

A Remote Sensing–Assisted Risk Rating Study to Predict Oak Decline and Recovery in the Missouri Ozark Highlands, USA

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Abstract: Forests in the Ozark Highlands underwent widespread oak decline affected by severe droughts in 1999–2000. In this study, the differential normalized difference water index was calculated to detect crown dieback. A multi-factor risk rating system was built to map risk levels of stands. As a quick response to drought, decline in 2000 mostly occurred in stands at low to medium risk, which often recovered within a few years. Decline in 2003, as longer-term response to drought, dominated in stands at medium to high risk. This study demonstrates that remote sensing can be applied to predict oak decline and to mitigate damage before another stressor event occurs.

INTRODUCTION

Oaks (*Quercus* L. spp) are of the dominant tree species of the Central Hardwood Forests in the United States. They are distributed widely throughout the eastern U.S., and have a high timber value. Furthermore, oak forests provide unique habitats for numerous wildlife species and services for human recreation (Starkey and Oak, 1989). However, oak forests are experiencing decline due to numerous historical and management reasons (Millers et al., 1989). As a result of periodic dieback and mortality of oak species in the overstory, oak decline has become one of the most widespread and complex problems in the Central Hardwood Forests (Wargo et al., 1983).

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Trees affected are mostly in the red oak group (*Quercus* section *Lobatae*), including northern red oak (*Quercus rubra* L.), southern red oak (*Quercus falcate* Michx.), scarlet oak (*Quercus coccinea* Muenchh), and black oak (*Quercus velutina* Lam.) (Oliveria et al., 2001). Trees in the white oak group (*Quercus* section *Quercus*) live longer and are much less affected by the stress (Shifley and Smith, 1982; Starkey et al., 2004).

The Ozark Highlands is a rugged and hilly region extending across southern Missouri, northern Arkansas, northeastern Oklahoma, and southeastern Kansas (Keys et al., 1995). The Highlands are dominated by old oak-hickory forests primarily regenerated from cutover of shortleaf pine (*Pinus echinata* Mill.) forests and abandoned agricultural lands during the Great Depression in the 1930s (Cunningham and Hauser, 1989). A severe episode of oak decline occurred in the interior Highlands region of Arkansas and Missouri, triggered by a continuous drought in 1999 and 2000 (Mielke, 2000; Oliveria et al., 2001). Following this severe drought, millions of red oak borers (*Enaphalodes rufulus* Haldeman) emerged in summer 2001 and became a significant pest agent contributing to oak decline (Lawrence et al., 2002). With aerial sketch map surveys in 2000, the USDA Forest Service detected up to 300,000 gross acres of red oak forests in Arkansas and 100,000 acres in Missouri that have exhibited moderate to severe oak decline and mortality (Mielke, 2000; Starkey et al., 2004; Dwyer et al., 2006). Data from 2000 and 2002 plot re-measurements on the Ozark National Forest in Arkansas showed that mortality and dieback continued after drought, and an additional 16–20% of basal area per acre died within three years. Many red oak stands with high basal area have experienced nearly 100% mortality (Starkey et al., 2004).

Based on *in situ* surveys and field measurements, intensive studies have been conducted to identify primary factors associated with oak decline in upland hardwood forests. Different results have been reported. Oak et al. (1996) found that a set of biophysical and environmental variables—such as soil clay content, soil depth, slope, aspect, oak dominance, tree age, and site index (height of red oak tree when it is 50 years old)—were associated with oak decline. Starkey and Oak (1989) noted that oak dieback was present on all topographic-position categories (ridge, slope, bench, terrace, and bottom), although plots with the highest incidence of mortality often occurred on west and northwest aspects, least on northeast and east aspects, and intermediate in southeast to southwest aspects. Contrarily, Manion (1991) found south slopes and ridgetops to be high-risk sites, north slopes medium-risk sites, and toe slopes and floodplains as low-risk sites. Starkey and Oak (1989) reported that aspect was not statistically correlated with decline and was one of the weakest factors associated with oak decline. Some studies showed that oak mortality was also significantly related to tree crown class, tree diameter, and recent rate of growth (Shifley et al., 2006; Kabrick et al., 2004), while others suggested that the number of large stems and basal area per acre were not correlated to increased mortality (Starkey and Oak, 1989). Oak et al. (1996) reported a logistic regression procedure to correlate the incidence of oak decline to slope, clay content in soil, and oak basal area. However, this procedure yielded low correlation when applied to the Ozark Highlands ($R^2 = 0.32$ based on 25 stands surveyed in this region).

The discrepancy of these studies in addressing primary factors of oak decline was attributed to complex site and forest conditions, limited field plots, and discrete

observations on the ground. As an alternative, optical remote sensing provides an effective tool to document the continuous extent of oak decline in large areas, which could be better used in risk studies.

Oak mortality could be easily detected with multi-temporal satellite images when trees are completely dead and no green foliage is observed. However, oaks in crown dieback often have similar spectral responses as healthy trees and cannot be easily detected in moderate-resolution satellite images. Water absorption bands of satellite images could be used to detect water deficiency (Wang et al., 2007). Sims and Gamon (2002) identified several wavelength regions (950–970 nm, 1150–1260 nm and 1520–1540 nm) that had the best overall correlations with water content. With these “water bands,” numerous spectral indices have been developed to predict plant water status, such as relative water content and leaf water potential (Cibula et al., 1992; Penuelas et al., 1996; Ustin et al., 1998). If water deficiency of canopies could be detected with these bands, crown dieback and tree mortality, the phenomena closely related to water deficiency in affected forests, can be efficiently mapped using satellite imagery. By examining environmental and ecological conditions in declining forests, the driving factors could also be evaluated to predict the risk of oak decline in forests under current conditions. With proper silvicultural managements in high-risk forests, the damage could be mitigated before next cycle of stress occurs.

