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Use of Landsat Data to Characterize Burn Severity, Forest Structure and Invasion by Paulownia (Paulownia Tomentosa) in an Eastern Deciduous Forest, Kentucky

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Use of Landsat Data to Characterize Burn Severity, Forest Structure and Invasion by Paulownia (*Paulownia Tomentosa)* in an Eastern Deciduous Forest, Kentucky

THESIS

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

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ABSTRACT OF THESIS

Use of Landsat Data to Characterize Burn Severity, Forest Structure and Invasion by Paulownia (*Paulownia Tomentosa)* in an Eastern Deciduous Forest, Kentucky

Landsat imagery has been used successfully to assess burn severity and monitor post-fire forest structure in a variety of ecosystems, but to date there are few documented studies on its application in the eastern deciduous forests of the eastern United States. The occurrence of a wildfire in the Daniel Boone National Forest in2010 provided a rare opportunity for research into the use of Landsat data for assessing burn severity and its ecological effects. We used differenced normalized burn ratio (ΔNBR) to quantify burn severity. The ΔNBR based burn severity classification had 70% agreement with a qualitative ground-based burn severity assessment. We also examined the relationship between the presence of an invasive species (*Paulownia tomentosa*), and our assessment of burn severity, where we found a weak but statistically significant relationship (adj R^2 0.13, $p<0.0001$). We also examined the relationship between the normalized difference vegetation index (NDVI) and forest structure measurements. The relationship between NDVI and basal area was strongly and significantly related (adj R^2 0.41, $p<0.0001$). The relationship of NDVI with stem density was weak but significant (adj R^2 0.23. $p=0.004$).These results indicate that data from Landsat imagery have great potential for quantifying burn severity, identifying potential hotspots for invasive species, and assessing post fire forest structure in the eastern deciduous forest.

Keywords: differenced normalized burn ratio, normalized difference vegetation index, wildfire, remote sensing, basal area, stem density

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July 31, 2015

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DEDICATION

I would like to dedicate my work to my parents, Laxmi Kant Upadhaya and Uma Laxmi Upadhaya, who cherished me in my childhood and always pray for my better future.

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Chapter One
INTRODUCTION

Introduction

Wildfire, also referred to as wildland fire, is defined as an uncontrolled fire in an area of combustible vegetation that occurs in the countryside or wilderness area (Firewise, 1998). Wildfires occur in most forest ecosystems and are an important ecosystem process that impacts terrestrial, atmospheric and aquatic systems throughout the world (Lentile et al., 2006; Zimmerman, 2012).

Many ecosystems are dependent on wildfires for establishment, development and maintenance of vegetation. Some of the physical impacts of wildfire are decreased albedo, increased soil temperature and alterations in productivity (Dyrness et al., 1989). Fire affects species composition and age structure of forest stands. Mosaic patterns of burn severity can increase habitat heterogeneity and biodiversity. Additionally, the absence or presence of wildfire may increase the probability of successful invasion of non-native invasive species to forest land (Jenkins et al., 2011).

Wildfires have occured in eastern deciduous forests for thousands of years. Native Americans used fire to enhance hunting and gathering, and early settlers adopted these techniques (Delcourt and Delcourt, 1998). Fire in eastern deciduous forests are typically low-intensity, but vary spatially and temporally with severity ranging from benign to extreme (Maingi and Henry, 2007; Wade et al., 2000). Before European settlement, surface fires were regular and frequent events, occurring every 5-15 years over most of the region. These fires were largely confined to combustion of surface fuels such as small woody debris, leaf litter and understory vegetation (Anderson, 1982; Wade et al., 2000; Lafon et al., 2005).

Today, forest and land managers working in this region are adopting prescribed fires as a silvicultural and restoration tool to address various management objectives including use of fire as a method for reducing fuels and restoring historical disturbance processes to the landscape (Arthur et al., 2012).

Wildfire is an important natural disturbance and driver of multi-aged stand creation in eastern deciduous forests, and is a major factor influencing landscape patterns and species diversity in these forests. (Delcourt and Delcourt, 1997). Monitoring and understanding the impacts of spatially and temporally variable wildfires has been a key challenge for forest and land managers, particularly in formulating strategies to monitor forest response to wildfire burned areas (Dale, 2006). Quantifying burn severity and its impacts on forest structure are crucial because variability in burn severity creates a variety of conditions for post-fire colonization that ultimately impacts successional dynamics (Arseneault, 2001).

Remote Sensing and Wildfire

Multispectral, remotely-sensed data have become widely-used for assessing wildlife and its effects (Key and Benson, 2005; Cansler and Mackenzie, 2012). Physical changes that wildfire creates on land cover, such as vegetation consumption and ground charring, make wildfire-burned landscapes suitable for detection by remote sensing (White et al., 1996). High spatial and temporal resolution make satellite imagery pragmatic for assessing ecological changes in response to disturbances such as wildfires. Topographic, vegetation, and meteorological factors create variable patterns of burn severity in burned areas, which can be mapped using remotely-sensed data. Forests where a high-severity fire has occurred typically experience an increase in mineral soil exposure, light level, and nutrient availability, and a decrease of canopy cover (Keeley et al., 2003) which creates change in spectral signatures. The change in spectral signatures that occur following a fire can be used to measure burn severity, and create severity maps to predict the effects of fire on physical and biological processes (Cocke et al., 2005; Wimberly and Reilly, 2007). With the use of these data, other ecological attributes such as forest structure (basal area, stem density) of burned areas can be extracted.

Arseneult (2001) suggested that it is important to understand and measure burn severity at the landscape scale because its spatial and temporal variability creates a variety of changes in forest structure (i.e., basal area, stem density), and favorable conditions for post-fire colonization of various native and nonnative invasive species

(NNIS). Various studies (see e.g., Fornwalt et al., 2010; Kaczynski et al., 2011) have found that a relationship exists between the distribution of NNIS and burn severity. Such studies found that NNIS abundance is directly proportional to the burn severity, i.e., higher burn severity is correlated with higher density of NNIS.

NNIS can quickly spread and have detrimental impacts on the native ecosystems they invade (Chapin et al., 2000). Once NNIS enter an ecosystem, many possess the ability to quickly expand their populations and outcompete local native species, ultimately leading to environmental and economic loss (Pimentel, 2001). For this reason, accurate and reliable estimations of burn severity are necessary for studying and understanding the response of wildfire and its impacts on forests and NNIS.

Several studies have revealed the usefulness of using remotely-sensed data such as Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) for mapping burn severity, assessing post-fire forest structure, and predicting the spread of NNIS. Key and Benson (2003) developed the vegetation index, normalized burn ratio (NBR), for Landsat data using near infrared and mid-infrared bands. Normalized difference vegetation index (NDVI), a commonly utilized vegetation index, uses the near-infrared and red bands (van Leeuwen et al., 2010). The use of Landsat imagery has been frequently used to assess burn severity in the southwestern United States (Cocke et al., 2005) and boreal forests in Alaska’s interior (Epting et al., 2005). Change in vegetation indices such as NBR and NDVI are commonly utilized in the literature and are particularly effective indices of burn severity and forest structure. These techniques of using vegetation indices have been applied primarily to study wildfire in coniferous forests of the western United States (Wimberly and Reilly, 2007); very few studies have used Landsat based vegetation indices to assess wildfire in eastern deciduous forest ecosystems (Picotte and Robertson, 2011; Wimberly and Reilly, 2007). It is still uncertain whether these methods of remote sensing will be as effective for mapping burn severity and assessing forest structure in deciduous forest landscapes in the eastern United States where the species composition and vegetation structure tends to be more complex than that in coniferous forests. For this reason, this research project focused on using Landsat-based vegetation indices to assess burn severity and its impacts in an eastern deciduous forest.

The recent occurrence of a 673.8-ha wildfire in Kentucky's Daniel Boone National Forest (DBNF) provided a rare opportunity for research into the uses of remotely sensed data for assessing burn severity and ecological effects. Here, we assess the non-native invasive species, *Paulownia tomentosa*, and its colonization within areas of burned deciduous forest in DBNF across varying levels of burn severity identified using Landsat imagery. We examined the relationship between four classes of burn severity (i.e., unburned, low, moderate and high), and the relative density of NNIS. Furthermore, we assessed the relationship between the vegetation indices derived from Landsat data and post fire forest structure (i.e., basal area and stem density).

Chapter Two

Assessment of burn severity and response of a non-native invasive species (*Paulownia tomentosa*) in an eastern deciduous forest using Landsat Thematic Mapper (TM) imagery

Introduction

Fire is an important disturbance in many ecosystems in the eastern United States (U.S.) and globally (Pyne et al., 1996; Wade et al., 2000). Many plant communities are dependent on wildfire for establishment, development and maintenance, which in turn strongly influence landscape patterns and species diversity (Delcourt and Delcourt, 1997). Before European settlement, wildfires in the eastern US were regular and frequent events occurring every 5 to 15 years (Lafon et al., 2005; Wade et al., 2000). They were mostly low intensity fires consuming surface fuels such as small woody debris, leaf litter, and understory vegetation, which created spatially and temporally variable patterns of vegetation composition and structure (Anderson, 1982; Maingi and Henry, 2007). Recently, forest managers have been using moderate severity prescribed fires in eastern deciduous forest ecosystems to restore prehistoric fire regimes and alter forest structure with variable management goals (Arthur et al., 2012).

Burn severity can be defined as the degree of change in the soil and vegetation caused by fire (Escuin et al., 2008). Variable terrain and vegetation conditions lead to heterogeneous burn severity in which some areas affected by wildfire experience near-complete vegetation consumption and mineral soil exposure, whereas other areas are burned at very low severity or not at all (Knapp et al., 2009; Maingi and Henry, 2007). Understanding and mapping the distribution of burn severity following wildfire is essential for the forest manager tasked with formulating and implementing post fire treatments, restoring disturbed areas, and understanding post-fire vegetation succession (Escuin et al., 2008). However, using field-based methods to map severity is difficult in inaccessible terrain with steep slopes across large spatial extents.

To address this challenge, Landsat imagery has been used to assess burn severity, especially in conifer-dominated forests of the western US (Key and Benson, 2006). Wildfire effects such as vegetation combustion, exposure of mineral soil, charring of roots, and alteration of soil moisture can create change in the electromagnetic spectrum (Keeley et al., 2003; Key and Benson, 2005; White et al., 1996). This change can be captured by remote sensing imagery and used to measure burn severity, map its distribution, and make predictions of fire effects on physical and biological changes across large landscapes (Cocke et al., 2005; Lentile et al., 2006; Wimberly and Reilly, 2007). Landsat Thematic Mapper (TM) provides imagery with adequate spectral, temporal and spatial resolution for examining burn severity and conducting wildfire assessment. Reliable results compared with ground collected data have been reported in Douglas-fir (*Pseudotsuga menziesii*) forests in western Oregon (Kushla and Ripple, 1998), ponderosa pine (*Pinus ponderosa*) forests in Arizona (Cocke et al., 2005), spruce (*Picea* sp.) forests in central Alaska (Duffy et al., 2007; Epting et al., 2005; Kasischke et al., 2008), and mixed-conifer forests in California (Miller and Thode, 2007). Similar studies have been conducted in other conifer forests including the Mediterranean coast of Spain (Garcia-Haro et al., 2001) and Kalimantan, Indonesia (Fuller and Fulk, 2001). Although several burn severity indices have been evaluated, the differenced normalized burn ratio (ΔNBR) has emerged as an effective index to capture burn severity in conifer forests due to its ability to detect charred blackness after a fire (Bobbe et al., 2003). Despite its widespread application in conifer forests, there are very few studies using ΔNBR (or any other remote-sensing derived vegetation index) to assess and map burn severity in eastern deciduous forests of the US. Exceptions include work conducted by Wimberly and Reilly (2007) in the southern Appalachians of western North Carolina, and Picotte and Robertson (2011) in northern Florida-southern Georgia. However, both study sites contained an abundant pine component. Wildfires in deciduous forests are predominantly surface fires that seldom remove green crown vegetation, thus making it more difficult to detect fire effects using satellite imagery (Maingi, 2005).

