Research Article

# Comparison of Burn Severities of Consecutive Large-Scale Fires in Florida Sand Pine Scrub Using Satellite Imagery Analysis

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## ABSTRACT

Remotely sensed imagery has been used extensively in the western US to evaluate patterns of burn severity and vegetation recovery following wildland fires. Its application in southern US ecosystems, however, has been limited. Challenges in southern areas include very high rates of vegetation recovery following fire, frequent cloud cover, and the presence of standing water. Use of remote sensing in southern forests should therefore be coupled with concurrent ground-based assessments, at least until the methods are tested for different ecosystems. Here, we assessed burn severity using remote sensing in a sand pine scrub ecosystem, which occurs on the central ridge of the Florida peninsula and is characterized by infrequent (>40 years on average) high severity fire. Two overlapping fires that burned in 2006 and 2009 provided a unique opportunity to explore compounded fire severity patterns. Landsat-based imagery analysis matched ground-based severity measures roughly half of the time. In general, higher severity fire led to lower severity or unburned conditions, while low severity fire had a less pronounced impact on either preventing or reducing fire severity in the subsequent fire. The unusually frequent fires both occurred during drought conditions. As the region's climate is predicted to be drier and hotter in the future, this work has implications for potential climate change effects on sand pine scrub fire regimes and, hence, ecosystem perpetuity.

*Keywords:* burn severity, Juniper Prairie Wilderness, *Pinus clausa*, sand pine

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## INTRODUCTION

Fire, whether wild or prescribed, has variable effects on vegetation and fuels and can influence post-burn vegetative patterns and fuel loads for periods of time ranging from months to years. Following landscape level fires, accurate measures of the size, shape, and ecological effects of fire can be difficult to assess without the use of maps (Lentile *et al*. 2006, Holden *et al*. 2010). Post-fire maps are used by managers to determine the results and impacts of prescribed fires and wildfires within managed landscapes. Even though remotely sensed methods of mapping fires have existed for years, many land management agencies still utilize manual methods that involve personnel physically walking the burned area perimeter with a global positioning system (GPS) unit, or flying over the burned area and sketching the fire by hand (van Wagtendonk *et al*. 2004). These techniques can be costly and time consuming and may not be feasible on very large landscape level fires, in rough terrain, or in dense vegetation (Henry 2008). Furthermore, such methods may be limited in ability to capture quantitative information describing the variable severity of fire effects on vegetation, soils, and wildlife habitat. Post-fire maps that are developed using remotely sensed imagery can quantify and delineate the heterogeneous effects of fire on fuels and vegetation across large areas. The efficacy and usefulness of maps of post-fire effects, or burn severity, has been demonstrated by numerous studies across a wide range of forest types and regions (van Wagtendonk *et al*. 2004, Epting and Verbyla 2005, Miller and Thode 2007). Several definitions and terminologies have been used in the published literature to describe the concept of burn severity, at times inconsistently and confusingly (Keeley 2009). For the purpose of this paper, burn severity will follow the definition described in detail in Eidenshink *et al*. (2007), where burn severity is a measure of the amount of change to the vegetation and biomass caused by fire within one year within the fire perimeter as a result of fire intensity and residence time.

Burn severity maps are useful tools for both managers and scientists as planning aids for post-burn vegetative management or harvest, for estimates of habitat change and restoration needs, and as quantitative spatial assessments of landscape level change patterns over time (Karau and Keane 2010). In this study, burn severity analyses used normalized differences between the near infrared band (0.76. μm to 0.90 μm) and the mid infrared band (2.08 μm to 2.35 μm) from geometrically and radiometrically corrected Landsat-7 Enhanced Thematic Mapper Plus (ETM+) imagery taken before and after a fire. These calculated Normalized Burn Ratio (NBR) burn severity indices were compared pre- and post-fire using the multi-temporal differenced Normalized Burn Ratio index (dNBR or ΔNBR) (Key and Benson 2006). This technique has been frequently applied for delineating and mapping burn severity in other ecosystems and regions (Cocke *et al*. 2005, Epting and Verbyla 2005, Key and Benson 2006, Clark and Bobbe 2007). These indices have been used in a few previous studies of Florida vegetation: to measure burn patterns over a decade in the Osceola National Forest (Malone 2010); to assess agreement with ground measures in flatwoods, sandhill, and depression swamps in the Apalachicola National Forest, Osceola National Forest, and Okefenokee National Wildlife Refuge (Picotte and Robertson 2011); and to delineate the boundaries of fire scars in the Ocala National Forest (Henry 2008).

The intent of our study is to utilize Landsat satellite imagery to produce burn severity maps of two overlapping fires that occurred over a three-year period. The study of interacting events such as fires and hurricanes on ecological processes has garnered increased attention in recent years, in part due to managing agencies that seek to encourage ecologically resistant and resilient ecosystems as part of global climate change adaptation and mitigation strategies (Joyce *et al*. 2009, Holden *et al*. 2010). Little research has been done to explore the ecological effects of interacting fire severity, particularly in the southeastern US (Collins *et al*. 2009, Holden *et al*. 2010). Our work is conducted within Florida's Ocala National Forest, home to the largest remaining tract of sand pine (*Pinus clausa* [Chapman ex Engelm.] Vasey ex Sarg) scrub in the world. The Ocala National Forest is managed by the Forest Service for multiple uses, including the perpetuation of the ecotype and the provision of habitat for threatened and endangered species. Sand pine scrub is a threatened and endemic ecosystem found only in Florida and southern Alabama that can exhibit highly variable patterns of burn severity and is characterized by infrequent (>40 years fire return interval) high severity, high intensity stand-replacement fires (Myers and Ewel 1990, Godwin 2008, Freeman and Kobziar 2011). The development of burn severity mapping procedures calibrated for sand pine scrub ecosystems would provide a method for the Forest Service to assess and quantify the impact of wildfires and prescribed fires across the vast 155 000 ha Ocala National Forest. The forest is an area containing many pyrogenic vegetative communities that are associated with frequent fire (<20 years) and threatened and endangered plant and animal species (Myers 1985). The more accurately and precisely that the forest staff can track the impact of wildfires and prescribed fires, the better they can tune their management responses to meet management goals. Despite this need for tracking impacts, studies of remotely sensed imagery for mapping fires in sand pine scrub are few, with only two known studies in the sand pine ecosystem (Godwin 2008, Henry 2008).