In this study, we develop a risk rating system based on a series of biophysical variables in a forest in the Ozark Highlands. A normalized difference water index (NDWI) in near-infrared and short-wave infrared bands was first applied to detect oak crown dieback, an indicator of oak decline. The biophysical properties in decline sites were then examined to identify the potential risk factors. A multi-factor risk rating system was finally developed to forecast the risk of decline of forest stands in the study area. From 2000 to 2003, new decline, persistent decline, and recovery were also compared with the rated risk levels in affected stands to explain post-drought decline and recovery processes.

STUDY AREA AND DATA SETS

The study area is the Salem-Potosi Ranger District, one of the seven ranger districts of the Mark Twain National Forest in the northern Ozark Highlands (Fig. 1). With an area of more than 200,000 acres, the district covers six counties in Missouri: Crawford, Dent, Iron, Reynolds, Shannon, and Washington. The major land cover type in the study area is eastern upland hardwoods, primarily composed of oak species including red oak, white oak, and black, scarlet, and post oak (USDA Forest Service, 2002). Conifers such as shortleaf pine are not abundant. Open grassland is the second largest land cover type in the study area. Human construction and cropland cultivation are quite limited. Logging, especially salvage logging in declining forests, is the major forest management practice. However, for practical reasons, salvage operations can only mitigate a relatively small percentage of the study area (Lea, 2005). Due to a lack of detailed logging records, human-induced forest changes are not considered in this study.

The study area is located in the Current River Hills and the Meramec River Hills ecological subsections (Keys et al., 1995). The predominant topographic features in the study area are broad ridges of the Ozark Mountains, characterized by ridgetops

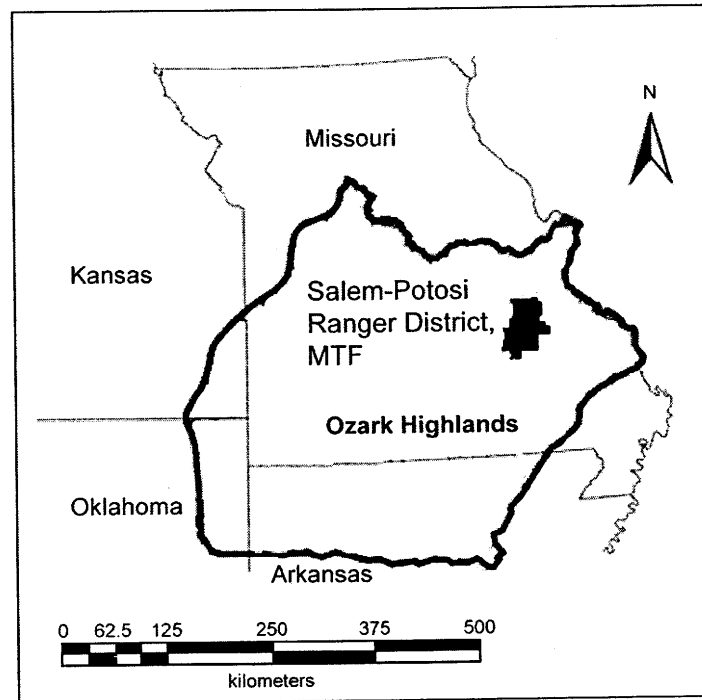


Fig. 1. The Salem-Potosi Ranger District in the Mark Twain National Forest, northern Ozark Highlands.

and abundant karst features. Soils vary considerably, but many are gravelly and generally have a low water and nutrient supply (Rafferty, 1980). Scarlet oak and black oak are typically the dominant tree species in the sawtimber size class (i.e., > 30 cm diameter at breast height) and are commonly 70–90 years old. These forests are especially susceptible to stresses such as drought and pests (Kessler, 1992; Oliveria et al., 2001).

Heavy oak decline was observed following the severe drought in 1999–2000, along with increased populations of red oak borer in 2001 (Oliveria et al., 2001). According to Mielke (2000), the Salem/Potosi district has experienced the most severe decline of black and scarlet oaks within the Mark Twain National Forest. In September 2000, more than 16,000 acres of mortality were mapped via aerial survey in the district. More areas were heavily affected by wood borer damage by December 2001 (Mielke, 2000; Oliveria et al., 2001; Lawrence et al., 2002).

A series of Landsat TM and ETM+ images (10/03/1992, 10/01/2000, and 09/24/2003) were analyzed to map the onset and partial recovery from oak decline. Forests in 1992 were assumed to be relatively healthy and served as reference in this study, although it should be noted that there was another episode of drought in the mid-1980s, and forests in 1992 might have suffered from that drought. Atmospheric effects of these images were corrected with the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) program (Vermote et al., 1997). To further reduce the temporal variation in the images, the 2000 and 2003 images were normalized to

the 1992 image with a histogram match algorithm (Helmer and Ruefenacht, 2005). Geometric distortion of the three images was corrected with the rectified 1 m Digital Ortho Quarter Quad (DOQQ) airphotos. The overall root-mean-square error (RMSE) was less than 15 meters.

Forest inventory data in a GIS resource database were requested from the Mark Twain National Forest, USDA Forest Service. The database contained spatial information of individual stands, topographic features, species composition, and biophysical information such as tree age, basal area, and site index for each stand. The inventories were re-measured every 10–20 years by local foresters to develop and implement management systems in public forests. These data were combined with satellite-detected decline patches to examine primary risk factors of oak decline.

APPROACH

Responding to the severe drought in 1999–2000 and increased populations of red oak borer in subsequent years, major forest changes in the study area included oak mortality, crown defoliation, and recovery from previous stresses. Non-forest areas were identified from the Missouri Land Use Land Cover (LULC) map in 1993, published by the Missouri Resource Assessment Partnership (MoRAP). All classes except broadleaf forests in the LULC map were treated as non-forests and were masked out in following processes.