Post-fire colonization by non-native invasive species (NNIS) has been reported in several ecosystems, emerging as a critical threat to native species biodiversity and posing potentially significant ecological and economic impacts (Gucker et al., 2011; Hunter et al., 2006; Wilcove et al., 1998). Government agencies annually spend significant amounts in NNIS removal on federal lands (Pimentel et al., 2000; Pimentel et al., 2001). High severity wildfires can consume most native vegetation and organic matter in the soil, temporarily reducing site nutrients, and increasing light penetration to the soil surface, creating favorable conditions for establishment of NNIS, which typically have lower site nutrient requirements than native species (Funk, 2013). Additionally, a number of traits such as the ability to sprout, prolific seed production, rapid growth rate, and early age to seed production contribute to the rapid dispersal of NNIS in fire-disturbed areas (Rebbeck, 2012).

Several studies have reported colonization of NNIS to be related to burn severity (Crawford et al., 2001; Fornwalt et al., 2010; Keeley et al., 2003). In eastern deciduous forests, paulownia (*Paulownia tomentosa)* has been found in many disturbed areas and reported to establish rapidly across different habitats immediately after fire (Kuppinger et al., 2010). However, its relationship with burn severity has not been studied. The Fish Trap fire (FTF) that occurred in 2010 in the Daniel Boone National Forest (DBNF) in eastern Kentucky offered an opportunity to evaluate the potential of using remotely sensed data to assess burn severity and its relationship with NNIS colonization, specifically *Paulownia tomentosa*. In this study, we used pre- and post-fire Landsat imagery to compute the ΔNBR and used it to determine site-specific burn severity classes. We also determined the relationship between Landsat-derived burn severity classes and the presence of paulownia. Although our investigation focuses on a case study in the DBNF, results are broadly applicable to the Cumberland Plateau physiographic region and other similar eastern deciduous forests.

Methods

Study Area

The study site is the area burned by the FTF in 2010 located on the Cumberland Plateau, within DBNF, in Powell County, Kentucky (lat. 37° 49′ N, long. 83° 41′ W) (Figure 2.1). The FTF was started unintentionally by campers on 24 October 2010 and was fully contained on 9 November 2010. The exact area burned is unknown, but DBNF personnel installed a containment perimeter encompassing an area of 674 ha, 645 ha of which were within the DBNF and 29 ha on private land. The burned land occurred within the Red River Gorge Geological Area, a landscape of highly dissected uplands and streams of the Red River watershed near the western edge of the Cumberland Plateau in east-central Kentucky.

The landscape is dominated by upland oak-hickory forest type. Canopy species include oaks [scarlet oak (*Quercus coccinea* Muenchh.), chestnut oak (*Quercus montana* Willd..), black oak (*Quercus velutina* Lam), and white oak (*Quercus alba* L)], hickories [pignut hickory (*Carya glabra* Mill.) and mockernut hickory (*Carya tomentosa* Poir.)], and pines [shortleaf pine (*Pinus echinata* Mill.), Virginia (*Pinus virginiana* Mill.), pitch (*Pinus rigida* Mill.), and white (*Pinus strobus* L.)]. The midstory is dominated by red maple (*Acer rubrum* L.), sourwood (*Oxydendrum arboreum* L.), black gum (*Nyssa sylvatica* Marsh.) and sassafras (*Sassafras albidum* Nut.).

Soil type along the ridges is mostly Alticrest-Ramsey (ArF) and Helechawa (HeF) on midslopes and Bledsoe-Berks (BsF) on lower slopes. The underlying geological substrate is comprised of Pennsylvanian sandstones and conglomerates (Corbin sandstone member of Lee formation) and shales of the lower Breathitt formation (Hayes, 1998). Elevation ranges from 177 - 439 m.a.s.l. Mean annual temperature is 12.9°C, with mean high and low temperatures of 19°C and -4.3°C occurring in July and January, respectively. Mean annual precipitation is 119.2 cm, most of it occurring from March to June (Kentucky Climate Center, 2006).

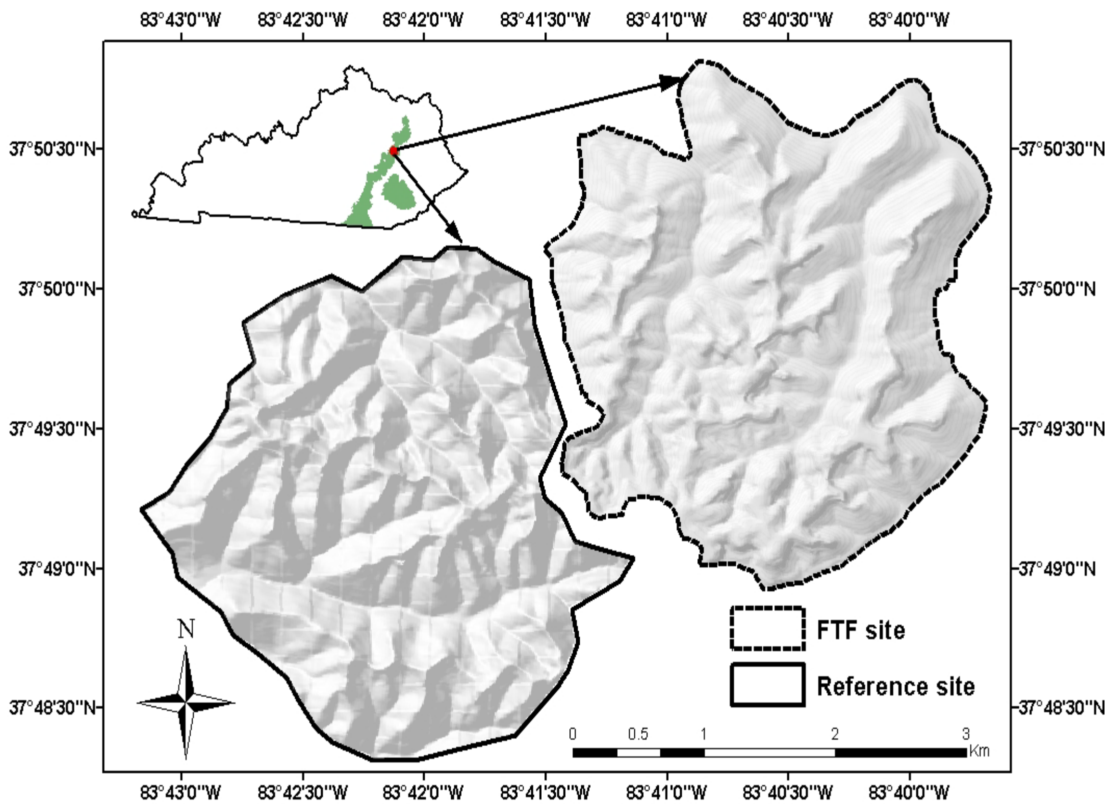

Figure 2.1: Location of Fish Trap fire and reference site area within the Daniel Boone National Forest, Kentucky, USA.

Image Processing and Field Data

Landsat-5 Thematic Mapper images (path 19, row 34) from October 2nd, 2010, were acquired to represent the pre-burn vegetation conditions encompassed in the FTF. Post-fire images were Landsat-5 TM from October 5th, 2011, selected to capture relatively similar vegetation moisture and temperature conditions to that of pre-burn images. Both sets of images (pre- and post-fire) were cloud free and terrain-corrected by the Earth Resources Observation and Science (EROS) data center, providing the highest level of correction available for Landsat scenes (Chander and Markham, 2003).

Raw digital number (DN) values for each band of Landsat 5 were converted into top of atmosphere (TOA) spectral reflectance to account for eco-atmospheric solar irradiance and daily sun angle variation. TOA is a unitless measure of the ratio between the amount of light energy reaching the Earth's surface and the amount of light reflecting off the surface and returning to the top of the atmosphere to be detected by the satellite's sensors (Chander and Markham, 2003; Johnson, 2013). Atmospheric scattering is negligible in the infrared bands (Avery and Berlin, 1992; Miller and Thode, 2007), so atmospheric correction was not performed.

The normalized burn ratio (NBR) values were computed as follows where:

$$\mathrm{NBR} = 1000 \times \left[\frac{\mathrm{NIR} - \mathrm{MIR}}{\mathrm{NIR} + \mathrm{MIR}}\right]$$

where, IR and MIR are the Thematic Mapper bands 4 and 7, respectively. Band 4 covers wavelengths 0.76-0.90 µm (near-infrared) and band 7 covers wavelengths 2.08-2.35 µm (middle-infrared). Bands 4 and 7 are sensitive to chlorophyll content of live vegetation and moisture (Jensen, 1996; Jensen, 2006) and are effective in identifying fire scars (Pereira and Setzer, 1993) and thus commonly used to map burn severity (White et al., 1996).

The difference between pre-fire and post-fire NBR ($\Delta\mathrm{NBR} = \mathrm{NBR}_{\mathrm{prefire}} - \mathrm{NBR}_{\mathrm{postfire}}$) was also computed. Unchanged areas typically possess values near zero, while positive values indicate the area burned (Key and Benson, 2006; Picotte and Robertson, 2011). This unburned-burned threshold of ΔNBR varies among burns in different ecosystems. These differences are mostly due to natural phenological variation as well as site-specific pre- and post-fire vegetation differences. As NBR values are sensitive to phenological and vegetation moisture changes, we used an area adjacent to the FTF with similar vegetation and terrain conditions as a reference site to identify ΔNBR thresholds that capture the site-specific natural variation in vegetation conditions pre- and post-fire.

The reference site was 630 ha in size (Figure 2.1) and was completely contained within the same two Landsat images used for the FTF. ΔNBR values across the reference site were also computed. We then fitted two normal distribution functions to the ΔNBR values covering the FTF site and the reference site (Figure 2.2). Although, on average, both the reference and FTF sites had positive ΔNBR values (suggesting vegetation loss), the amount of vegetation loss in the FTF site is much larger (mean ΔNBR value of 78 vs. 21 on the reference site), which was expected due to the fire. The positive intersection point between the two distributions (ΔNBR = 56) was considered as the break point between unburned and burned areas (Figure 2.2). This objective approach was used because: (i) there is more area (85% of total pixels) in the reference site that experienced relatively small increases in NBR (ΔNBR ≤ 56) and probably reflects phenological variation in vegetation between the 2010 and 2011 images, and (ii) there is more area (45% of total pixels) in the FTF site with positive ΔNBR values, suggesting relatively large vegetation loss across the landscape (ΔNBR > 56) assumed to be due, in most cases, to combustion by fire. Consequently, pixels in the FTF with ΔNBR values ≤ 56 were considered unburned and pixels with ΔNBR > 56 were considered burned. Several studies have developed ranges of ΔNBR values to classify areas into different burn severity classes (Key and Benson, 2005; Miller and Thode, 2007). To identify the remaining three burn severity classes (low, moderate, and high) for our study, we used a ground-based qualitative assessment of burn severity from 30 field plots located across the burned area to guide our determination of the break points for range of ΔNBR associated with difference in burn severity.