Here, we explore how the patterns of burn severity from one fire affect a subsequent fire in a Federal Wilderness Area of the Ocala National Forest. In late July 2006, prescribed fire was ignited within the Juniper Prairie Wilderness with the intent of burning a number of grassy prairies associated with isolated wetlands. Within several days of burning operations, the fire escaped initial prescriptions and moved into neighboring sand pine and slash pine (*Pinus elliottii* Engelm.) stands and was reclassified as a wildfire. In spite of active fire suppression activities, the wildfire continued to burn into August 2006, ultimately burning approximately 4500 ha across numerous vegetative communities and multiple sand pine stand ages and conditions (Godwin 2008, Freeman and Kobziar 2011). On 10 March 2009, following a period of vegetative regrowth, fuels changes, and drought, an escaped campfire ignited a second wildfire that burned over a period of several weeks despite active fire suppression. By the time it was extinguished, the fire had burned 2600 ha within the same area of the 2006 fire. The unprecedented repeated burning of such large tracts of sand pine scrub, under wilderness area management restrictions, presented a unique opportunity to study remote sensing mapping techniques and burn severity trends among a variety of sand pine scrub stand types. Within that context, this study seeks to address the following questions: How well did the remotely sensed burn severity map represent on-the-ground burn severity measurements? How did the burn severity from the 2006 fire influence burn severity following the 2009 fire? What are the implications for the perpetuation of sand pine scrub of two fires occurring within an unprecedented short time period?

## METHODS

### *Study Area*

This study took place within the Juniper Prairie Wilderness (henceforth JPW), a 56 $km^2$ federal wilderness area within the Ocala National Forest in north central Florida, USA (29° 12 N, 81° 41 W) (Figure 1). Federally designated as a wilderness area in 1984, the JPW falls under the resource management protection of the US 1964 Wilderness Act (The Wilderness Act 1964). The JPW is within a geographic region comprised of Miocene-Pleistocene marine and aeolian deposits that form the interior highlands of the Florida peninsula, where many of the uplands consist of well-drained sandy Entisols (Myers 1985, Carrington 1999). The JPW is relatively high in elevation for peninsular Florida and has a maximum, minimum, and mean elevation of 29.4 m, 2.80 m, and 13.54 m (respectively). The climate is warm, with a mean annual temperature of 21.5 °C; a mean January minimum temperature of 7.61 °C, and mean maximum July temperature of 33.4 °C (NOAA-NCDC 2001). Precipitation is predominantly from rainfall and averages 126.19 cm annually, with

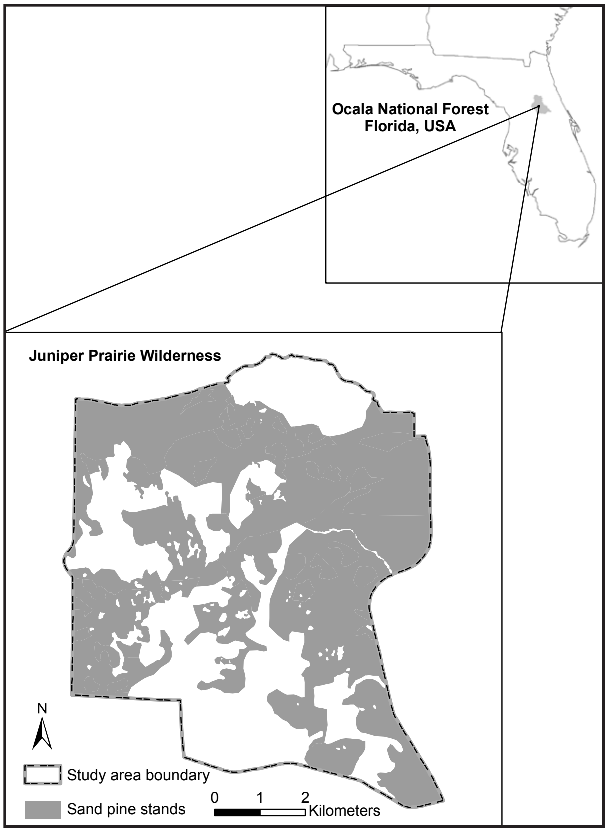


**Figure 1.** Juniper Prairie Wilderness Area, Ocala National Forest, USA.

63.09 cm falling during the summer months of June through September, with the months of October through December and the month of April as the driest months of the year (NOAA-NCDC 2001). Sand pine scrub is the dominant forest type, with 64% of the JPW classified as covered by some type of sand pine scrub community. Other forest types found within the JPW include: longleaf pine (*Pinus palustris* P. Mill.) forest, slash pine flatwoods, and mixed sweet bay (*Magnolia virginiana* L.)–tupelo (*Nyssa biflora* Walt.) swamp. Sand pine scrub is typically dominated by an even-aged monoculture overstory of sand pine, and the understory and midstory generally dominated by scrubby sclerophyllic oaks (*Quercus* spp. L.) (Veno 1976, Myers 1985, Outcalt and Greenberg 1998). Sand pine tends to be a short-lived species on most sites with mortality increasing dramatically after age 40 yr (Outcalt 1997). The pine is an obligate seeder that releases seeds from semi-serotinous cones when sufficiently heated by fire, similar to jack pine (*P. banksiana* Lamb.) and lodgepole pine (*P. contorta* Dougl. ex Loud.) (Myers 1985, Custer and Thorsen 1996, Freeman and Kobziar 2011). Without fire, sand pines release only limited seeds, resulting in sparse natural regeneration. Relying on lightning ignitions, sand pine scrub is believed to burn every 15 years to 100 years, with more recent evidence suggesting optimum burning when stands are approximately 23 years of age (Myers 1985, Menges and Hawkes 1998, Fonda 2001, Freeman and Kobziar 2011).