Oak Decline Mapping

Oak mortality and regrowth can be easily classified using regular LULC mapping techniques (Wang et al., 2007). Oak crown dieback, a very common indicator of oak decline, was rather a process of gradual degradation. For years before mortality, oak canopies remained green, although with less foliage than healthy trees. Oaks in declining forests could also recover and foliage appeared to be healthy within a few years (Spetich and He, 2008). Gradual change of degradation or recovery cannot be effectively mapped with binary classification in regular LULC mapping techniques.

When affected by drought, leaves of oak species desiccated and resulted in significantly higher reflection in SWIR (Jensen, 2000, p. 209). The Normalized Difference Water Index (NDWI) was thus more helpful in detecting crown dieback and recovery (Gao, 1996; Sims and Gamon, 2003). The NDWI was calculated as:

$$NDWI = \frac{NIR - SWIR}{NIR + SWIR} \quad (1)$$

In this study, we applied Band 5 (1.55–1.75 μm) and 4 (0.76–0.9 μm) of the Landsat images to represent SWIR and NIR in Equation 1. Band 7 (2.08–2.35 μm) was not used because of its high sensitivity to atmospheric conditions.

Using the NDWI image in 1992 as a reference, the 2000 and 2003 NDWI images were normalized with histogram match. The differential NDWI (ΔNDWI) could then be calculated:

$$\Delta NDWI_{1992-2000} = \frac{NDWI_{2000} - NDWI_{1992}}{NDWI_{1992}} \quad (2)$$

$$\Delta NDWI_{1992-2003} = \frac{NDWI_{2003} - NDWI_{1992}}{NDWI_{1992}}$$

where the subscripted numbers 1992, 2000, and 2003 represent the years of image acquisition, respectively.

The histograms of both NDWI images had a standard Gaussian distribution centered at approximately $\Delta NDWI = 0$ (Wang et al., 2007). Non-change forests had $\Delta NDWI \approx 0$, which may vary slightly because of atmospheric, radiometric, or temporal variations that cannot be fully removed via histogram match. Negative $\Delta NDWI$ in the left tail of the histogram revealed oak crown dieback and tree mortality attributed from loss of leaf moisture content. Positive $\Delta NDWI$ in the right tail of the histogram represented crown recovery of oaks from stresses in previous years. Newly planted forests fell in the very right end of the histogram while logged areas were in the very left end. Since logging/planting in the study area was limited, these human-induced forest changes were not discussed here.

In field-based studies, oak crown dieback was often grouped into three categories: slight (<33% crown dieback), moderate (33–66% crown dieback), and severe (more than 66% crown dieback) (Starkey and Oak, 1989; Dwyer et al., 2006). $\Delta NDWI$ revealed the percent variation of foliage moisture content and was closely related to crown dieback and recovery. As a result, we used the same thresholds regarding the levels of oak decline recovery:

Severe decline:	$\Delta NDWI \leq -66\%$;	
Medium decline:	$-66\% < \Delta NDWI < -33\%$;	
Healthy oak forest:	$-33\% < \Delta NDWI < 33\%$;	(3)
Medium recovery:	$33\% < \Delta NDWI < 66\%$	
Strong recovery:	$\Delta NDWI > 66\%$.	

In moderate-resolution satellite images, slightly declining or recovering forests cannot be effectively separated from healthy forests. They were merged into healthy forests in this study.

Risk Rating of Oak Decline

It was found in past studies that, when oak forests were affected by droughts and red oak borers, biophysical variables played a role in evaluating the risk of decline. After the 1992–2000 and 1992–2003 decline patches were extracted from the $\Delta NDWI$ images, large patches (>5 ha) of medium and severe decline were selected and split with polygons of predefined stands in the Mark Twain National Forest's GIS database. The resulted decline polygons thus contained attributes of topographic (aspect and slope) and biographical variables (tree age, site index, and basal area). To reduce noise and edge effects, only decline polygons larger than 1 ha were used in following statistical analysis.

A six-bin histogram of all decline polygons was constructed for each biophysical variable. The total number of decline polygons (medium and severe) was defined as D . Then, for each biophysical variable, the percentage of decline (decline%) in a certain bin of the histogram was calculated as:

$$\text{decline\%} = \frac{d_{\text{medium}} + d_{\text{severe}}}{D} \quad (4)$$

where d_{medium} and d_{severe} were the number of polygons of medium decline and severe decline in each range (bin), respectively. Here the number instead of total area of declining polygons was counted in order to give the same weight to polygons with different sizes.

In a certain range of a biophysical variable, a high value of decline% represented a large number of occurrences of decline in this range. However, it did not necessarily represent high risk of decline in this range. A large decline% value may be merely due to greater abundance of stands in such a range of biophysical features in the forest (Kabrick et al., 2008). To account for the variation of stand abundance in a risk rating, the stand percentage (stand%) of each risk range should also be considered. Similarly, the stand% can be calculated as:

$$\text{stand\%} = \frac{n}{N} \quad (5)$$

where n is the number of stands in certain range of a biophysical variable, and N is the total number of stands in the study area.

For each biophysical variable, by comparing decline% and stand% in each risk range, its risk level in this range was inferred to be:

$$\text{risk}(i, j) = \begin{cases} 3; & \text{decline\%} > \text{stand\%} \\ 2; & \text{decline\%} \approx \text{stand\%} \text{ (within } \pm 5\%) \\ 1; & \text{decline\%} < \text{stand\%} \end{cases} \quad (6)$$

where i was the i -th risk factor that was selected from biophysical variables (aspect, slope, tree age, site index, and basal area) examined in this study, and j was the j -th range (bin) in the histogram of this risk factor.