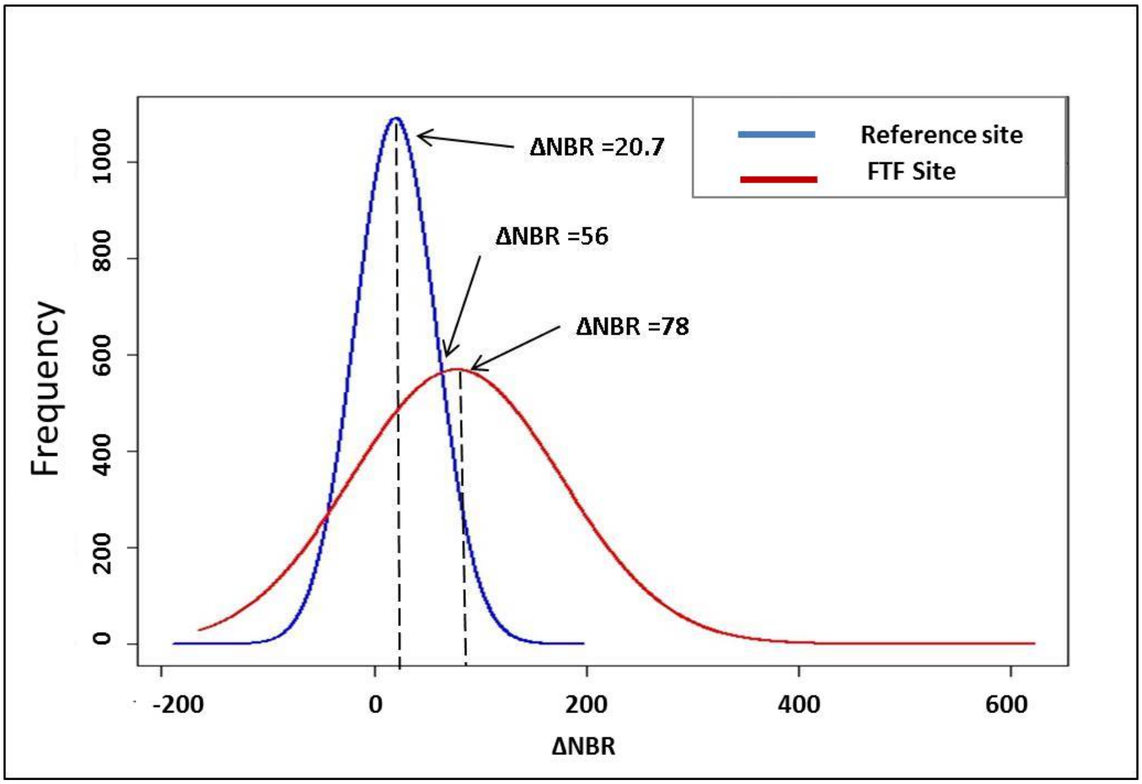

Figure 2.2: Frequency distribution of the differenced normalized burn ratio values (ΔNBR) across the reference and FTF sites in the Daniel Boone National Forest, Kentucky.

Thirty 500 m^2 (0.05 ha) circular plots were located in the burned area in the FTF in August 2011 for post-fire vegetation and severity assessment (Figure 2.3). Based on terrain features retrieved from topographic maps, plots were located at random across landscape positions within the containment perimeter with the purpose of capturing effects within the entire range of burn severity. Within each plot the diameter at breast height (DBH) and species of all trees ≥2 cm DBH were recorded. Forest floor cover transects were measured using two perpendicular transects that intersected at the center of the plot. At every 10 cm along each 25.2 m transect the soil cover was recorded as litter, organic matter, mineral soil, rock, tree, stump or woody debris. In addition, a qualitative measure of burn severity was determined and later used to validate burn severity classifications generated with remotely sensed data (ΔNBR). Assessment of burn severity was based on the presence of bare mineral soil, tree char damage and mortality, overall vegetation consumption, and the presence of burned out stump holes covered in moss (Table 2.1).

Table 2.1: Description of characteristics used to identify qualitative burn severity classes for Fish Trap fire in the Daniel Boone National Forest, Kentucky, during assessments made in summer 2011 and 2013.

Burn Severity Class	Description
Unburned	No evidence of char on standing or downed vegetation or within/under litter layer
Low	Some low char on standing vegetation, very little char in litter layer; no mineral soil patches; litter layer intact
Moderate	Litter layer consumed in places; patches of mineral soil present, some charred; char on most midstory vegetation, mostly standing, with moderate mortality; some midstory stump sprouts; char on most overstory vegetation with low to moderate mortality
High	Majority of litter layer consumed and charred mineral soil common; midstory vegetation consumed and mostly absent; lots of midstory stump sprouts; standing overstory trees have heavy char, and in some cases, are mostly consumed; overstory trees experience moderate to heavy mortality; moss patches present where tree stumps burned out

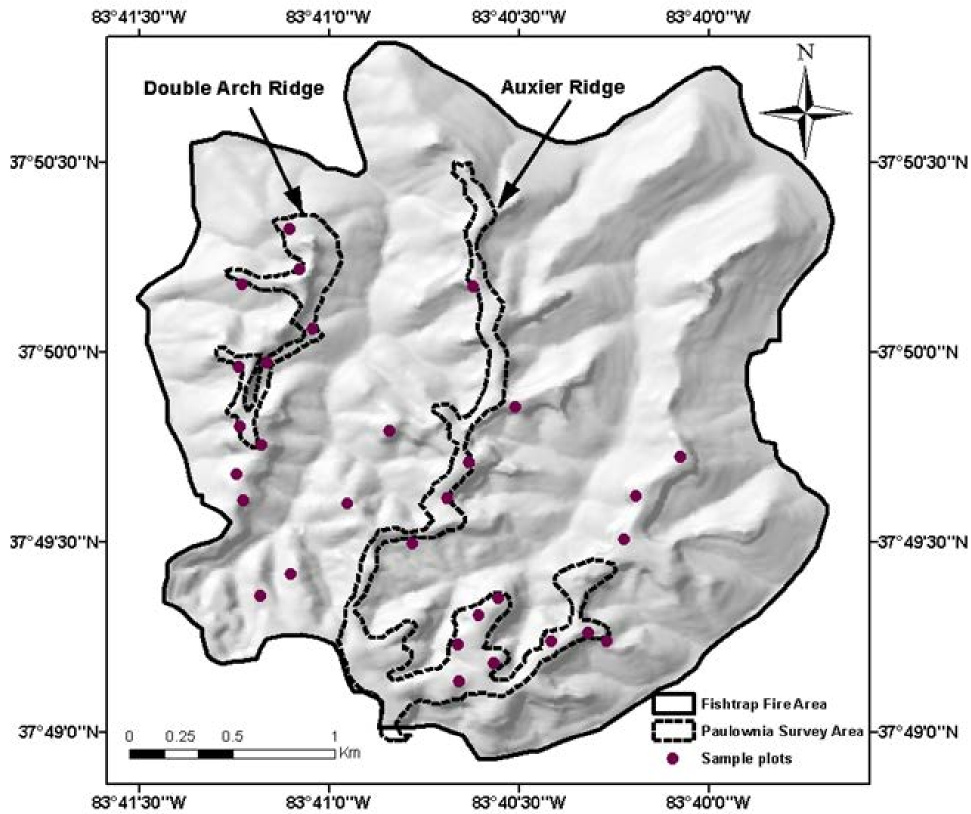

Figure 2.3: Location of field plots within burned areas in the Fish Trap fire for burn severity assessment. Thirty plots of $500m^2$ area were distributed over the burned area. Within the Fish Trap fire perimeter, paulownia stems were surveyed in areas indicated.

Non-native invasive species

Paulownia tomentosa was introduced into North America from Asia in the 1840s (Hu, 1961) and due to its showy flowers and rapid growth, it has been widely planted in United States as an ornamental (Tang et al., 1980). *P. tomentosa* occurs in a variety of habitats and plant associations throughout the eastern US that are similar to those of its native range. It occurs in disturbed upland areas associated with early successional species such as maple (Acer spp.), oak (Quercus spp.), and pine (Pinus spp.) (Ramsey et al., 1993). Characteristics such as early maturation (8-10 years of age), heavy production of wind-dispersed seeds (one mature tree can produced 20 million seeds a year), and vigorous ryesprouting makes *P.tomentosa* an invasive species (Innes, 2009).

In 2011, USDA Forest Service personnel conducted a walk-through survey along the ridge where moderate or high burn severity was concentrated but also captured areas with all 4 burn severity classes of the FTF to search for the presence of paulownia and other NNIS. Of the area surveyed, 18.5% of the pixels were unburned, 25.6% had low severity burn, 34.2% pixels were moderately burned and 21.7% were burned at high severity. This area contained 15 of the 30 established field plots and was about 24 ha in size (Figure 2.3). The location of single paulownia stems encountered was recorded as a point using a handheld GPS unit. When groups of stems growing within 3 meters were encountered, their location was recorded as a small polygon or line where a polygon represents at least 3 paulownia stems and a line may represent 2 to 10 plants. The total number of stems encountered was estimated and tallied by pixel.

Data analysis

Linear regression analysis was used to describe the relationship between burn severity and paulownia stem presence, with paulownia stems as the dependent variable and ΔNBR as the independent variable. Analysis of variance was used to detect difference in attributes among burn severity classes. All statistical tests were conducted using the “Stats Package” in version 3.1.2 of the R-Statistical Computing Software (R Core Team, 2014).

Results

After the wildfire, stem density and basal area of live trees were lowest on the plots classified as receiving moderate and high burn severity (Table 2.2). Basal area and stem density differed statistically among the different burn severity classes ($F(3,26)=8.998$, $p<0.001$) and $F(3,26)=5.719$, $p<0.001$) respectively). Sites burned with high severity experienced near-total mortality of trees. We found no statistically significant difference in forest floor cover among different burn severity classes. But differences in forest floor cover were more variable, and didn’t reflect burn severity fully. For example, while litter cover (29 %) on the plots burned with low severity was higher than that on plots burned with high (11%) or moderate (4%) severity, mineral soil exposure was higher on moderate and high burn severity plots compared to low severity, unburned plots had low litter cover and high mineral soil exposure (Table 2.2).

Table 2.2: Average percent cover of mineral soil, woody debris, and litter; stem density; and basal area for FTF measured after fire in 2011 and 2013 on 30 forest plots. Stem density and basal area include stems ≥ 2cm DBH. Same uppercase letters within groups are not significantly different (Tukey's HSD, p>0.05). Standard errors are in parentheses.