Of the forest types found within the JPW, six were represented in this study: mature longleaf pine, mature slash pine, mature sweet bay, mature sand pine, sapling sand pine, and damaged senescent sand pine. The damaged sand pine stands were identified by the Forest Service following the 2004 hurricane season, during which many stands suffered significant windthrow due to high wind events, resulting in high fuel loads and altered stand structure (Freeman and Kobziar 2011).

### *Image Classifications*

We acquired four preprocessed level LT1 Monitoring Trends in Burn Severity (MTBS) Landsat-5 scenes (path 16, row 40) from the US Geological Survey (USGS) Earth Resources Observation and Science (EROS) data center in Sioux Falls, South Dakota, USA. Image acquisition dates were as follows: 13 September 2005 (pre-burn), 19 November 2006 (post-burn), 13 March 2008 (pre-burn), and 16 March 2009 (post-burn). These datasets came prepackaged with NBR calculated, although without delineated severity thresholds (for information on NBR calculation methods, see Key and Benson 2006). We selected pre-burn and post-burn scenes for each fire to minimize cloud cover and seasonal differences. Using a geographic information system (GIS) (ESRI

ArcGIS 9.2, ESRI Inc., Redlands, California, USA), we clipped all four scenes by the boundary of the JPW to reduce image size and allow for calculations based only on the fires that burned within the study area. The ΔNBR spectral index is used to assess the amount of ecological change caused by fire by subtracting post-burn NBR values from pre-burn NBR values (Key and Benson 2006, Miller and Thode 2007, Holden *et al*. 2010). The advantage of this technique is that the magnitude of vegetation change between image acquisition dates is captured and quantified (Key and Benson 2006, Holden *et al*. 2010). We created the ΔNBR scenes using the NBR image pairs for each burn using the following equation in the ArcGIS 9.2 raster calculator (Key and Benson 2006):

$$\Delta NBR = NBR_{pre\text{-}burn} - NBR_{post\text{-}burn} \quad (1)$$

We manually derived four burn severity thresholds (unburned, low, moderate, and high) following Key and Benson (2006) using the histogram slider in ArcGIS for the 2006 ΔNBR scene (Table 1). The thresholds between burn severity classes that we determined used natural breaks in the data and followed recommendations based on the observations of field personnel who were familiar with the post-burn landscape conditions. We then applied these thresholds to the 2009 ΔNBR scene, and both scenes (2006 ΔNBR and 2009 ΔNBR) were reclassified as four color thematic maps (Figure 2). We completed the ΔNBR scene pixel count calculations using ArcGIS 9.2, Microsoft Excel 2007 (Microsoft Inc., Bellevue, Washington, USA), and SAS 8.0 (SAS Institute Inc., Cary, North Carolina, USA).

**Table 1.** Differenced normalized burn index (ΔNBR) thresholds selected to delineate Landsat satellite images into four classes of burn severity following fire in the Juniper Prairie Wilderness, Florida, USA.

| Year | Severity | ΔNBR threshold |
|---|---|---|
| 2006-2009 | Unburned | <57 |
| | Low | 58 to 382 |
| | Moderate | 383 to 596 |
| | High | >597 |

### *Burn Severity Plots*

To assess the agreement of the 2006 ΔNBR with ground observations, we established 60 Composite Burn Index (CBI) (Key and Benson 2006) plots within the burned and unburned sapling sand pine, damaged sand pine, and mature sand pine stands (Godwin 2008, Freeman and Kobziar 2011). In the winter and spring following the 2006 JPW burn (December 2006 and May 2007), we recorded the CBI observations. We collected plot data following an adaptation of the Key and Benson (2006) FIREMON: Landscape Assessment sampling approach. We systematically located our plots in stands visually identified at four levels of burn severity (unburned, low severity, moderate severity and high severity) from surveys on the ground and from aerial images taken within days of the 2006 burn (Godwin 2008, Freeman and Kobziar 2011). Within each stand type and burn severity combination, we established five plots ($n$ = 60). To avoid edge effects, we systematically located the plots a minimum of 20 m from edges (including edges between visual severity levels and other vegetation or stand types) with a minimum separation of 100 m between plots. At each 10 m × 10 m CBI plot, we visually assessed burn severity at multiple vertical layers of vegetation: substrate (forest floor and surface fuels), herbs, shrubs, small trees (>20 cm diameter), and large trees (<20 cm diameter). We assessed burn severity for each layer and assigned a value ranging from 0 (unburned) to 3 (severely burned) as described in Landscape Assessment (Key and Benson 2006). We combined the CBI strata values of each plot to give us a total overall plot severity value, henceforth referred to as CBI Total. We used this CBI Total to assign