Using percent slope as an example, Figure 2 demonstrates the categorization of risk levels in Equation 6. Slope distributions of decline patches (decline%) and all stands (stand%) were extracted and compared in the figure. Around 34% of decline occurred in slope range of [15, 21] and 31% in [22, 28]. This may give the impression that oaks at slopes in these two ranges were in high risk of decline. However, as shown in the distribution of stand%, the majority of oaks in the study area grew at slopes in these two ranges (35% and 24% of all stands). As a result, we cannot simply assume that stands with large decline% were in high risk of decline. Instead, only stands at slope range [22, 28] were in high risk because its decline% was much higher

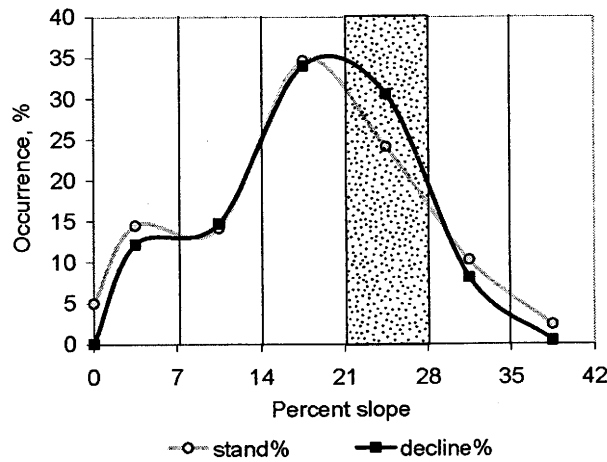


Fig. 2. Comparison of stand% and decline% to determine risk levels in Equation 5 (percent slope as an example). The only range assigned high risk (with respect to slope) was at slopes between 21 and 28%. This range is shaded in the figure.

than stand%. Based on the criteria in Equation 6, stands at slope range [8,14] and [15,21] were in medium risk while stands at other slope ranges were in low risk.

With Equation 6, each stand in public forests was assigned a risk value for each risk factor. A more comprehensive risk assessment could be made by combining individual risk factors into a single risk rating system. This was done by calculating the combined risk for all risk factors:

$$risk = \frac{\sum_{i=1}^r risk(i)}{r} \quad (7)$$

where r was the number of risk factors, e.g. the biophysical variables that played an effective role in oak decline. Risk factors were given the same weight in this study. The risk level of each stand was thus determined:

$$\begin{aligned} \text{High risk:} & \quad risk = 3 \\ \text{Medium risk:} & \quad 2 \leq risk < 3 \\ \text{Low risk:} & \quad 1 \leq risk < 2. \end{aligned} \quad (8)$$

Although the onset of oak decline can lead to tree mortality, it has been reported that some oak trees appear to recover from decline within a few years after the onset (Dwyer et al., 2006). Accordingly, we assessed the fate of decline and recovery stands in 2000–2003 after the drought. Decline polygons detected in either 2000 or 2003 were named *decline00_03*. Decline occurring in 2000 was considered a quick response to the drought, whereas decline in 2003 represented a longer-term response. All polygons were further allocated into three categories: *new_decline* (healthy forest

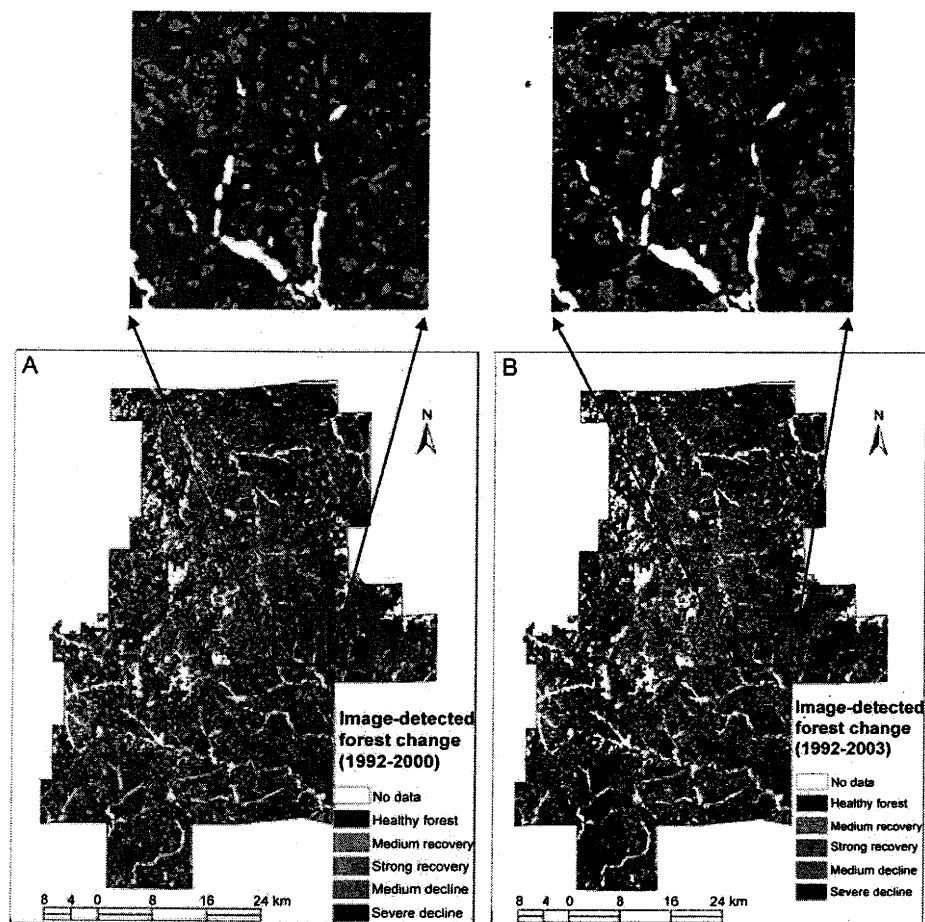


Fig. 3. Forest change maps in 1992–2000 (A) and 1992–2003 (B) derived from Landsat TM/ETM+ images. The subset in the southeastern part of the study area is displayed to show details of decline patches.

in 2000 but declining in 2003), *recovery* (declining in 2000 but recovered in 2003), and *persistent decline* (declining in 2000 that remained declining in 2003). Statistical properties of each category were studied to examine oak decline and recovery in 2000–2003 and the biophysical controls of the change in this period.