Burn Severity	Mineral soils (%)		Woody debris (%)		Litter (%)		Stem density (trees ha^{-1})		Basal area (m^2ha^{-1})	
	2011	2013	2011	2013	2011	2013	2011	2013	2011	2013
Unburned	40 (12.5)	7 (2.0)	13 (2.8)	2 A (0.8)	6 (3.1)	81 A (4.1)	550 A (149.4)	573 A (122.5)	23 A (4.7)	23A (5.3)
Low	12 (5.6)	5 (2.9)	9 (1.6)	3 A (1)	29 (14.3)	76 A (5.6)	560 A (116.6)	932 B (219.2)	19 A (2.5)	19A (2.3)
Moderate	38 (5.0)	10 (2.7)	8 (1.3)	3 A (0.6)	11 (4.3)	60 A (7.6)	450 A (98.2)	447 A (80)	14 A (2.5)	12A (1.9)
High	39 (8.1)	20 (6.4)	9 (1.1)	6 B (1.2)	11 (5.4)	44 B (7.8)	37 B (14.4)	213 A (47.3)	3 B (1.1)	1B (0.8)
p-Value for ANOVA	0.102	0.08	0.239	0.05	0.176	0.009	0.003	0.002	0.0002	0.000

Pre-fire, NBR values expressed a similar range on the FTF (25-730) and reference sites (66-735). ΔNBR values on the FTF ranged from -164 to 622, compared to -190 to 197 on the reference site, reflecting much greater reduction in vegetation on the FTF site, as expected. As previously mentioned, pixels with ΔNBR values < 56 were classified as unburned (Table 2.3) based on a quantitative comparison with ΔNBR values in the adjacent reference site. ΔNBR ranges for the remaining three categories were subjectively selected to maximize agreement with qualitative assessment of field plots, resulting in 5 plots classified as unburned, 4 plots as burned with low severity, 11 plots as burned with moderate severity, and 10 plots as burned with high severity. Pixels with ΔNBR values between 56-105 were classified as low burn severity, between 105-312 as moderate burn severity, and > 312 as high burn severity (Table 2.3).

Table 2.3: Range of differenced normalized burn ratio (ΔNBR) values by burn severity class and associated area within the Fish Trap fire study site within Daniel Boone National Forest (DBNF), Kentucky.

Burn severity class	ΔNBR range	Area (ha)	Percentage of FTF area
Unburned	< 56	366	55
Low	56 – 105	140	21
Moderate	105.1 – 312	127	19
High	> 312	34	5

The Landsat-derived burn severity and visually-assessed burn severity method had an overall agreement of 70%; 70% of total plots were categorized as the same burn severity class by both Landsat-derived burn severity and visually-assessed burn severity method (Table 2.4). Producer and user accuracies – the proportion of field plots visually assessed as a certain burned severity class and classified as such using ΔNBR and vice versa, respectively – by burn severity class ranged between 50 and 88%. For example, 70% of plots visually assessed as burning with high severity on the ground were also classified as high burn severity based on ΔNBR. And conversely, 88% of the plots classified as high severity based on ΔNBR were also classified as such based on the visual assessment. Overall accuracy refers to the percentage of ΔNBR-derived burn severity classes that matched with the visually-assessed burn severity class. In general, accuracies were lower for the unburned severity class and higher for the high burn severity class (Table 2.4). Based on these ΔNBR ranges for burn severity, about 55% of the FTF area was assigned as unburned, 21% burned with low severity, 19% moderately, and about 5% burned with high burn severity (Table 2.3 and Figure 2.4). High and moderate burn severity areas were concentrated mostly along Auxier ridge, where the initial ignition occurred.

Table 2.4: Accuracy results from comparing the visual assessment and of differenced normalized burn ratio (ΔNBR)-derived burn severity classes on the 30, 500 m2 field plots. The term 'accuracy' refers to the degree to which ΔNBR-derived burn severity classes matched visually-assessed burn severity class.

Burn severity level	Producer accuracy (%)	User accuracy (%)
Unburned	60	50
Low	75	60
Moderate	73	73
High	70	88
Overall Accuracy	70%	

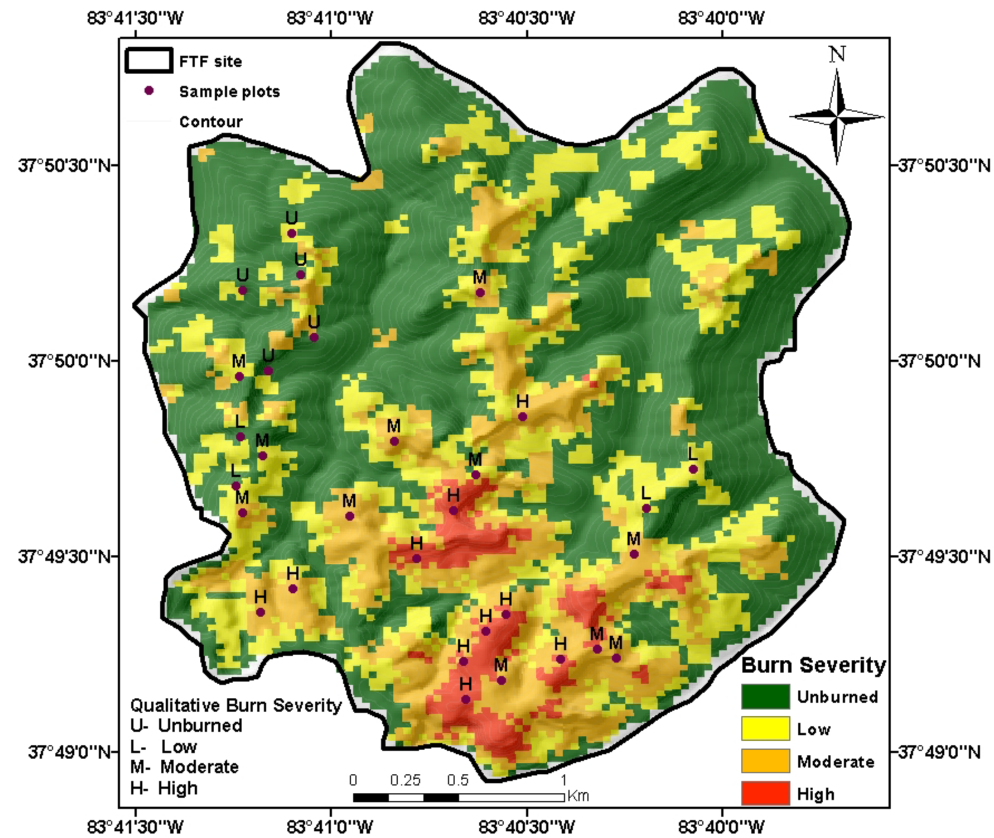

Figure 2.4: Burn severity surface map derived from of differenced normalized burn ratio (ΔNBR) values for the Fish Trap fire site, and visual burn severity assessment for the 30 field plots in Daniel Boone National Forest, Kentucky.

The NNIS walk-through survey was focused on areas that visually appeared to have been severely or moderately severely burned. Based on ΔNBR values, the surveyed area included pixels that were in all four burn severity classes (Figure 2.5). There were 2,061 paulownia stems or groups of stems recorded, about 69% of which were located in areas burned with high severity, despite that high burn severity areas accounted for only 22% percent of the area surveyed for NNIS (Figure 2.5; Figure 2.6). Twenty six percent of recorded paulownia stems were located on moderate burn severity, which made up 34% of the area surveyed. Thus, 95% of the paulownia stems recorded were found on 56% of the surveyed area. The remaining stems were found on low burn severity (2%) and unburned (3%) pixels which made up 44% of the surveyed area. Burn severity and number of paulownia stems were weakly, but significantly, related (adj. R^2 = 0.13, p<0.0001) (Figure 2.7). Looking at it another way, paulownia was present in about 60% of pixels classified as high burn severity, 32% of pixels with moderate burn severity, and about 5% and 7% of pixels classified as low burn severity and unburned, respectively (Figure 2.5).

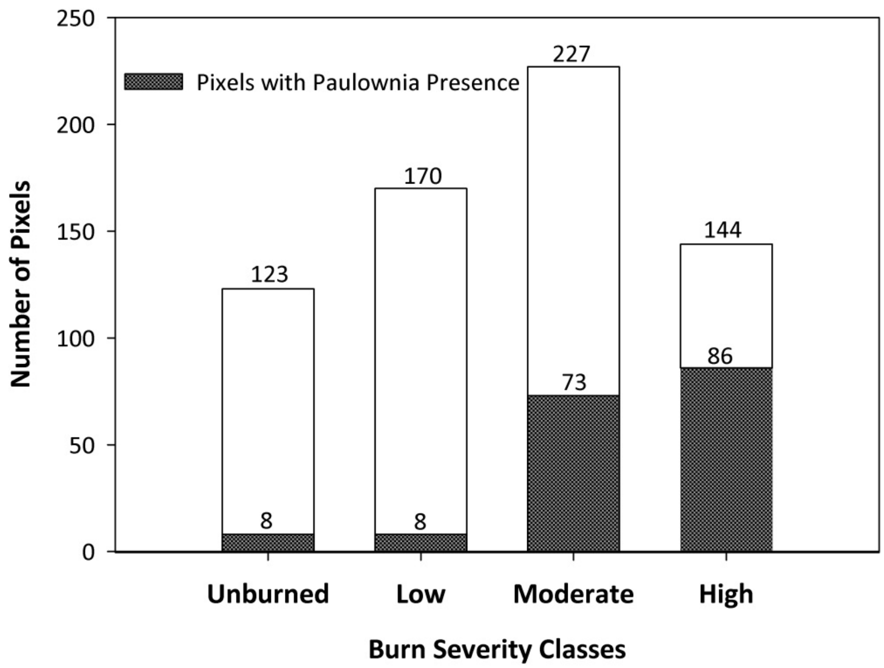

Figure 2.5: Number of pixels surveyed for paulownia, the number of pixels in which paulownia was recorded, by burn severity within the Fish Trap fire site in the Daniel Boone National Forest, Kentucky.

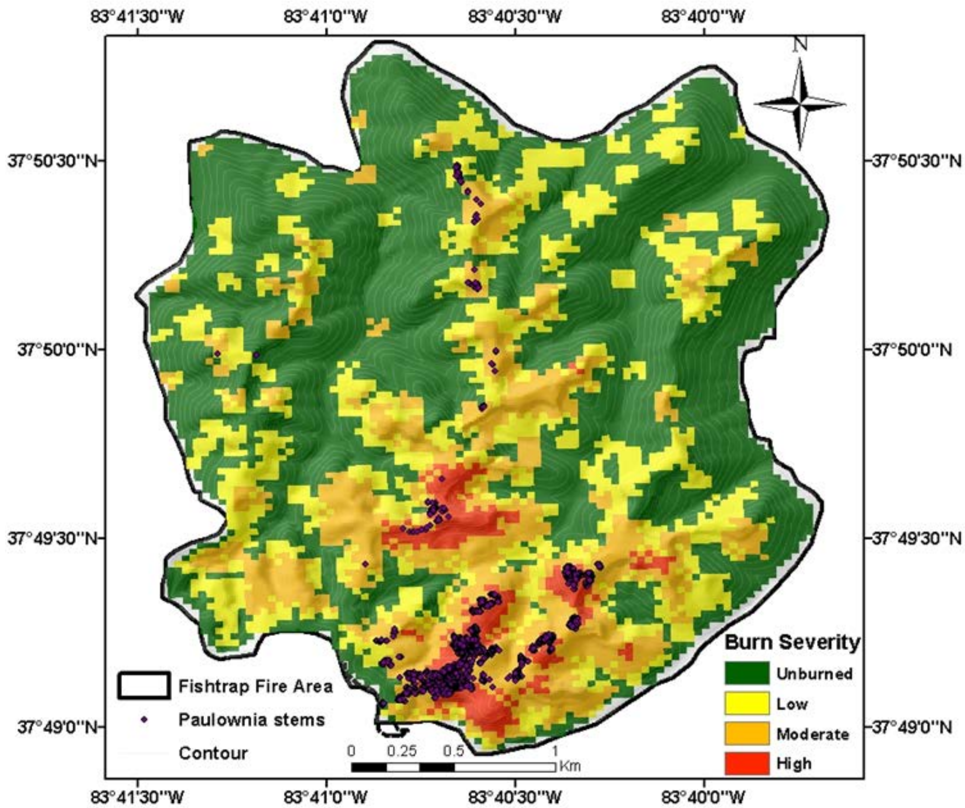

Figure 2.6: Burn severity map and location of paulownia stems within the Fish Trap fire site in the Daniel Boone National Forest, Kentucky.