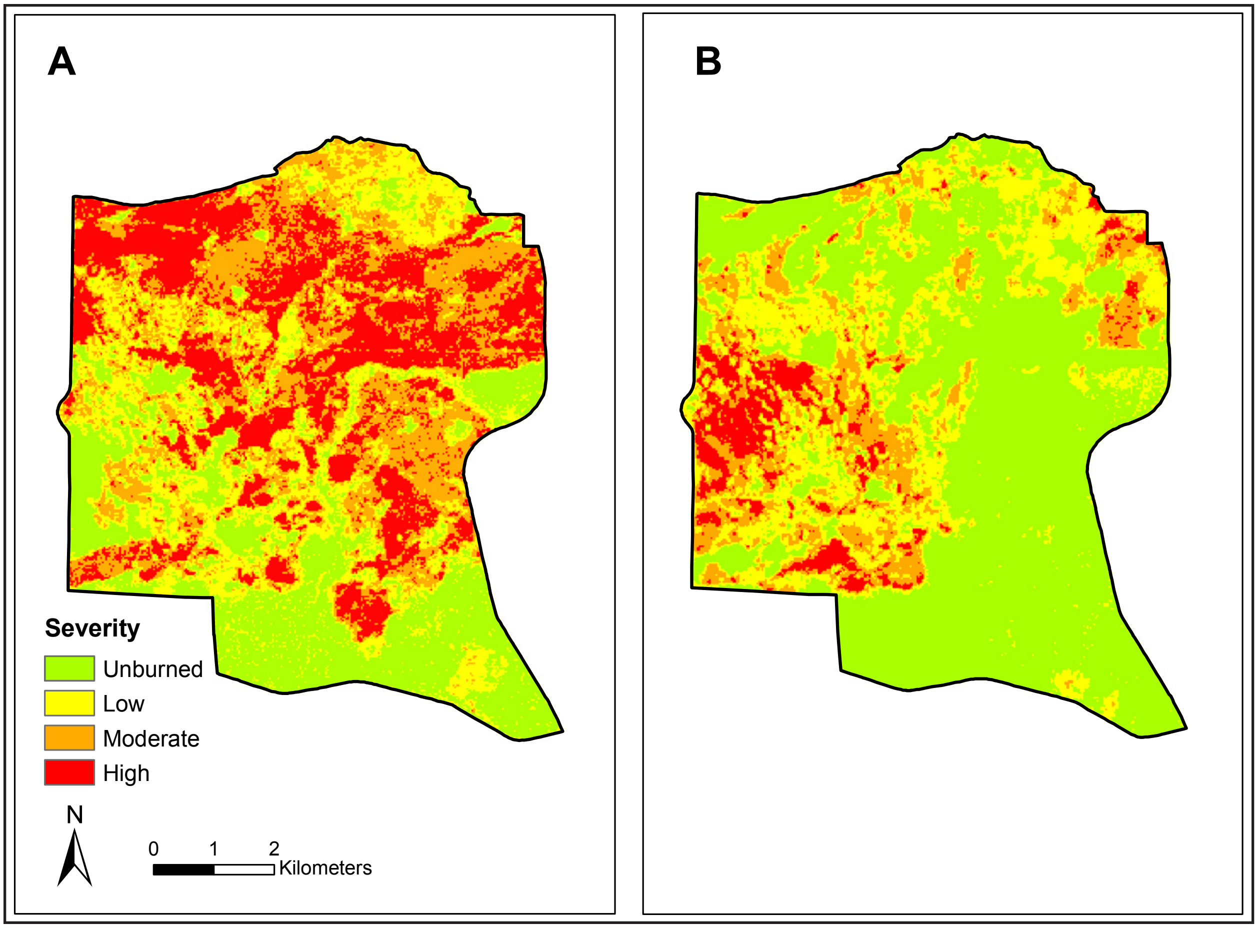


**Figure 2.** Four class burn severity thematic map of the 2006 (A) and 2009 (B) fires in the Juniper Prairie Wilderness area, Ocala National Forest, Florida, USA. Burn severity was mapped using ΔNBR classifications of Landsat satellite imagery.

each plot a categorical burn severity level of unburned, low, moderate, or high severity. We based the somewhat subjective ocular severity values on post-burn overstory and understory foliar consumption approximations recorded by field crews within weeks of the 2006 fire. Under the ocular system, unburned plots exhibited no foliar combustion; low severity plots had some evidence of foliar consumption in the plot; moderate severity plots had evidence of consumption within the entire plot; and high severity plots had nearly complete consumption of foliar material (Freeman and Kobziar 2011). We used the categorical CBI severity classes and ocular severity classes in an error matrix to assess agreement with the categorical severity classes assigned in the thresholding procedure of the 2006 ΔNBR categorical scene (Jensen 2005).

## RESULTS

### *Overall Severity*

Two four-class categorical burn severity images were created: one for the 2006 fire (Figure 2A) using the 2006 ΔNBR scene, and one for the 2009 fire (Figure 2B) using the 2009 ΔNBR scene. The two fires together burned 85 % of the entire wilderness area within a three-year time period (Figure 3). Individually, the fires burned different amounts of the JPW: the 2006 fire burned over three quarters of the wilderness area (76.32 % or