RESULTS

Forest Change Maps (1992–2000 and 1992–2003)

Based on the thresholding method in Inequity 3, four levels of forest change were identified from the Δ NDWI images: medium decline, severe decline, medium recovery, and strong recovery. In the 1992–2000 forest change map (Fig. 3A), medium and severe decline patches in various sizes were identified in many locations, especially

in the west of the study area. Recovery in the 1992–2000 forest change map represented trees that recovered from the drought or human activities such as harvesting in previous years; these patches were in much smaller size than decline patches. Recovery from the previous drought in mid-1980s may also contribute to these noisy small patches in 2000.

In the 1992–2003 forest change map (Fig. 3B), some large patches of severe decline in 2000 remained the same as in 2003, whereas others changed to medium decline or recovered to healthy forest. Small decline patches in 2000 tended to recover, and many of them could not be detected three years after the drought. More decline patches in 2003 occurred in the southeast of the study area, a possible effect of red oak borers that emerged after the drought. As shown in the two subsets, medium and severe decline often clustered into larger patterns.

The Δ NDWI-derived forest change map has been validated with the Forest Inventory Analysis (FIA) databases. Based on tree species at the FIA points surveyed in 1989 and 2003 (Hansen et al., 1992), a FIA forest change map was developed that contained 158 validation polygons in various sizes. The overall accuracy of the satellite-derived forest change map was 76%, bearing in mind that the FIA data at each point were discrete observations by USDA Forest Service crew at a rough resolution of about 3 miles (Dr. David Larsen, Department of Forestry, University of Missouri, personal comm., May 2007). Detailed steps of the comparison were described in Wang et al. (2007).

Effects of Biophysical Variables on Oak Decline

A total of 556 polygons of decline (*decline00_03*) were extracted when medium and severe decline patches in 2000 and 2003 were split with predefined stand boundaries in the Mark Twain GIS database (Fig. 4). These polygons could be grouped into three categories: (1) *new_decline* (healthy forest in 2000 and decline in 2003): 274 polygons; (2) *recovery* (decline in 2000 and healthy forest in 2003): 223 polygons, and (3) *persistent_decline* (decline in both 2000 and 2003): 59 polygons.

These data indicated that decline and recovery continuously occurred from 2000 to 2003. About 79% of decline in 2000 recovered and cannot be detected from satellite image in 2003. As a longer-term response to drought, *new_decline* in 2003 accounted for 40% of all decline patches. All these polygons were used in following processes to identify effective risk factors in risk rating.

Effects of Topographic Variables on Oak Decline. It has been reported in past studies that topographic positions of oak trees played a role in oak decline (Starkey and Oak, 1989; Manion, 1991; Oak et al., 1996). Based on topographic features in selected decline polygons, we examined the distributions of slope and aspect in declining forests.

The Mark Twain GIS database recorded stand-level aspects in a range of $[0^\circ, 360^\circ]$. Surprisingly, in some stands it recorded 0° while in some others it recorded 360° , even though the stands were not flat (slope >0). To reduce this uncertainty, decline polygons with either 0° or 360° were extracted to reflect stands with flat surface or with slopes facing north. These polygons were represented by the first bin $[-60^\circ, 0^\circ]$ in Figure 5A. In this way, the aspect of decline polygons had an approximately uniform distribution. Frequency of occurrence in each range of aspect was

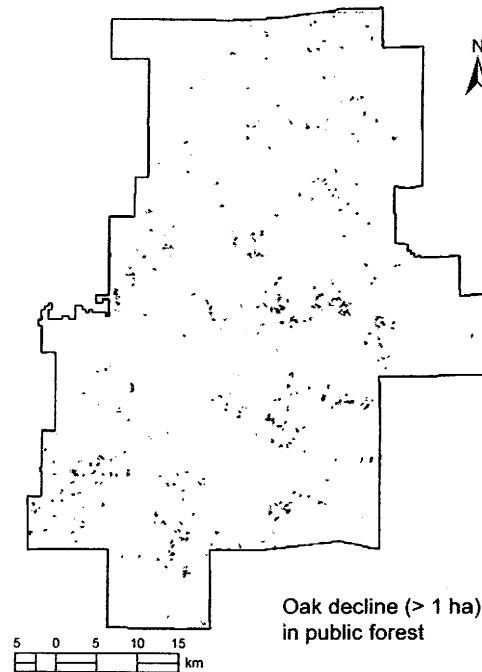


Fig. 4. Forest decline polygons (> 1 ha) in 2000 and 2003. Extracted from Landsat-derived forest change maps and forest inventory data.

similar in both stand% and decline% (Table 1), indicating that decline could equally occur at slopes facing any direction. As a result, aspect was not an effective factor of oak decline in this study area. Contrarily, an approximately normal distribution of slope in decline polygons was observed in Figure 5B. A large portion of oak decline occurred in forests at slopes [7,28]. Trees at slopes [22,28] had a much higher portion of decline (31%) relative to its proportion in all stands (24%), indicating a high risk of decline in this slope range (highlighted in Table 1). All other slope classes were assigned a medium or low risk of decline.

As shown in the four boxplots in Figure 5C, while the median aspects were similar in decline polygons of *decline00_03*, *new_decline*, and *persistent_decline*, the median aspect of *recovery* was much lower. Therefore, forests exhibiting decline symptoms on northeast-facing aspects had a higher chance of recovery, consistent with the findings of Starkey and Oak (1989). In four decline categories, the 50% quartile ranges in boxplots of slope were much narrower (Fig. 5D). The median slopes in polygons of *new_decline* and *persistent_decline* were similar to that of *decline00_03*. The median slope of polygons of *recovery* was much smaller, which meant that oaks at shallower slopes had higher chance of recovery from 2000 to 2003.