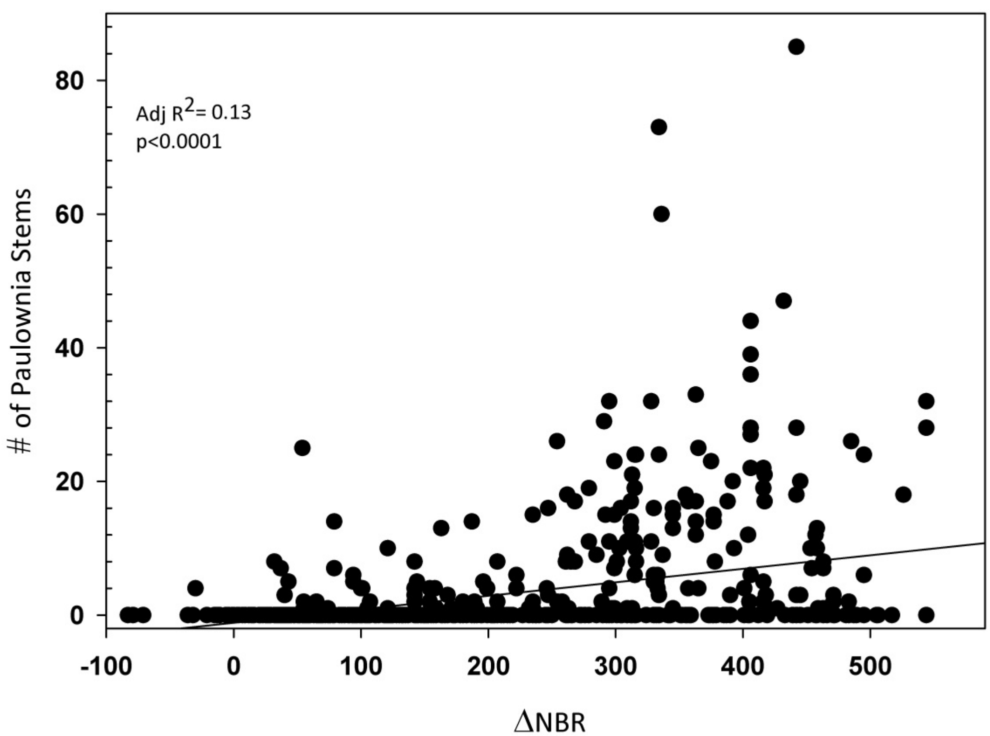

Figure 2.7: The number of paulownia stems recorded per pixel within the paulownia survey area in the Fish Trap fire site in the Daniel Boone National Forest, Kentucky.

Discussion

The use of ΔNBR derived from Landsat TM imagery was successful at assessing wildfire burn severity in the FTF site. We classified pixels with ΔNBR values <56 as unburned based on a quantitative comparison with ΔNBR values from the control site within the same landscape, a useful approach for determining the ΔNBR threshold for the unburned severity category. Our 70% agreement of qualitative (plot based) and quantitative (ΔNBR) methods of burn severity classification was comparable to values reported in other studies. For example, Cansler and McKenzie (2010) reported overall accuracy of 59% between ΔNBR and ground burn severity assessment. Overall, correlation of ground-based data and classification accuracies using ΔNBR indices is good, but varies among regions. French et al. (2008) reviewed 26 studies using ΔNBR and found the average accuracy of 73%.

The burn severity map derived from ΔNBR values and the four burn severity classes shows high spatial variation in burn severity, typical of wildfire severity patterns in the region (Wimberly and Reilly, 2007). The high and moderate burn severity areas were concentrated mostly on Auxier Ridge (Figures 2.3 and 2.4). The fire started at the south end of Auxier Ridge and moved counter-clockwise along ridge lines where vegetation was much dryer than that on mid-slopes and valleys. This pattern of fire severity across the landscape was further influenced by the duration of fire, topography, moisture conditions, species and the techniques and tools used to contain the fire (personal communication, Claudia Cotton, Forest Soil Scientist, DBNF, August 15, 2014). A similar relationship between fire severity and topography has been observed in other studies in the Southern Appalachians (Wimberly and Reilly, 2007). Species distribution likely also played a role in the spatial pattern of burn severity. Ridge tops in this area are typically dominated with by oaks and pines (Blankenship and Arthur, 2006), whose litters are more flammable than the mesophytic species typically found on lower slopes (Kreye et al., 2013), as well as the ericaceous species, Vaccinium and mountain laurel, which have higher concentration phenols and waxes, which are more flammable (Gilliam,2014).

The variability in forest floor cover found on the FTF did not reflect burn severity fully. Mineral soil exposure was higher on moderate and high burn severity plots compared to low severity; however, high mineral soil exposure was also found on unburned plots. Relatively high mineral soil exposure on the unburned sites is probably a result of turkeys scratching for food, a process that can readily scrape down to mineral soil, but that is dispersed very heterogeneously across the landscape.

Fire severity influenced regeneration density of paulownia. Because of variation in fuels and topography, wildfire creates a variety of microsites within a burned area (Kuppinger, 2008). Kuppinger et al. (2010) suggests that areas burned with high severity will have higher variability of microsites than areas burned with lower severity and landscapes with high severity may provide favorable habitat for Paulownia. About 95% of the paulownia stems recorded were found on 56% of the surveyed area in FTF sites. Areas that burned with high severity contained more than half (69%) of recorded paulownia stems suggesting a positive relationship between Paulownia colonization and burn severity. The heterogeneous distribution of burn severity brought change in moisture regime where are area was found wetter after wildfire. The area burned with high severity experienced the great change in moisture regime where soil moisture increased tremendously because most of the vegetation got consumed. This likely led to better site conditions for Paulownia (Kuppinger et al., 2010).

NNIS are an increasing threat to forest ecosystems after burning (Rebbeck, 2012) and wildfires can lead to an increased likelihood of colonization as high severity fires kill dominant vegetation, making light, nutrient and soil moisture resources more available (Fornwalt et al. 2010). For example, paulownia requires a large scale disturbance such as wildfire for germination and seedling establishment (Shiu-Ying, 1961). While paulownia is more likely to succeed in post-fire areas with less vegetation, it may not persist in mature forest areas where the canopy is too dense to regenerate this shade-intolerant species (Kuppinger, 2008). Unfortunately, paulownia grows rapidly and quickly becomes sexually reproductive, with a single tree producing 20 million or more tiny wind-dispersed seeds/year that can germinate readily in disturbed sites with exposed mineral soil (Shiu-Ying, 1961; Tang et al., 1980). Thus, while paulownia may not persist in the burned area as the forest canopy closes, its prevalence in the burned areas provides a significant seed source from which to colonize nearby disturbed sites in the region.

Studies conducted across a range of ecosystems have found similar relationships between the density of NNIS stems and burn severity (Crawford et al., 2001; Dodge et al., 2008; Kaczynki et al., 2011; Symstad et al., 2014). For example, in a northern Arizona ponderosa pine forest, NNIS comprised about 26% of the understory cover two years after a wildfire, with NNIS being more abundant in areas that burned with high severity compared to those burned moderately or unburned (Crawford et al., 2001). Fornwalt et al. (2010) also found NNIS richness and cover generally increased with fire severity in a ponderosa pine forest in central Colorado. Similar results were reported by Keeley et al. (2003) in oak savanna, chaparral and conifer forest in southern Sierra Nevada, California. This study is one of the first to demonstrate a significant relationship between burn severity and invasion by a non-native species, *Paulownia tomentosa,* in an eastern deciduous forest. Our results confirm that remote sensing derived metrics of fire severity can serve as predictors of non-native invasive species response to fire. Remotely sensed imagery can be used to assess burn severity for large areas and can serve as a useful tool to locate potential outbreaks of NNIS such as *Paulownia tomentosa*.

Conclusions and management implications

Land managers need accurate and efficient approaches for capturing the complex changes in the landscape after wildfires to develop appropriate management activities. While visual assessments of small-scale (less than 125 ha) disturbances are possible, large-scale visual assessments are impractical (USGS, 2010). Remote sensing imagery such as Landsat TM can provide an efficient and cost effective approach to quantifying and assessing disturbances at large scales in eastern deciduous forests of the US. Landsat derived information can greatly increase forest managers' abilities to efficiently assess burn severity and allocate restoration treatments accordingly.

Results from several studies using Landsat imagery suggest that ΔNBR value ranges for burn severity classes vary based on forest type, topography, weather conditions, and other factors. The ranges of ΔNBR presented in this study for classification of burn severity are applicable for upland oak-hickory dominated forests of the Cumberland Plateau region, and should only be cautiously applied to other areas with different vegetation and terrain conditions. However, our method of using a reference site to identify the break point between unburned and burned sites should be widely applicable.

The multi-temporal approach of burn severity assessment is also helpful to understanding invasion by NNIS. Our results suggest that areas burned with high severity have a larger chance of colonization by NNIS such as paulownia. Land and forest managers can use burn severity maps to design strategies to manage NNIS outbreaks and allocate treatments. Given limited resources, we recommend prioritizing high burn severity sites for monitoring the initial establishment of NNIS and predicting potential changes in forest communities on the DBNF.

Chapter Three

Using Landsat Imagery to Monitor Post-Wildfire Forest Structure in an Eastern Deciduous Forest

Introduction

Fire is an important ecosystem process that significantly impacts terrestrial systems throughout the world (Pyne et al., 1996; Lentile et al., 2006). The prehistoric role of fire in eastern deciduous forests has been well established over the past several decades (Delcourt and Delcourt, 1997), where fire in this region has been associated with the presence of humans over the past 10,000 years (Delcourt and Delcourt, 2000). Historically, fires in eastern deciduous forests varied from low intensity surface fires to high severity stand replacement fires (Wade et al., 2000). It is crucial to understand and assess fire's effects for forest managers tasked with formulating and implementing treatments or restoring disturbed areas (Escuin et al., 2008). Since forest managers in the eastern deciduous forest are using fire as a tool for management (Brose et al. 2001), it is necessary to assess the effects of wildfire on many aspects of forests, such as structural, functional and species diversity, which will help with achieving the stated management objectives. However, these structural measurements often depend on extensive and expensive fieldwork in large landscapes with rugged terrain across large spatial extents (Chapter 2). Remotely sensed images available at high spatial and temporal resolutions can extend the measurement capability where extensive field-based measurements are in practical (Ingram et al., 2005; Wilkie and Finn, 1996). The alliance between remote sensing techniques and forest structure could provide valuable means for monitoring and assessing forest conditions after wildfire in an eastern deciduous forest.

Vegetation indices derived using different bands of remotely sensed imagery can be used to assess the forest structure (basal area and stem density) in deciduous forests (Gamon et al., 1995). These indices are formed from different combinations of several spectral values that are quantitatively recombined in such a way as to yield a single value indicating the amount or vigor of vegetation within the pixel (Campbell, 1996). The spectral image reflects multiple aspects of the landscape, including the reflectance properties of forest structure, which potentially captures aspects such as stem density and basal area (Ingram et al., 2005; Lee and Nakane, 1996). For example Foody et al**.** (2001) associated vegetation indices with tree species diversity and forest biomass in a Bornean tropical rain forest. Freitas et al. (2005) assessed the relationship between forest structure and vegetation indices in an Atlantic rainforest in Brazil.