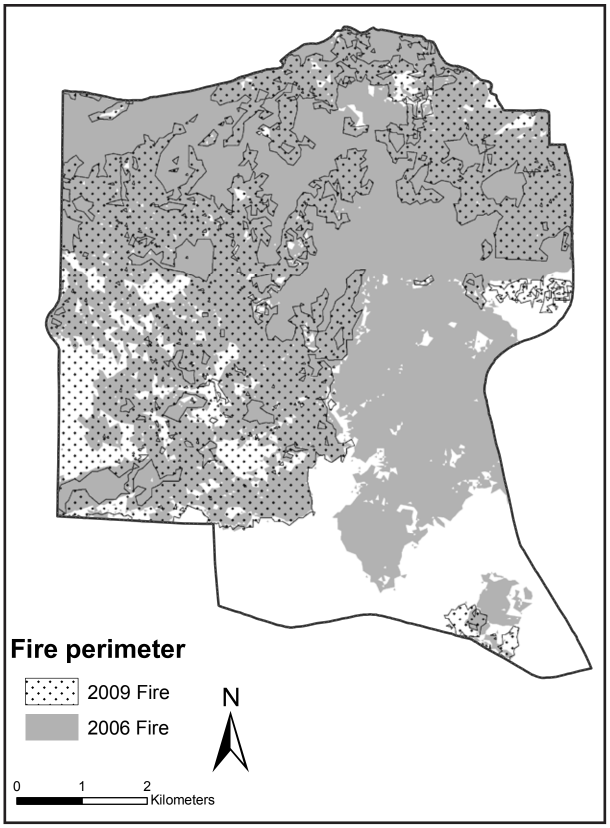


**Figure 3.** Area burned in the 2006 and 2009 fires in the Juniper Prairie Wilderness, Ocala National Forest, Florida, USA, as detected by Landsat 7 ETM+ classification.

4519.4 ha), while the 2009 fire burned less than half of the wilderness area (44.87% or 2656.71 ha). In total, the 2009 fire burned 41% fewer hectares than the 2006 fire. The total area of each burn severity class of the 2006 fire and the 2009 fire were also very different (Figure 4). The 2006 fire had a nearly even distribution by area of each severity class (Figure 4A), while the 2009 fire was heavily skewed toward the unburned class, with the high severity class having the least area burned (Figure 4B). Thirty-two percent (1895 ha) of the JPW burned as high severity at least once in either the 2006 fire or the 2009 fire, while 15% (892 ha) of the JPW remained unburned throughout the two fires (Figure 5). Twenty percent, or 1236 ha, of the JPW burned as low severity in either the 2006 or 2009 fire.

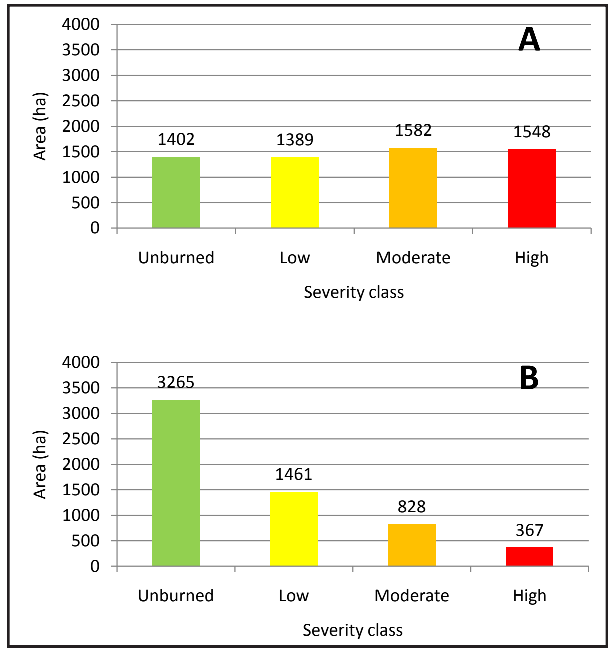


**Figure 4.** Area (ha) for each burn severity class for the 2006 (A) and 2009 (B) fires in the Juniper Prairie Wilderness, Ocala National Forest, Florida, USA.

**Figure 5.** Post-burn view of the Juniper Prairie Wilderness following the fire in 2009. Near total consumption of aboveground vegetation and surface organic material was typical of the areas observed in the high severity sand pine scrub field plots.

### *Effect of the 2006 Fire on Fire Severity in 2009*

We refer to burn severity "direction" as the categorical change in burn severity for any given point within the JPW from the 2006 fire to the 2009 fire. When assessing the burn severity direction of any given 30 m × 30 m pixel within the JPW, only 0.33% (20 ha) of the JPW burned with high severity twice, and only 3.29% (194.58 ha) burned with high severity followed by moderate severity, or moderate severity followed by high severity. Of the area that burned with high severity in 2006, 67% did not burn again in the 2009 fire. Moderate severity fire in 2006 had similar results, with only 0.82% (48.53 ha) and 4.58% (271.17 ha) of the JPW burned as either high severity or moderate severity in the 2009 fire, respectively.

### *Individual Stand Type Severity*

Burn severity differed by forest and stand type (Table 2). The most notable differences occurred in the longleaf pine, damaged sand pine, mature sand pine, and sapling sand pine stand types. Nearly the entire longleaf pine stand type burned in 2006, with most (66%) of it burning as low severity. In 2009, most of the longleaf pine burned again with almost all of it also classified as low severity (82%). In the heavily fuel-ladened damaged sand pine stands, over 85% was burned in 2006, with 95% of the burned area classified as either moderate or high severity fire. In 2009, only 26% burned again, with 85% of the burned

**Table 2.** Burn severity by fire year and forest stand type, with the area (ha) and percent (%) of each burn severity class for the Juniper Prairie Wilderness, Florida, USA.