Effects of Biological Variables on Oak Decline. All histograms of site index, tree age, and basal area in decline polygons had approximately normal distributions, which indicated that decline occurred more frequently in certain ranges of these biological variables. Statistical output (Table 2) showed that although a high portion of

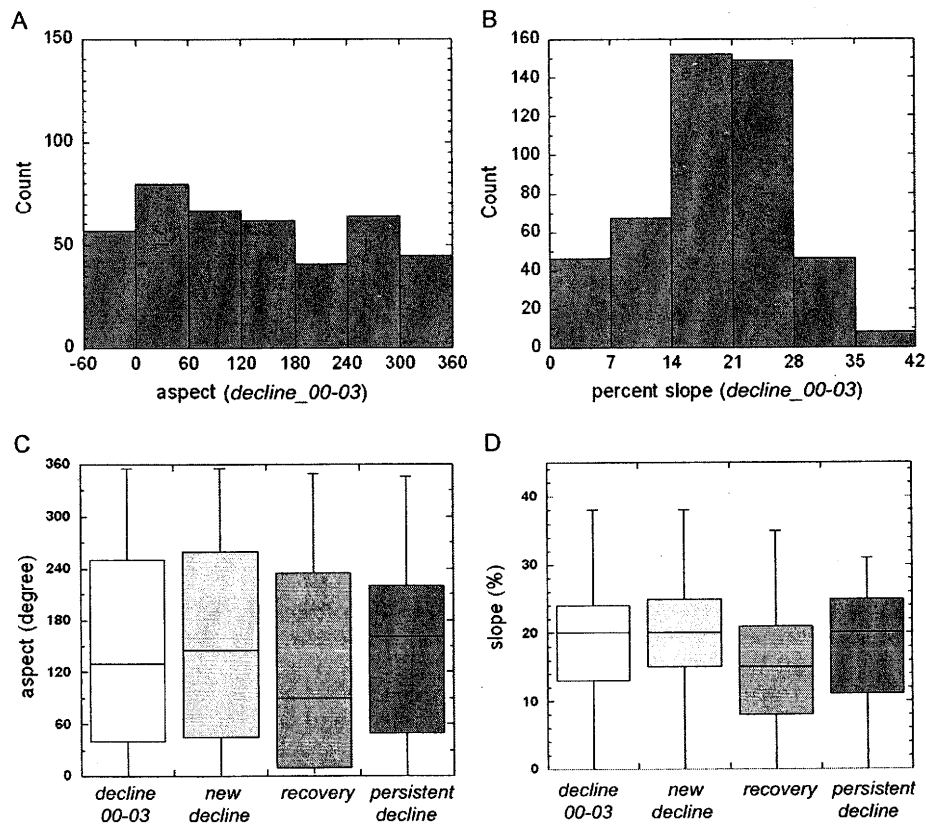


Fig. 5. Histograms of aspect (A) and slope (B) of all decline polygons and boxplots of aspect (C) and slope (D) in four decline categories (*decline_00-03*, *new decline*, *recovery*, and *persistent decline*).

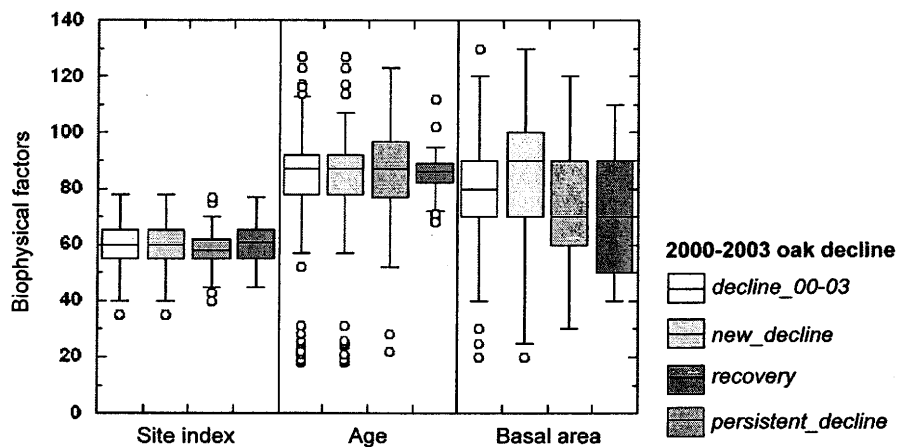
decline occurred in forests with site indices ranging from 46 to 72 m (20%, 50%, and 23%), decline% in these ranges was similar to or even lower than stand%. For site indices ranging from 73 to 91 m, decline% was larger than stand%. However, forests in this range of site index accounted for a very limited portion of entire stands (stand% = 3.2%) and decline polygons (decline% = 5.3%). They could not representatively explain the role of site index in oak decline in the study region. We concluded that site index was not a strong factor of oak decline in the study area. Contrarily, some ranges of age and basal area had significantly larger decline% than stand% (Table 2). Our findings suggested that tree age and basal area were effective risk factors because forests at these ranges (67–110 years old with basal area of 47–115 ft²/acre) were more sensitive to drought.

In Figure 6, most declines occurred at around a median site index (60), age (86), and basal area (80), with narrow ranges of 50% quartile boxes. No obvious difference could be observed in the four decline categories of site index and age. In boxplots of basal area, *new decline* tended to occur in forests with higher basal area, while *recovery* more likely occurred in forests with lower basal area.

