). The southeastern U.S. a period of drought from 1998 to 2002 that could lead to increased mortality beginning in 2002. The greater mortality found across portions of northern portions of Alabama and Georgia and eastern Tennessee and western North Carolina could be a result of such drought conditions and align with previous findings in the regions that indicate drought and increased annual temperature range could be inciting factors leading to mortality (Crosby et al. 2012).

Older trees generally have a higher susceptibility to mortality in poor site conditions (e.g., sandy soils, dry ridge tops), during periods of drought, and during extreme weather events (e.g., ice storms, severe wind events, etc.) (Johnson et al. 2009). In this study, larger trees have higher mortality levels, as evidenced by the CART results; therefore, the factors related to the mortality patterns align with previous findings if tree size is accepted as a proxy for age (i.e., that larger trees are typically older). Oak wilt is another factor that can lead to rapid mortality in forests in the southeastern U.S. and through 2005, has been found in most states in the study area (na.fs.fed.us/fhp/ow/maps/ow_dist_fs.shtm). Other factors exist that can lead to greater levels of mortality across various portions of the study area. Ice storms periodically impact the region and can cause extensive widespread damage (Bragg et al. 2003) and serve as an inciting factor for further damage. The gypsy moth (*Lymantria dispar* (Linnaeus)), a very efficient defoliator whose infestations can lead to mortality, has been quarantined in portions of North Carolina and is beginning to encroach into other areas in the southeastern United States (see Johnson et al. 2009). Another factor that can lead to mortality is a reduction growth rate. Dendrochronological evidence suggests that reduced growth rates result from growing-season drought (Speer et al. 2009). A reduction in growth rate impacts overall tree health and could serve as a catalyst for widespread mortality.

Extreme wind events can cause immediate mortality or stress trees through defoliation and further damage that does not cause immediate death but sufficiently stresses the tree so that it eventually dies. Tornadoes impact the southeastern United States regularly and can cause destruction to many thousands of acres (Wilkinson and Crosby 2010). Additionally, hurricanes cause widespread destruction and lead to many years of recovery for forested areas. This is particularly notable when looking at red oak species mortality in cycle two (Figure 3c). There are several areas of mortality greater than 15 percent with some areas having approximately 30 percent mortality that nearly follow the track of Katrina. Hurricane Katrina damaged approximately 44,000 acres of hardwood timber alone when it made landfall along the Mississippi Gulf Coast in 2005; approximately 9 million tonnes of timber (includes all timber types) was damaged in Mississippi alone (Crosby et al. 2008). Further, the downed/damaged timber and lack of rainfall in the months following Katrina led to an increase in wildfires in southern Mississippi that led to additional acreage being damaged (Cooke et al. 2007). Previous research has found that wind throw has a greater impact on red oak species than decline related symptoms (Greenberg et al. 2011). This could offer one possible explanation as to why the areas of highest damage follow such patterns. Further stresses and large-scale mortality events, coupled with potential climate change and/or changes in fire regimes (e.g., fire exclusion), could lead to changes in forest composition across forested areas in the region. While this study considered all non-harvest mortality together, future studies should consider both climate/weather impacts and causes of mortality (i.e., harvesting vs. natural disturbance), which are obtainable from the FIA database, to better explain the causes of regional changes in decreased basal areas within species groups.

CONCLUSIONS

This study presented the spatial patterns of mortality over the course of two five-year inventory cycles and variables related to mortality levels for four species groups. The use of kernel smoothing provides an accurate means of determining spatial patterns in mortality as noted by comparisons to previous studies (Greenberg et al. 2011; Fan et al. 2012b). While the CART models show differences between variables related to the highest mortality levels during the two cycles, they only provide a general idea of the variables that are associated with the greatest mortality levels. The relationship between mortality and abiotic causes (e.g., drought, wind-throw) may exist, particularly during the second inventory cycle and should be considered in future analyses. Preliminary study for one group (red oak species) has shown that there is a relationship between mortality and drought across the region (Crosby et al. 2012) but more extensive analysis should be conducted to see if that trend extends to other groups.

Regardless of cause, oak mortality across portions of the southeastern United States is extensive. As variables from cycle one indicate, larger trees are succumbing due to any number of causal factors. This can lead to a variety of potential impacts. Most immediate are impacts to wildlife that rely on hardwood species for nesting habitats, cover and as a source of food. Over the long-term, loss of larger trees (specifically oaks) in the overstory and understory will negatively impact species dominance in the overstory. Shade tolerant species could become dominant and impede regeneration and overstory recruitment of shade intolerant oak species. Large-scale loss of oak species not only reduces seed sources for regeneration but could also significantly diminish biodiversity and future economic opportunities for landowners and managers.

As this study has shown, for both inventory cycles, large areas of the southeast have mortality levels greater than 15 percent for trees that are greater than seedling size (that is greater than 12.7 cm (5 in) dbh). These mortality rates, when annualized, are three times higher than the average mortality rates for most hardwood species. This information can be useful to natural resources managers by highlighting areas that may have few or no FIA sample sites but, based on our analysis, warrant monitoring for signs of increased mortality. Future research should also consider climate information such as drought, temperature extremes, and/or impacts by severe storms. Continuous monitoring is important and will hopefully lead to methods to prevent large scale declines or at least mitigate or manage the impacts on these vitally important species.

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