| Stand | Unit | Unburned | Low | Moderate | High | Total burned | Total ha |
|---|---|---|---|---|---|---|---|
| **2006 fire** | | | | | | | |
| Longleaf pine | ha | 30.7 | 214.4 | 108.9 | 3.3 | 326.7 | 357.4 |
| | % | 8.6 | 65.6 | 33.3 | 1.0 | 91.4 | |
| Damaged sand pine | ha | 224.3 | 188.6 | 583.3 | 518.8 | 1290.7 | 1515.0 |
| | % | 14.8 | 14.6 | 45.2 | 40.2 | 85.2 | |
| Mature sand pine | ha | 79.4 | 103.9 | 176.7 | 91.7 | 372.3 | 451.7 |
| | % | 17.6 | 27.9 | 47.4 | 24.6 | 82.4 | |
| Sapling sand pine | ha | 103.1 | 160.6 | 392.1 | 819.6 | 1372.3 | 1475.4 |
| | % | 7.0 | 11.7 | 28.6 | 59.7 | 93.0 | |
| Slash pine | ha | 42.6 | 154.1 | 88.0 | 35.2 | 277.4 | 319.9 |
| | % | 13.3 | 55.6 | 31.7 | 12.7 | 86.7 | |
| Sweet bay | ha | 537.8 | 304.2 | 102.9 | 45.2 | 452.3 | 990.1 |
| | % | 54.3 | 67.3 | 22.8 | 10.0 | 45.7 | |
| **2009 fire** | | | | | | | |
| Longleaf pine | ha | 145.5 | 174.3 | 34.3 | 3.3 | 211.9 | 357.4 |
| | % | 40.7 | 82.3 | 16.2 | 1.6 | 59.3 | |
| Damaged sand pine | ha | 1113.2 | 227.7 | 119.2 | 54.9 | 401.8 | 1515.0 |
| | % | 73.5 | 56.7 | 29.7 | 13.7 | 26.5 | |
| Mature sand pine | ha | 159.1 | 155.3 | 125.0 | 12.3 | 292.6 | 451.7 |
| | % | 35.2 | 53.1 | 42.7 | 4.2 | 64.8 | |
| Sapling sand pine | ha | 668.3 | 351.1 | 313.9 | 142.1 | 807.1 | 1475.4 |
| | % | 45.3 | 43.5 | 38.9 | 17.6 | 54.7 | |
| Slash pine | ha | 40.9 | 106.3 | 84.8 | 87.9 | 279.0 | 319.9 |
| | % | 12.8 | 38.1 | 30.4 | 31.5 | 87.2 | |
| Sweet bay | ha | 701.5 | 141.1 | 86.0 | 61.5 | 288.6 | 990.1 |
| | % | 70.8 | 48.9 | 29.8 | 21.3 | 29.2 | |

area classified as either low or moderate severity. In the mature sand pine stands, over 82% burned in 2006 with the majority of the burned area classified (47%) as moderate severity. In 2009, over 64% of the mature sand pine stands burned again, with 95% of the burned area classified as low or moderate severity. In 2006, 93% of the sapling sand pine burned with nearly 60% of the burned area classified as high severity (88.3% as combined moderate or high severity). In 2009, 54% of the sapling sand pine stands burned again with nearly all of it classified as either low or moderate severity (81%).

### *Comparing Ground and Remote Sensing Assessments of Burn Severity*

CBI Total values derived from CBI field plots established in the damaged sand pine, sapling sand pine, and mature sand pine stands showed moderate agreement with categorical burn severity levels assigned in the 2006 ΔNBR scene, with 48.33% accuracy and kappa = 0.32. Ocular severity index values showed slightly increased agreement with 50.0% accuracy and kappa = 0.33. The producer's and user's accuracies showed that agreement between field reference plots and the 2006 ΔNBR scene varied among severity levels, with the unburned severity class having the highest producer's accuracy and the low severity class having the lowest producer's accuracy. Correlation analysis of burn severity values from the 2006 ΔNBR scene and field measures showed positive agreement: 0.70 (CBI) and 0.72 (ocular).

## DISCUSSION

### *Influence of Burn Severity from the 2006 Fire on Burn Severity in the 2009 Fire*

Even though the JPW was capable of burning three years following the initial fire, the mitigating effect of the first fire was evident in burn severity patterns of the subsequent 2009 fire. Burn severity direction changes were found to differ by stand type. In the longleaf and slash pine stand types, the low and moderate severity results may reflect the rapidly growing fine fuel loads typical of these forests (Myers and Ewel 1990). In the sweet bay stand type, the low burn severity values and relatively low percent burned may be attributed to the hydric and mesic characteristics of the stand type, inhibiting ignition under all but the driest of conditions (Myers and Ewel 1990). In the sapling sand pine stand type, it was surprising that sufficient fuels existed following the 2006 fire to reburn over half of the sapling sand pine area in 2009, because the fuel loads were likely significantly reduced following extensive moderate and high severity fire in 2006. It is likely that the high proportion of high severity fire in 2006 led to the much lower severity values observed in 2009. In the mature sand pine stand type, the results followed a similar trend with fewer hectares burned in 2009, likely due to reduced fuels after greater than 80% of the stand type burned in 2006. Because the severity of the 2006 burn was mostly moderate, sufficient fuels may have remained for the majority of the stand type to burn again in 2009 at low to moderate severity. The high and moderate severity fire effects observed in the damaged sand pine stands in 2006 are likely due to their high fuel loading following the 2004 hurricane season. Only a fraction of the damaged sand pine type burned again in 2009, with over half of the burned area classified as low severity. This suggests that high severity fire in 2006 reduced the likelihood of high severity fire again in 2009. Across all stand types, burn severity decreased in 2009, suggesting that the 2006 fire mitigated fire severity in 2009. These results may support efforts to introduce prescribed fire into unburned sand pine scrub by documenting that high severity fires under prescribed conditions may reduce the likelihood of subsequent high severity fires under future wildfire scenarios. However, the longevity of the effect of one fire on the next is closely tied to the time between fires. There likely exists a threshold beyond which the initial fire has little effect on subsequent fires, and this can be determined for future overlapping fires using the methods developed here across a range of times between fires.