Table 1. Percentage Distribution of Topographical Variables in All Public Stands (stand%) and in Declined patches (decline%)^a

Aspect (°)			Slope (%)			
Range	Stand%	Decline%	Range	Stand%	Decline%	Risk
0	9.49	14.53	0	4.99	0	0
1–60	17.21	18.38	1–7	14.49	12.18	1
61–120	16.42	15.81	8–14	14.16	14.74	2
121–180	14.66	15.17	15–21	34.63	33.97	2
181–240	11.96	10.47	22–28	24.10	30.56	3
241–300	13.70	14.32	29–35	10.26	8.12	1
301–359	16.56	11.32	36–42	2.37	0.43	1

^aThe risk for ranges of Aspect was not considered because of its nearly uniform distribution of stand% and decline%. The stand% is the portion of stands in a bin compared with all stands. The decline% is the portion of decline polygons in a bin compared with all decline polygons. Bins with decline% effectively larger than stand% are highlighted in bold (risk level = 3).

**Fig. 6.** Boxplots of biological variables in four decline categories.

Predicting and Validating Potential Oak Decline Sites

A risk map was derived based on combined criteria of all risk factors (slope, tree age, and basal area) in Equation 7. As shown in Figure 7, high-risk stands clustered in the southern, southeastern, and northern parts of the study area, a similar pattern as the decline patches detected from Landsat images (Fig. 4). Regenerated from abandoned agricultural lands in the 1930s, the majority of the public stands in the study

Table 2. Percentage Distribution of Biological Variables in all Public Stands (stand%) and in Declined Patches (decline%)^a

Range	Age			Site index			Basal area				
	Stand%	Decline%	Risk	Range	Stand%	Decline%	Risk	Range	Stand%	Decline%	Risk
0-22	13.66	1.28	1	0-36	0.49	0.21	1	0-23	5.23	0.21	1
23-33	5.13	1.71	1	37-45	2.53	2.77	3	24-46	4.65	3.91	1
34-66	4.22	2.56	1	46-54	19.95	15.78	1	47-69	14.45	23.27	3
67-88	47.65	56.72	3	55-63	50.45	52.67	2	70-92	48.99	57.54	3
89-110	23.98	35.39	3	64-72	23.18	23.03	2	93-115	16.95	24.21	3
111-132	5.06	2.13	1	73-91	3.21	5.33	3	116-138	3.56	4.07	3

^aBins with decline% effectively larger than stand% are highlighted in bold (risk level = 3).

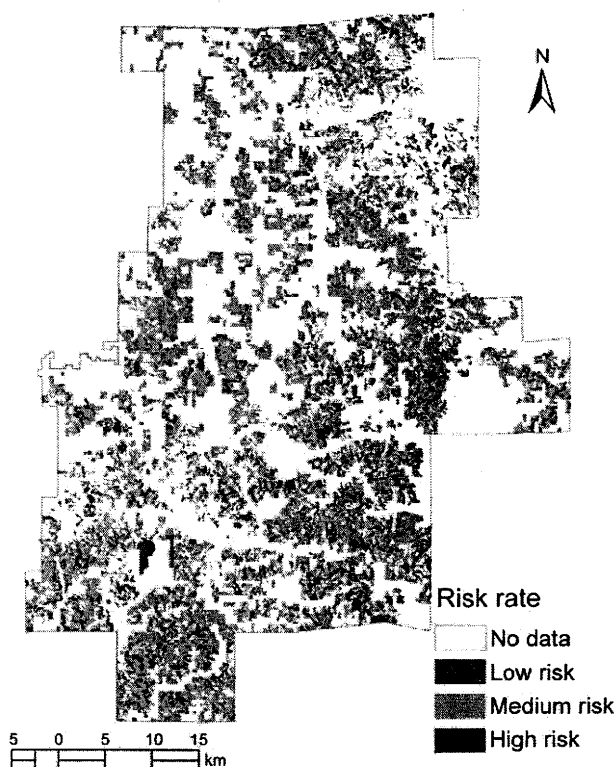


Fig. 7. Risk rating map based on multiple risk factors (slope, tree age, basal area) in the study area.

area consisted of older oak trees and was at high age-based risk (71%). Most stands had a higher basal area and were also in the high basal area-based risk category (80%). These two risk factors determined that most stands in the study area were at least at medium risk. Stands were at high risk when their slopes were also in the high-risk range. Stands at low risk were limited to areas where trees were younger, with lower basal area, or located at shallow slopes. Unlike the large clusters of high- and medium-risk stands, stands at low risk were often small, isolated, and dispersed in the study area, a possible result of local-scale forest regeneration activities in recent decades.

Among all decline patches from satellite images, a total of 9,920 acres of oak decline (medium to severe) occurred in 2000–2003, composed of 4% of the public forests in the study area (Table 3). The majority of these decline patches were in stands at medium risk (56%). Overall 74% of the area of moderate and severe decline identified in satellite images occurred in stands at medium to high risk.

Different processes of decline and recovery in 2000–2003 (Table 3) were associated with the risk levels of stands. Decline in stands at low risk accounted for 26% of the total area in decline in 2000–03 (*decline00-03*), among which 16% occurred in 2000 and recovered in 2003 (*recovery*). On the other hand, 13% of the total 19% of

Table 3. Characteristics of Decline in All Public Stands in the Study Area^a

	Decline area (acres)	Percent of decline			
		<i>decline00_03</i>	<i>new_decline</i> ^b	<i>persistent_decline</i> ^b	<i>recovery</i> ^b
Low risk	2,535	25.55	2.73	6.44	16.38
Medium risk	5,533	55.77	30.74	6.6	18.43
High risk	1,853	18.68	12.90	1.69	3.09

^aTotal oak forest: 245,118 acres; 2000–2003 decline: 9,920 acres (4.05%).