There are many vegetation indices, but the normalized difference vegetation index (NDVI), which uses the surface reflectance values for the red and near-infrared wavelengths (van Leeuwen et al., 2010), is frequently used to examine post-fire forest structure and vegetation response in the western US (Cocke at al., 2005; Key and Benson, 2006; Kushla and Ripple, 1998; Song et al., 2007). While a few recent studies have used Landsat data to map burn severity in eastern deciduous forest (Maingi and Henry, 2007; Wimberly and Reilly, 2007), they did not examine the potential of this freely available, high resolution remotely sensed data for assessing post-fire forest structure. Based on its application in other forested ecosystems, Landsat imagery has the potential to provide accurate and inexpensive information in support of landscape scale management objectives in the eastern deciduous forests.

An initial assessment of the utility of remote sensing data for assessing forest structure in an eastern deciduous forest following wildfire is a crucial step towards developing a program for the monitoring of forest change using Landsat data. Thus, the objective of this study was to analyze the relationship between Landsat imagery-derived vegetation indices and field-measured forest characteristics of basal area and stem density in an eastern deciduous forest. The use of vegetation indices as an indicator of forest structure may be a valuable tool for planning, conservation and restoration strategies in a landscape burned by wildfire.

Methods

FishTrap Fire

The FishTrap fire (FTF) burned approximately 674 ha of deciduous forest in the Cumberland Plateau, within the Daniel Boone National Forest (DBNF), in Powell County, Kentucky (lat. 37° 49' N, long. 83° 41' W) (Figure 3.1). It was started unintentionally by campers on 24 October 2010 and was fully contained on 9 November 2010. Prior to burning forest was dominated by upland oak-hickory forest type. Oaks [scarlet oak (*Quercus coccinea* Muenchh.), chestnut oak (*Quercus montana* Willd..), black oak (*Quercus velutina* Lam), and white oak (*Quercus alba* L)], hickories [pignut hickory (*Carya glabra* Mill.) and mockernut hickory (*Carya tomentosa* Poir.)], and pines [shortleaf pine (*Pinus echinata* Mill.), Virginia (*Pinus virginiana* Mill.), pitch (*Pinus rigida* Mill.), and white (*Pinus strobus* L.)] dominate the canopy while the midstory is dominated by red maple (*Acer rubrum* L.), sourwood (*Oxydendrum arboreum* L.), black gum (*Nyssa sylvatica* Marsh.) and sassafras (*Sassafras albidum* Nut.).

Elevation ranges from 177 - 439 m.a.s.l. across the study area. Mean annual temperature is 12.9°C, with mean high and low temperatures of 19°C and -4.3°C occurring in July and January, respectively. Mean annual precipitation is 119.2 cm, most of it occurring from March to June (Kentucky Climate Center, 2006).

Plot Data

In August 2011, after the wildfire, thirty 500m^2 (0.05ha) circular plots were arrayed across the burned area for measurement of forest structure (Figure 3.1). Plots were placed at random within the FTF area, based on terrain features retrieved from topographic maps. Center points of plots were permanently marked with rebar and GPS coordinates recorded. Within each plot the diameter at breast height (DBH) and species of all trees $\geq$2.0 cm DBH were measured and recorded. Measurements were made in all plots in summer 2011 for initial post-fire assessment, and re-measured in summer 2013 to assess change.

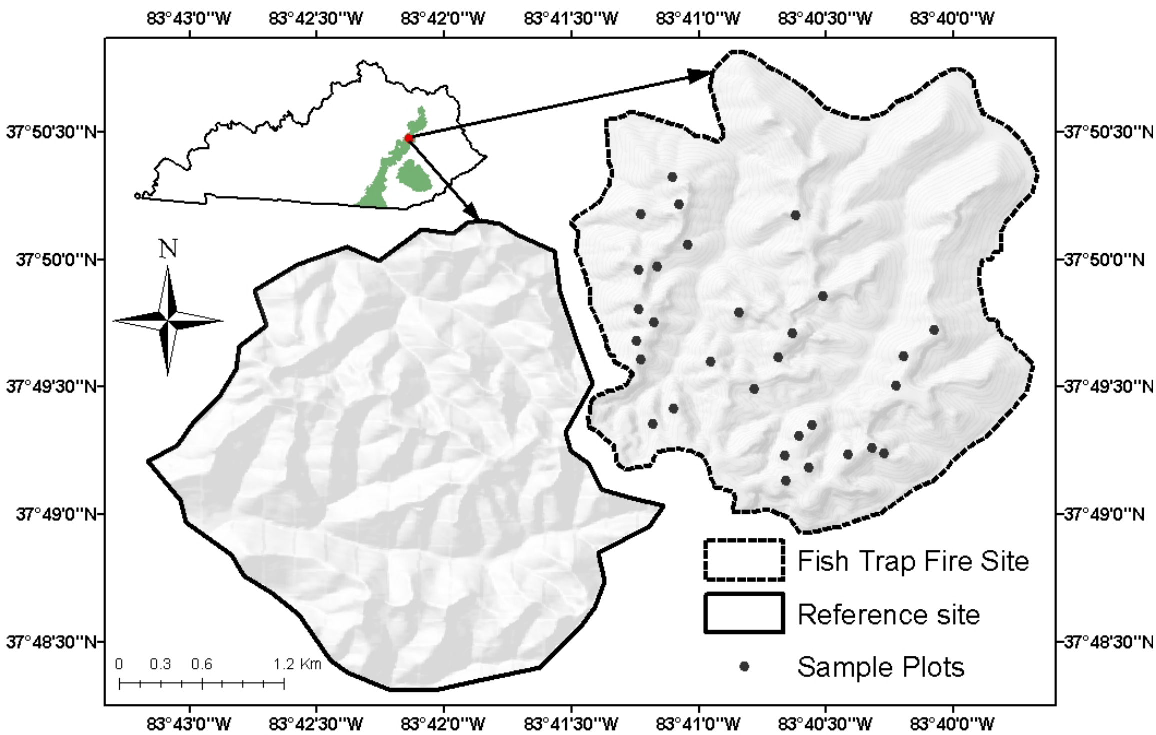

Figure 3.1: Location of Fish Trap fire and reference site area within the Daniel Boone National Forest, Kentucky, USA.

Remote Sensing Data and Image Processing

Using Landsat imagery, two spectral vegetation indices, differenced normalized burn ratio (ΔNBR) and normalized difference vegetation index (NDVI), were calculated for 2010, 2011 and 2013 to explore forest dynamics across the fire severity gradient. Landsat 5 TM (path 19, row 34) from October 2nd, 2010 and October 5th, 2011, and Landsat 8 from October 10th, 2013, images were acquired from the US Geological Survey and pre-processed using ArcMap 10.1. An area adjacent to the FTF with similar vegetation and terrain conditions was selected as a reference site to assess the pre-burn NDVI and its nature. All of the sites of interest are located within the same image, which were cloud free and terrain-corrected by the Earth Resources Observation and Science (EROS) data center, providing the highest level of correction available for Landsat scenes (Chander and Markham, 2003). The digital number (DN) for each Landsat band was converted into top-of-atmosphere (TOA) reflectance, a normalized, unitless measure of the ratio of the amount of light energy reaching the earth's surface to the amount of light reflecting off the surface and returning to the top of the atmosphere and thus detected by the satellite's sensors (Johnson, 2013; Stapp et al., 2015; USGS, 2013). The burn severity was calculated using differenced normalized burn ratio (ΔNBR) which was used to prepare a burn severity map of FTF (Chapter 2). All pixels were classified into four burn severity classes, unburned (ΔNBR<56), low (ΔNBR=56-105), moderate (ΔNBR-105-312) and high (ΔNBR>312), where 55% of FTF area was found to be unburned, 21% low,19 % moderate and 5% area was burned with high severity (Chapter 2).

There are many spectral vegetation indices, but the one most commonly used for assessing biophysical characteristics of forests is the normalized difference vegetation index (NDVI), which uses the ratio between red (visible) and near-infrared (NIR) bands, is computed as NDVI=(NIR-RED)/(NIR+RED) (Rouse et al.,1974). The NDVI value is based on the difference between the reflectance of NIR and red light. It is an index of plant "greenness" or photosynthetic activity. The red and near-infrared bands are sensitive to greenness; photosynthetically active vegetation absorbs most of the red light while it reflects much of near-infrared light. NDVI values thus range from -1 to +1, where negative values correspond to an absence of vegetation. The vegetation index values were extracted from each pixel within the burned and reference areas.

We first established that NDVI was similar across landscapes before wildfire, necessary due to the lack of pre-fire forest structure measurements. To do this, we used an area adjacent to the FTF, with similar vegetation and terrain conditions as a reference site (Figure 3.1). Pre-burn differences in NDVI among FTF and the reference site were tested with a t-test using all pixels from the reference and FTF sites in 2010.

The wildfire burned the FTF area with varied burn severity. Thus, it was also necessary to establish that NDVI was similar among different future burn severity classes before the wildfire occurred. One-way ANOVA was used to test pre-burn differences in NDVI among pixels from four different post-burn fire severity classes; unburned, low, moderate and high to establish that there were no pre-burn differences among future burn severity classes. Significance was determined with $\alpha=0.05$.

To test whether burn severity altered NDVI, two types of approaches were used. First, one-way ANOVA was used to test for post-burn differences in NDVI for each of the four burn severity classes using a sub-sample of pixels (n=75 pixels/severity class) within FTF. Where ANOVA results were significant, Tukey's HSD post-hoc test was used to compare NDVI between burn severity classes. Secondly, as our forest structure measurements were measured on plot, it is important to assess the plot level relationship between NDVI and burn severity, to do so we used the linear regression analysis.

To describe the relationship between forest structure (basal area and stem density) and NDVI, linear regression analysis was used, where basal area and stem density were used as the dependent variable and NDVI as the independent variable.

Post-wildfire change in forest structure (basal area and stem density) was evaluated by (1) computing the post-wildfire percentage change in forest structure measurement and (2) analyzing the differences between forest structure measurements in different burn severity classes between 2011 and 2013. Two-way ANOVA was used to analyze the interaction between year and burn severity on forest structure. All statistical tests were conducted using the ‘Stats Package’ in version 3.1.2 of the R Statistical Computing Software (R Core Team 2014).

Results

Pre-burn NDVI across landscape

T-test analysis using all pixels from the reference and FTF sites (14010 pixels) in 2010 revealed a statistically significant but numerically small difference in mean NDVI between reference and FTF sites $t(14008)=3.627$, $p=0.0002$, with mean NDVI of 0.656 and 0.659 for reference and FTF, respectively. On the FTF site only, we found no statistically significant difference among the groups of pixels that would be later classified as having burned at varying burn severity $F\ (3,296)=0.618$, $p=0.604$ (Figure 3.2, Table 3.1).