Studies of the subsequent effect of multiple overlapping fires on large landscapes are few (Collins *et al*. 2008, Holden *et al*. 2010). The results of a nineteen-fire study in the Illilouette basin in Yosemite National Park, California, USA, found that the temporal effect of a fire in a mixed conifer forest began to diminish nine years following the burn, prior to which there was a zero percent probability of burning again (Collins *et al*. 2008). Collins *et al*. (2008) also found that weather was a significant factor driving recurrent fire occurrence on the landscape, suggesting that extreme weather conditions, while rare, can increase fire intensity and severity in spite of reduced fuel accumulations due to past fires. In our study, it is impossible to rule out the effect of weather conditions on the subsequent burn severity patterns, as post-fire satellite images provide only a one-time snapshot of post-fire effects, which are the culmination of weeks of fire burning under dynamic weather conditions. While the 2006 fire was most likely driven by weather and fuel type, the 2009 fire was evidently fuel-limited, since the weather conditions were similar between the two burns, while fire severity patterns were not. A study of thirteen fires in the Gila Aldo Leopold Wilderness Complex, New Mexico, USA, found successive fires influenced by the severity of the initial fire, with high severity fire generally followed by high severity fire, and low severity fire followed by low severity fire (Holden *et al*. 2010). In addition, suppression actions on the part of the Forest Service, including aerial water drops and burn out operations, may have had an influence on the fire intensity and subsequent burn severity for both the 2006 fire and the 2009 fire. These two factors may have contributed to the burn severity patterns observed within stand types and across the whole of the study area for either fire.

### *Remotely Sensed Imagery and 2006 Field Plot Observations*

The temporal span between the initial 2006 burn in August and the collection of the ground level CBI and ocular burn severity measurements during the following winter and spring may have led to the limited agreement between the 2006 ΔNBR scene and the ground data. The ΔNBR index measures differential changes in soil cover and reflectivity as an indicator of vegetative consumption, and is sensitive to vegetative cover (Key and Benson 2006). The ΔNBR index has been shown to strongly agree with surface measures of burn severity in Florida sandhill and flatwoods sites (Picotte and Robertson 2011). Henry (2008) suggested that the ΔNBR index may not be suitable for application in sand pine scrub given the short vegetative response following fire. The vegetative response to fire in Florida can be very rapid, in some cases with post-fire vegetative fuels loads returning to pre-fire vegetative fuels loads within a few years (Lavoie *et al*. 2010), suggesting that collecting field plot data even a matter of months following the fire could influence ground plot and remotely sensed data agreement (Wimberly and Reilly 2007). During ground data collection, every effort was made to distinguish between vegetation recovery and vegetation survival. However, in the low severity areas, this was not always possible. Following the 2006 burn, the JPW continued to experience a period of prolonged drought, which may have aided the agreement between ground plots and the remotely sensed imagery by slowing the JPW vegetative recovery; however, an assessment of the effect of this drought on vegetative recovery to fire is unknown.

While not formally investigated in this study, both the 2006 and 2009 burns exhibited pronounced spatial heterogeneity of burn severity with a significant element of patchiness. In spite of the stratified sampling design that attempted to account for edges, spatial heterogeneity of burn severity may have resulted in decreased agreement between the 2006 ΔNBR scene and the field reference plots. Additional lack of agreement may have been due to variation in field GPS unit accuracies as such spatial offset could decrease agreement, even when GIS files are properly georeferenced (Wimberly and Reilly 2007). We suggest that the remotely sensed burn severity classifications derived in this study likely depict a more accurate representation of the post-fire vegetative characteristics on the ground than the accuracy matrix suggests. The agreement between the CBI plots and the 2006 ΔNBR scene was similar to the results of a multi-fire study of burn severity in the northern Rocky Mountains that also used CBI and ΔNBR (agreement 57.8% and kappa = 0.28) (Karau and Keane 2010). Karau and Keane (2010) noted that CBI and ΔNBR are designed to be similar for image assessments, but CBI plot measurements on the ground may not always match the characteristics of the vegetation and soils as recorded by the satellite sensor. The different spatial scales of the field plots (10 m × 10 m) as compared to the scale of the Landsat imagery (30 m) may have led to further discrepancy between the burn severity values assigned at the image pixel and those recorded in the field (Hudak *et al*. 2007). The image pixel values used to derive the thematic burn severity classifications are a summation of the surface reflectance captured within the sensor 30 m × 30 m footprint. It is possible, therefore, that the fire effects recorded within the CBI plots on the ground did not represent the average fire effects observed at the larger satellite sensor scale (Hudak *et al*. 2007). Picotte and Robertson (2011) overcame this obstacle in a study of ΔNBR burn severity mapping in north Florida and south Georgia by expanding the CBI plot to a 30 m circular plot and comparing those field measured values to an average of five ΔNBR pixel values contained or intersecting within the CBI plot.

The assignment of thresholds for delineating burn severity classes has been noted as a key step in the mapping process, wherein variability may be introduced due to the subjectivity of determining classes (Eidenshink *et al*. 2007). Thresholds in this study were determined based on the imagery at hand, knowledge of the burned area, and familiarity from working in the region during the establishment of CBI plots. As a potential option for future endeavors, Eidenshink *et al*. (2007) described a method for the verification of thresholding that may help to reduce cartographic bias by working with collaborative teams of experts across multiple burn units (Eidenshink *et al*. 2007).