^bWeighted by *decline00_03* in each risk level.

declined area that occurred in stands at high risk belonged to new decline in 2003 (*new_decline*). Decline in stands at medium risk was either in the category of *new_decline* (31% of all declined area) or the category of *recovery* (18% of all declined area). It was also shown that recovery mostly occurred in stands at low to medium risk, while *new_decline* dominated stands at medium to high risk. The majority of the declined area in 2000–2003 was *new_decline* or *recovery*, whereas *persistent_decline* was limited (Table 3).

DISCUSSION

Associated with the severe drought in 1999–2000 and a high population of red oak borers in subsequent years, the oak decline episode in the Ozark Highlands was severe and unique. This study examined the biophysical properties in affected stands to rate the risks of decline in oak forests in this region. Remote sensing images were analyzed to detect crown dieback and to monitor forest dynamics following the stress. Rather than mapping direct mortality and regrowth as a matter of land cover change, the differential NDWI provided a continuous measure of oak dieback and recovery when affected by drought. Because all decline patches in large areas were used to examine the primary risk factors, the risk rating system in this study had greater advantages than risk assessments made from discrete field observations that were often complicated by scale and extent of decline events and by the experience level of observers. Prediction and prevention of oak decline could then be more successful when another cycle of environmental stress occurs.

Three biophysical variables (slope, tree age, and basal area) were identified as risk factors. Stands within certain ranges of these risk factors were assigned high risk when frequencies of declined area in these ranges were disproportionately higher than the abundance of such stands in the entire study area. Conversely, aspect and site index were not effective risk factors. Our results were consistent with findings in Kabrick et al. (2008), who reported that high frequency of occurrence of decline did not necessarily represent high risk of decline in these stands. Rather, it may simply come from greater abundance of vulnerable stands with poor biophysical properties in

the study area. This study reduced the uncertainties that were related to the dominance of certain biophysical properties in risk rating.

As shown in past studies, conventional multivariate statistical analysis did not work well in predicting oak decline in Ozark forests, due primarily to the effects of extremely abundant oaks that were in vulnerable conditions (Oak et al., 1996; Kabrick et al., 2008). This study built an ordinal risk rating algorithm in which oak abundance was leveraged by comparing decline% with stand% in certain range of biophysical properties. It should be noted, however, that this risk rating system was somewhat subjective by grouping decline polygons of a certain risk factor into ranges (bins) in statistical analysis. The values of decline% and stand% may vary when the number and range of bins in Table 1 and Table 2 were changed. Nevertheless, because of the normal distribution of the three risk factors, the uncertainties of risk prediction by adopting different sets of bins would be slight when applying the study in a large area.

In general, the categorical risk rating system performed well in the study area. A total of 74% of the areas in decline in 2000–2003 was predicted as medium- to high-risk decline sites in the rating system. However, stands at high risk may be underestimated in the study area. Contrary to the hypothesis that actually declining stands should be at high risk, only 19% of all declining areas were predicted as high-risk stands. This may come from the assumption that all risk factors played equal roles in the rating system. For example, based on Equation 7, stands were assigned medium risk if one risk factor indicated low to medium risk while all other risk factors indicated high risk.

The accuracy of risk rating in this study was also affected by the efficiency of decline mapping in remote sensing imagery. The accuracy of image-based forest decline/recovery mapping reached 76% when compared with the ground-observed FIA database at three-mile resolution. It may be higher if better ground observations and multi-temporal satellite imagery at finer resolutions were available. Moreover, the accuracy was also affected by non-drought-related factors. Forest decline/recovery mapping may overestimate affected areas if human activities such as logging or planting are heavily involved in the study area. The risk rating would be less distorted if these non-natural processes could be recorded and the affected areas masked out in the study. Finally, the comparison of remote sensing-derived maps with stand-level biophysical observations in inventory data involved inevitable information lost by reducing continuous digital numbers (DN) into ordinal categories of decline levels. A possible improvement of the risk rating system might involve advanced geospatial analysis to build a multi-weight system based on spatial correlations between risk factors and occurrence of decline.

Oak decline was a continuous process and was related to the stand's risk level. After moderate to severe symptoms occurred as a direct response to the drought in 1999–2000, most patches of medium to severe decline (223 out of 282 decline polygons in 2000) recovered in three years. This was consistent with the findings of Dwyer et al. (2006), who observed that more than 50% of red oaks recovered regardless of silvicultural treatments. It indicated that red oaks had the ability to recover foliage naturally even if crown dieback was medium to severe. We also found that, as direct response to the drought, decline patches in 2000 were mostly in low- to medium-risk stands. New decline (medium or severe) patches in 2003, as a slower

response to the drought in three years, were mostly observed in stands at medium to high risk. As a result, more attention should be put on stands at medium to high risk for a long-term evaluation of post-drought oak decline. With proper silvicultural activities in these stands, damage may be mitigated and prevented when another cycle of stress occurs.

CONCLUSION

In this study, oak decline and recovery associated with the severe drought in 1999–2000 were mapped using the normalized difference water index (NDWI) of Landsat images. A risk rating study was then conducted by examining biophysical properties in image-detected decline patches. The primary results included:

1. Slope (21–28%), tree age (> 66 years), and basal area (> 46 ft²/acre) were major risk factors that contributed to oak decline in the study area. Stands in such biophysical ranges had disproportionally higher occurrence of decline than abundance of oak stands in these ranges. Aspect and site index were not effective risk factors.
2. The risk rating system based on these three risk factors predicted well in the study area. Approximately 75% of forests in moderate to high decline were in the high to medium risk categories.
3. Oak dynamics affected by drought appeared to be a continuous process of decline and recovery. Particularly noticeable was the observation that about 79% of quick decline (2000) recovered and cannot be detected from satellite images acquired a few years later (3 years in this study).
4. Oak decline and recovery in a stand was related to its risk level. The most decline in 2000 occurred in low-risk stands that recovered in the following years. New decline patches in 2003 often occurred in stands at medium to high risk, which should be the focus of greater attention in the prediction and evaluation of oak decline.

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