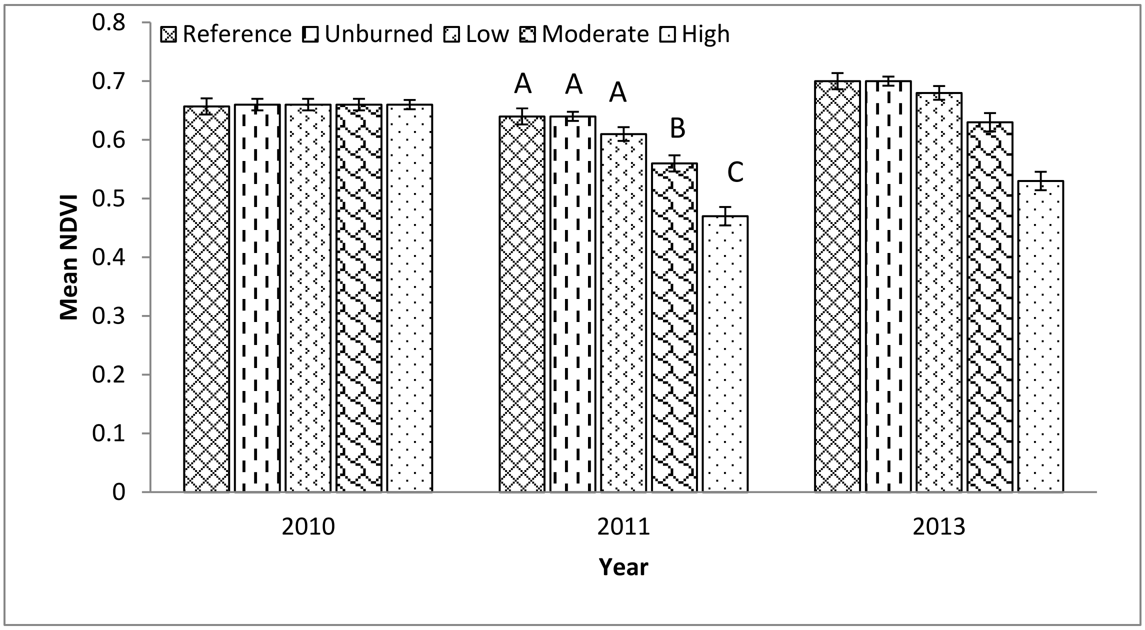

Figure 3.2: Mean NDVI for reference site and area with different burn severity within the FTF site based on a random sub-sample of 75 pixels per site on burn severity classification. Mean NDVI for three different years (2010, 2011, and 2013) was extracted from pixels from area burned with different severity. Mean NDVI (+SEM) with different uppercase letters are statistically significantly different (Tukey's HSD, $p>0.05$). Error bars are standard errors.

Table 3.1: ANOVA results for pre-fire (2010) and post-fire (2011) NDVI in four different burn severity pixels in Fish Trap fire area, Daniel Boone National Forest, Kentucky.

	Sources	Df	SS	MS	F	P
Pre-fire	Burn Severity Class	3	0.0033	0.001095	0.618	0.604
	Residuals	296	0.5243	0.001771		
Post-fire	Burn Severity Class	3	1.2609	0.4203	129	<0.0001
	Residuals	296	0.9643	0.0033		

Does burn severity alter NDVI?

After the wildfire, mean NDVI was significantly different among pixels burned with different severity (n=75/severity class with F (3,296) =129, *p*<0.0001 (Table 3.1)). Post-wildfire mean NDVI was similar between the unburned pixels in FTF (mean NDVI=0.636) and reference site (mean NDVI=0.639) t (148) =-0.45, p=0.646. Post hoc comparisons using the Tukey's HSD test indicate that the mean NDVI did not differ significantly between low and unburned area, but all other burn severity classes were statistically significantly different from each other (Figure 3.3).

To determine whether burn severity altered plot-based NDVI, linear regression analysis was used to describe the relationship between plot level NDVI and burn severity. We found a statistically significant relationship between burn severity and NDVI in 2011 as burn severity increased, NDVI decreased (adj R^2 0.58, p<0.0001) (Figure 3.4).

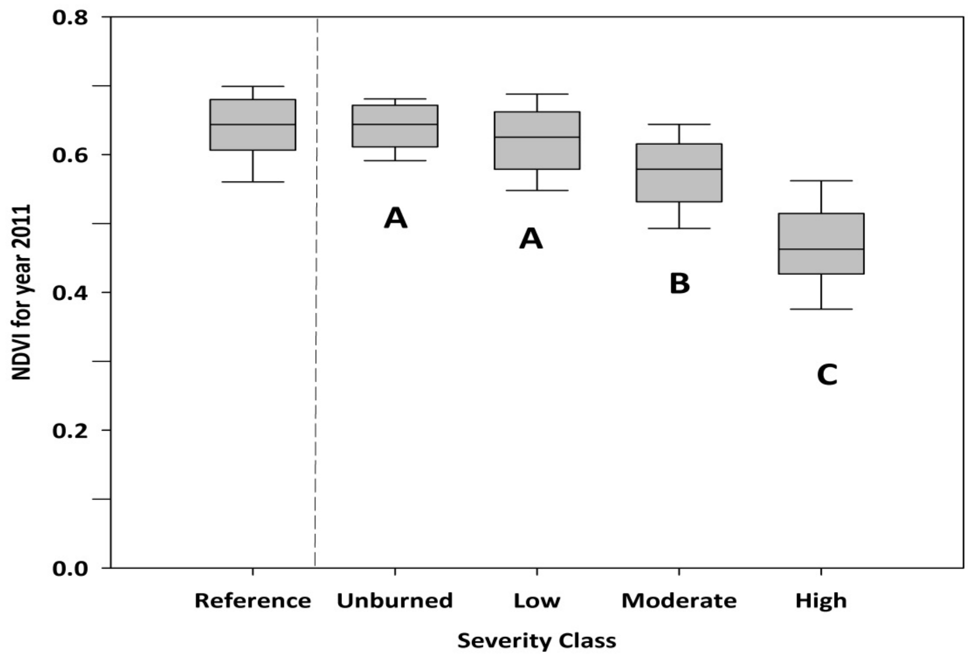

Figure 3.3: Boxplot for mean NDVI measured in year 2011 plotted by burn severity class (unburned, low, moderate and high) and reference site. Boxes with different uppercase letters are significantly different (Tukey's HSD, p<0.05).

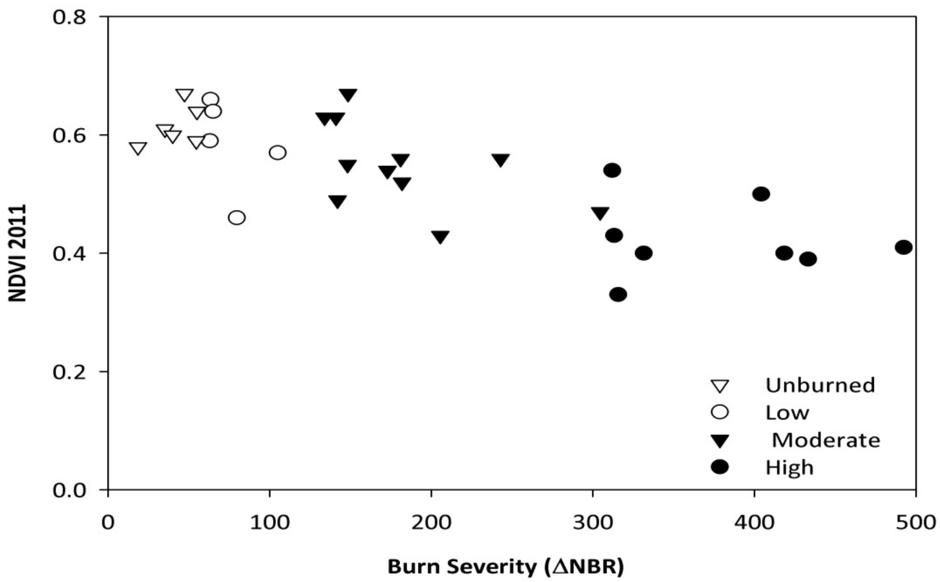

Figure 3.4: NDVI plotted against burn severity (differenced normalized burn ratio). NDVI was measured in 30 different plots in Fish Trap fire sites after wildfire (2011) in Daniel Boone National Forest, Kentucky.

NDVI and post-fire forest structure

There was a statistically significant positive relationship (adj R^2 0.41, $p<0.0001$) between NDVI and basal area (Figure 3.5). The relationship between stem density in 2011 and NDVI was weaker but also significant and positive (adj R^2 0.23, $p=0.0004$) (Figure 3.6).

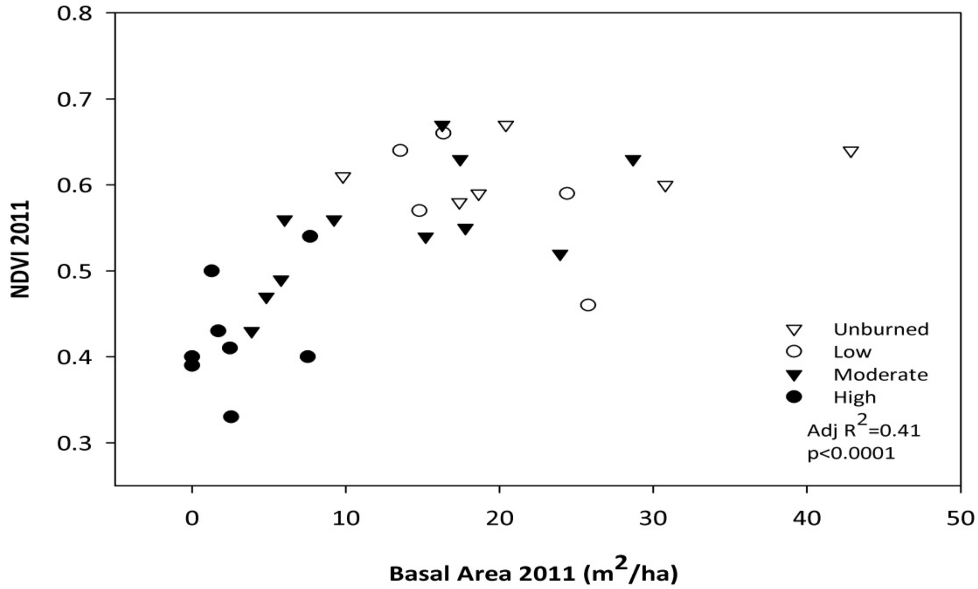

Figure 3.5: Basal area (m^2/ha) measured in 2011 plotted against post fire NDVI (n=30) for Fish Trap fire in Daniel Boone National Forest, Kentucky.

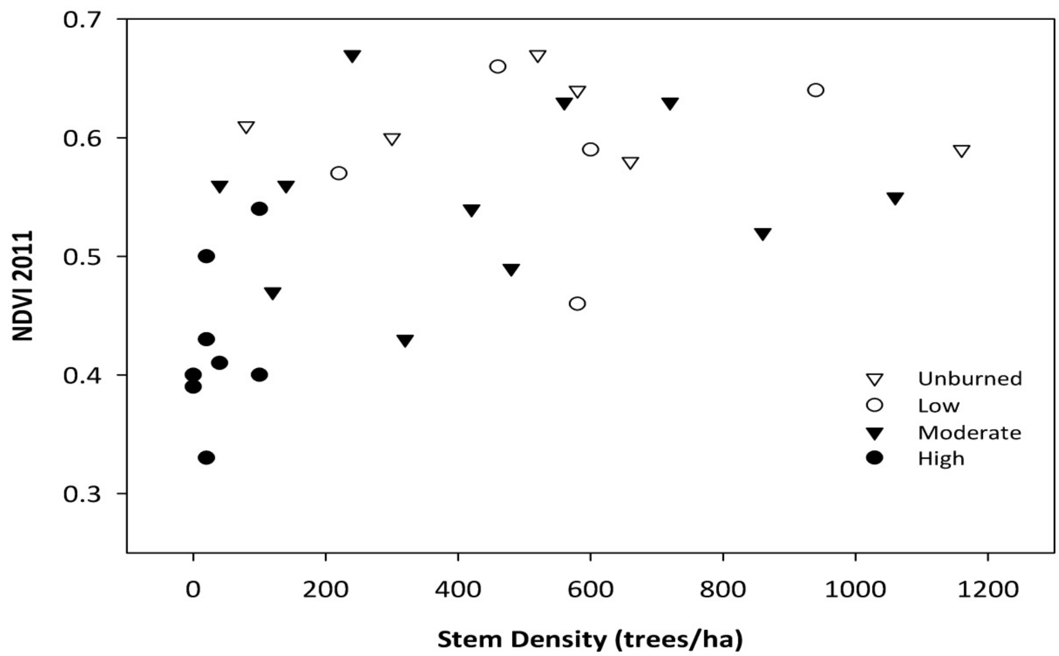

Figure 3.6: Stem density (trees/ha) measured in 2011 plotted against post fire NDVI (n=30) for Fish Trap fire, Daniel Boone National Forest, Kentucky.