### *Sand Pine Scrub Perpetuation*

The methods of mapping fire severity in sand pine scrub presented here may facilitate further study of the dynamics of fire severity and ecosystem response. The importance of high severity fire for the perpetuation of sand pine scrub and other stand replacement ecosystems has been documented, with post-fire severity shown to influence vegetative response following fire (Whelan 1995, Freeman and Kobziar 2011). In a study following the 2006 JPW fire, Freeman and Kobziar (2011) found that moderate severity fire was positively correlated with herbaceous species cover, while high and moderate severity fire was associated with adequate sand pine seedling recruitment in mature sand pine stands. Conversely, fire of any severity in sapling sand pine stands was shown to inhibit sand pine seedling recruitment nearly completely (Freeman and Kobziar 2011). These results implicate the importance of the need to integrate maps of post-fire severity with collaborative knowledge of the effect of burn severity on vegetation. Such understanding may allow managers to better assess wildfires and to prescribe fires to attain desired subsequent vegetative succession. Such assessments are particularly important in designated wilderness areas such as the JPW where the management objective is the survival of the ecosystem and the numerous endemic species therein.

Estimating and reconstructing long-term historical fire return intervals are a difficult task in any ecosystem (Whelan 1995). Fire regime reconstructions within the range of sand pine scrub are made further difficult by a lack of trees bearing fire scars due to bole consumption from high severity fire and rapid decomposition rates. The relatively short fire return interval of three years documented in this study raises some questions regarding the current estimates of 15 year to 100 year natural sand pine scrub fire return intervals (Myers and Ewel 1990, Menges and Hawkes 1998). The JPW fires suggest that the historical range of variability about and within that interval may have included some frequent fires of low to moderate severity. The frequent fires documented here may be somewhat atypical, given that both events occurred over a period of drought, with fires occurring at times of nearly identical regional Palmer Drought Severity Index (PDSI) scores (Figure 6). A 16 year study of natural ignitions on the nearby Merritt Island National Wildlife Refuge found that the majority of lightning-strike fires across a variety of ecosystems occurred during the summer months (June to August) (Duncan *et al*. 2010). These regional results, while not specifically a study of sand pine scrub, raise questions as to how the March 2009 fire will differ from the post-fire vegetative trajectories of the July to August 2006 fire. A recent vegetative succession study following the 2006 JPW fire found evidence based on sand pine scrub regeneration to suggest that high severity stand replacement fires within a ~23 year interval were optimal for seedling recruitment and ecosystem recovery (Freeman and Kobziar 2011). A three

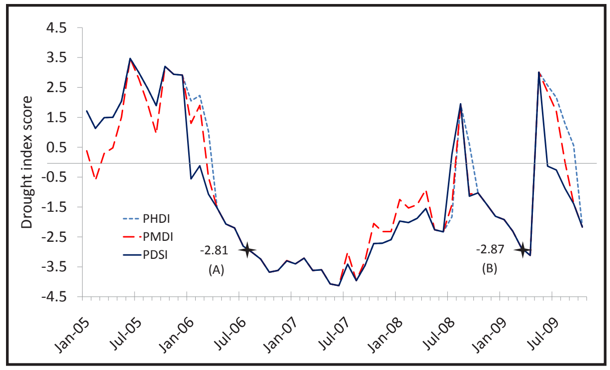


**Figure 6.** Regional drought severity index values from January 2005 through September 2009 for the study area. Both the 2006 JPW fire (A) and the 2009 JPW fire (B) occurred during similar periods of regional drought as measured by the Palmer Drought Severity Index (PDSI), Palmer Hydrological Drought Index (PHDI), and the Palmer Modified Drought Index (PMDI). Data from the NOAA-NCDC.

year fire return interval may result in the loss of a significant area of the sand pine scrub ecosystem. Given the predictions for future climate in the southeastern US to include more frequent drought and higher temperatures, fire frequency may increase, threatening recruitment in sand pine scrub.

The frequency of these two fires over a relatively short period of time also suggests that the hazard of low to moderate severity wildfire in sand pine scrub may return in less than three years following fire. In terms of sand pine scrub management in both wilderness and non-wilderness contexts, it is important for future research to determine whether these fires support long-term and short-term goals. Simply because portions of the JPW could support burning twice within the 3 year interval does not indicate that those fires of accidental anthropogenic ignitions support the perpetuation of the ecosystem.

## *Conclusion*

This study utilized the ΔNBR index to classify Landsat imagery to four levels of burn severity to assess two large wildfires that occurred in the Juniper Prairie Wilderness of the Ocala National Forest, Florida, USA. We reported an application of the ΔNBR and CBI indices in a region and ecosystem that has had comparably few studies of remote sensing mapping techniques. Using field plots to test agreement, it was determined that the ΔNBR burn severity index provided a suitable means of classifying Landsat imagery for the assessment of burn severity in sand pine scrub. Field plots using visual assessments of burn severity along with CBI measurements were positively correlated with ΔNBR index values (0.70 and 0.72) and had moderate overall accuracy (48.3 % and 50 %, respectively). This suggests that further use and assessment of the ΔNBR index is warranted for burn severity mapping applications and fire ecology studies in upland southeastern US ecosystems. Contrary to the notion that sand pine scrub always burns at high severity, burn severity differed between the two fires and among the forest types and stand types. Burn severity directional analysis at the pixel level found that high severity fire was typically followed by low severity fire in the sand pine stands, while low to moderate severity fire was followed by low to moderate severity fire in the longleaf and slash pine stands. These results suggest that forest stand type and age, as well as burn severity history, influence future fire effects on vegetation in sand pine scrub, even under severe fire weather and drought conditions. Further research is needed to understand the influence of fire severity thresholds on the perpetuation of the sand pine scrub ecosystem, as area managers seek to maintain ecosystems despite changing climate patterns that may increase the frequency of fire occurrence and influence post-burn vegetative responses.

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