Post-fire forest structure between 2011 and 2013

Based on field observations, basal area and stem density of live tree declined between 2011 and 2013, with the greatest reductions on the plots classified as moderate and high burn severity. The test for the effect of treatment shows a significant burn severity effect on basal area ($F=20.401$, $p<0.0001$) but not a significant year effect on basal area ($F=0.20$, $p=0.65$) (Table 3.2). Between 2011 and 2013, basal area decreased from 14 to 12 m^2/ha (or 14% reduction), on average, in plots burned with moderate severity, and 66%, from 3 to 1 m^2/ha in high severity plots (Figure 3.7). Stem density increased 4% on average from 550 to 573 trees/ha in unburned area, while increased 475% on average from 37 to 213 trees/ha in area burned with high severity (Figure 3.8).

Table 3.2: Results from the two-way ANOVA for the effects of years and burn severity on basal area (m2/ha) and stem density (trees/ha) measured in year 2011 and 2013 in FishTrap fire area, Daniel Boone National Forest, Kentucky.

	Sources	df	SS	F	P
Basal Area	Burn Severity	3	3471	20.401	<0.0001
	Year	1	11.50	0.2028	0.6543
	Burn Severity*Year	3	8.8357	0.0519	0.984
	Residuals	52	2949		
Stem Density	Burn Severity	3	2701705	11.005	<0.0001
	Year	1	188160	3.3682	0.0722
	Burn Severity*Year	3	282006	1.1487	0.338
	Residuals	52	4255222		

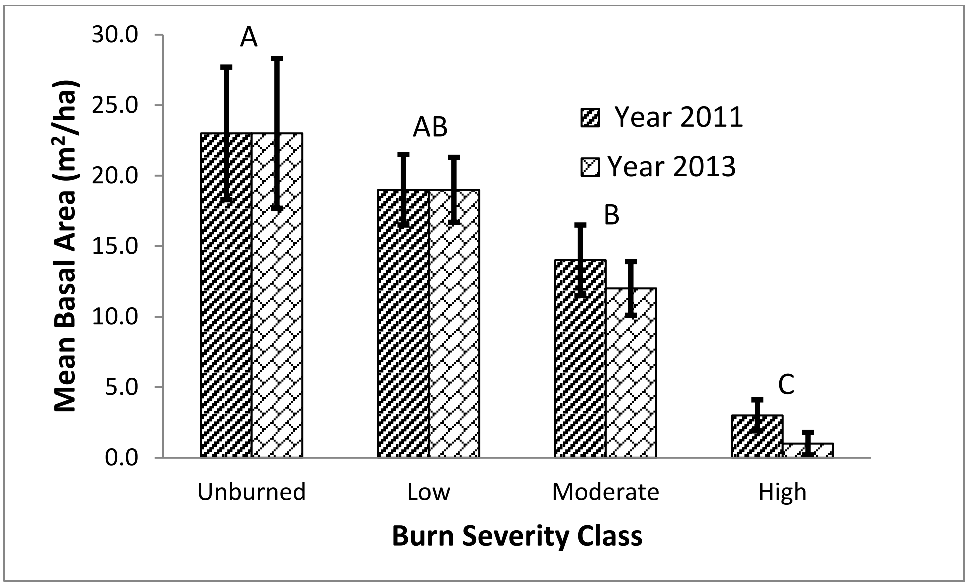

Figure 3.7: Mean basal area (m^2/ha) in different burn severity class for two different years (2011 and 2013) in Fish Trap fire area, Daniel Boone National Forest, Kentucky(n=30 per burn severity class). Means (+SEM) followed by the same letter within burn severity class are not significantly different (Tukey's HSD, p>0.05). Error bars are standard errors.

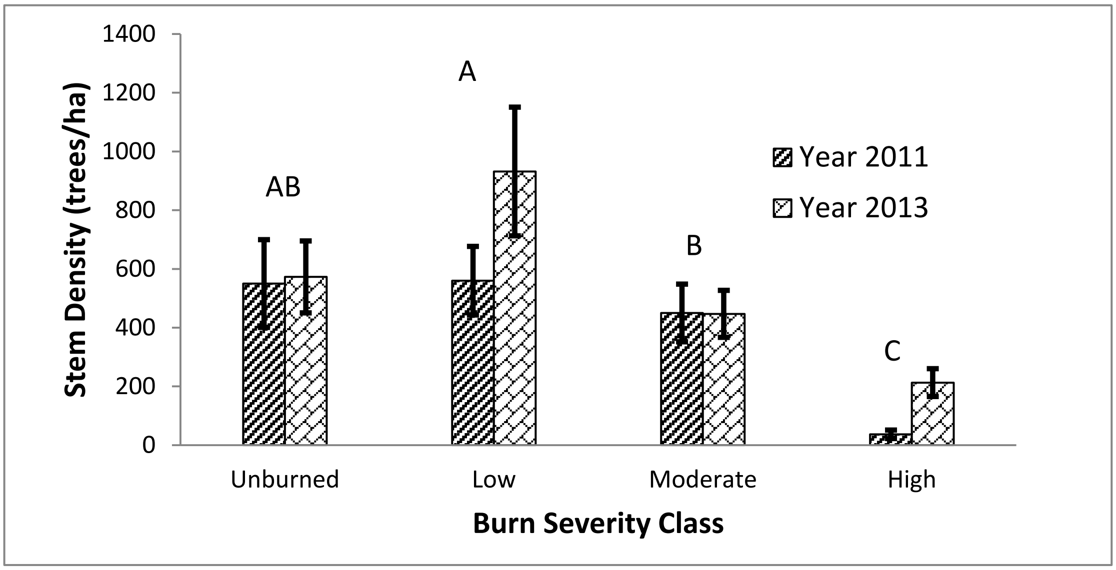

Figure 3.8: Mean stem density (trees/ha) in different burn severity class for two different years (2011 and 2013) in Fish Trap fire area, Daniel Boone National Forest, Kentucky (n=30 per burn severity class. Means (+SEM) followed by the same letter within burn severity classes are not significantly different (Tukey's HSD, p>0.05). Error bars are standard errors.

Discussion

Prior to the Fish Trap fire, the reference and Fish Trap landscapes had significantly but slightly different mean NDVI, with the area eventually consumed in the wildfire having slightly higher NDVI values than the reference site just before the fire. Pettorellie et al. (2005) showed a similar type of pre-fire NDVI between reference and burned area. Factors such as topography (Thomas, 1997), composition of species, vegetation vigor, leaf properties and vegetation stress (Markon et al., 1995) are factors that can affect variation in NDVI within a single landscape.

High variability in NDVI response following the FishTrap fire was not surprising as post-wildfire landscapes are typically characterized by a high degree of variability in vegetation due to variations in burn severity, which we also found for this landscape (Chapter 2). Areas burned with moderate and high severity had the greatest variability in NDVI value compared to plots unburned or burned with low severity (Figure 3.4). The variation in NDVI among severely burned pixels was due to pixels burned with heterogeneous severity which reduced the vegetation heterogeneously (Lentile et al., 2006; Reed et al., 1994). A similar result was documented following other large wildfires in Spain, U.S. and Israel (van Leeuwen, 2010).

At the landscape level, burn severity alters the forest structure which in turn affects the NDVI (van Leeuwan et al., 2010; Turner et al., 1999). Our results suggest a consistent decreasing trend in the plot level NDVI with increasing burn severity after fire (Figure 3.4). This may indicate that the differences in NDVI between areas burned with different severity are highest after the fire and slowly diminish with time after the fire.

The relationship between a Landsat-derived vegetation index and forest structural measurements from the linear regression analysis demonstrate that the NDVI from Landsat (30 m resolution) Thematic mapper are useful for estimating forest basal area for the eastern deciduous forest. Ingram et al. (2005) conducted similar studies in a tropical forest and found a similar relationship between forest structure and NDVI. Plots burned with moderate to high severity experienced the lowest basal area and stem density. The heterogeneous pattern of distribution in forest structure was observed in plots burned with moderate to high severity (Figures 3.5 and 3.6). The area burned with moderate to high severity experienced reduction in basal area in year 2013 from year 2011. High variability in stem density was observed in plot unburned or burned with low severity this might be because there might be positive effects of fire on regeneration, especially the regeneration of red maple and serviceberry, where over story stems were not affected by burning.

In this study, basal area and stem density showed a positive relationship with NDVI. This pattern between forest structure and NDVI suggests that NDVI could explain the structural maturity of forest. Huete et al. (1997) showed that NDVI could be explained by the saturation effect (asymptotic behavior of reflectance of visible and near-infrared band when a biophysical parameter of vegetation increases continuously), sensitivity over dense canopies. Freitas et al. (2005) showed a linear relationship between NDVI and vegetation measurements (density of trees, tree diameter, tree height, basal area). They observed the constraints caused by saturation but such constraints were not found on deciduous forest in India (Bawa et al., 2002). This shows that NDVI seems to provide good estimates in deciduous forests (Freitas et al., 2005).

This study is one of the first to demonstrate a significant relationship between NDVI and forest structure (basal area and stem density). Our results confirm that Landsat data derived vegetation index (NDVI) can be helpful on assessment of post-fire forest structure, particularly in areas that have high burn severity. More work is needed to clarify the relationship between post-fire forest stand structure and low, unburned and moderate burn severity.

Conclusions and management implication

Forest and land managers need tools to monitor the effect of wildfires on ecosystem health and evaluate the effect of post-fire forest management. As the forest structures such as basal area and stem density represents the condition of forest, they need information on these forests structural after wildfire for management. Remote sensing imagery such as Landsat TM can provide a best approach to assessing forest structure after wildfire at large scales in eastern deciduous forests of eastern United States.

The relationship between spectral information and ground-measured forest structural data can be a valuable tool to monitor modifications in structure due to forest disturbances (Lambin, 1999). Landsat data are shown to be an effective tool for monitoring both burned and unburned areas. This study has demonstrated the potential for using a ground-measured data and freely available Landsat thematic mapper spectral information from near infrared and red band for estimating the basal area and stem density of eastern deciduous forest. The significant relationship between Landsat derived NDVI and ground-measured stem density and basal area supports the utility of the methods presented here for assessments of stem density and basal area across a forest landscape in an eastern deciduous forest. The relationships between forest structure measurements and vegetation indices found in this study must be tested in other deciduous forest sites before they are widely used to assess forest structure using remote sensing. This tool may be useful to evaluate eastern deciduous forest instead of only mapping and assessing them. Such tools could provide a useful supplement to traditional ground-based forest inventories, which needs more time and high economic inputs.

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Vita

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