ACCURACY OF REMOTE SENSING WILDLAND FIRE–BURNED AREA IN SOUTHEASTERN U.S. COASTAL PLAIN HABITATS

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ABSTRACT

Accurate estimates of wildland fire perimeters and areas are essential for planning wildfire response, monitoring prescribed fire, estimating pollution emissions, and for other natural resource applications. Remote sensing can provide a low-cost and relatively accurate means to monitor burned area on the landscape. The most common methods of remote sensing use the Normalized Burn Ratio (NBR), which is the ratio of reflectance bands sensitive to burned areas, or differenced Normalized Burn Ratio (dNBR), which is the difference between pre- and post-fire NBR. The NBR and dNBR methods each can have advantages in different situations. Reflectance values are categorized into levels of burn severity using field-measured values of the Composite Burn Index (CBI). However, these methods have not been calibrated for the dominant vegetation types of the southeastern United States. Our objective was to calibrate and test the accuracy of these methods for remotely measuring burn area. We established 731 CBI measurement plots in prescribed burned areas within the Apalachicola National Forest in Florida during the 2007 and 2008 dormant season (November–February), early growing season (March–June), and late growing season (July–October) in flatwood and upland (sandhill) pine (*Pinus* spp.) forests to determine NBR and dNBR breakpoints delineating burned versus unburned areas. We mapped the perimeters of selected burned areas on the ground using Global Positioning System (GPS). Corresponding burned areas were estimated using the NBR and dNBR methods with the newly determined breakpoints for comparison with surface-measured areas. The average percent bias in estimating burned area was −5% (±15% SE) using NBR and −1% (±7% SE) using dNBR and was not significant based on *t*-tests. However, the percent error of commission plus error of omission ranged from 4 to 92% (average 22%) using NBR and from 0 to 38% (average 14%) using dNBR. Percent error increased with time elapsed between the burn and the post-fire Landsat flyover, revealing time limit bounds for the accurate use of this method. Our findings suggest that NBR and dNBR imagery may provide an unbiased method for inexpensively monitoring burned area from fires >10 ha in common southeastern U.S. habitats under the recommended set of conditions.

Keywords: Apalachicola National Forest, burn monitoring, composite burn index, depression swamp, differenced Normalized Burn Ratio, ecological change, prescribed fire, sandhill, upland pine, wet flatwoods.

Citation: Picotte, J.J., and K.M. Robertson. 2010. Accuracy of remote sensing wildland fire–burned area in southeastern U.S. Coastal Plain habitats. Pages 91–98 *in* K.M. Robertson, K.E.M. Galley, and R.E. Masters (eds.). Proceedings of the 24th Tall Timbers Fire Ecology Conference: The Future of Prescribed Fire: Public Awareness, Health, and Safety. Tall Timbers Research Station, Tallahassee, Florida, USA.

INTRODUCTION

The ability to measure the areal extent of wildfires and prescribed fires is essential for quantifying fire effects, assessing land management achievements, and monitoring fire regimes over time. Ground-based or aerial methods of measuring burned area using Global Positioning System (GPS) or aerial photography are costly and thus are generally limited to selected fire events on public land. On private land, estimates of prescribed burned area are generally restricted to records kept for burn authorizations or agency notifications. These likely exaggerate burned area because more hectares are often requested than needed, planned burns are not always applied, and unburned portions of burn blocks are typically not monitored (Cox et al. 2006). Thus, there remains a need to develop burn monitoring protocols that are affordable, accurate, and comprehensive in order to properly assess fuel conditions, fire danger, habitat quality, and resource needs for fire management. Remote sensing techniques may provide the most cost-effective and accurate approach.

Remote sensing approaches for measuring landscape changes must consider the trade-offs in choosing a scale of reflectance units. Coarse-scale (>100-m pixel resolution) approaches have been used for monitoring fire because of its low cost and short duration between screen captures (Chuvieco and Martin 1994). However, the low resolution (1 km) of coarse-scale imagery makes it unsuitable for mapping small-scale (<1 km) and low-severity fires. Fine-scale-resolution (<100 m) satellites have been shown to accurately determine the perimeter of small landscape changes (Miline 1986) with resolutions as fine as 1 m (e.g., IKONOS), but such methods are usually cost prohibitive. The 30-m-resolution Landsat Thematic (TM) data may provide the optimal tradeoff between cost and the ability to effectively map relatively small (5–100 ha) burned areas for achieving most burn monitoring objectives (Key and Benson 2006). Landsat TM images are currently available for download from the Internet free of charge (USGS 2009) and include archived images back to January 1983, allowing historical analysis of landscape change.

The Normalized Burn Ratio (NBR) developed by Key and Benson in 1996 is an algorithm that utilizes the ratio between two reflectance bands (4 and 7) from Landsat TM 5 and 7 satellite data to detect vegetation and soil reflectance conditions that are indicative of recent fires and burn severity (Key and Benson 2006). NBR can be used to estimate burn severity and has been found to be the preferred method under certain circumstances (Hudak et al. 2007). To measure vegetation changes attributable to fire based on pre-fire reference conditions, pre- and post-fire NBR images also

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can be compared to calculate the differenced Normalized Burn Ratio (dNBR). The dNBR protocol has been widely used to successfully map the area burned by wildfires as well as relative burn severity (Key and Benson 2006, Loboda et al. 2007, Miller and Thode 2007, Keane and Karau 2008). Although these methods have typically been used for large wildfires (> 200 ha) and fires of special interest on federal land (MTBS 2009), they show promise for use as a more comprehensive fire monitoring tool, including monitoring smaller areas burned by prescribed fires.

Although the usefulness of the NBR and dNBR methods has been demonstrated in the western United States (Cocke et al. 2005, Epting et al. 2005, Key and Benson 2006, Kasischke et al. 2008), there has been limited work validating their effectiveness in the southeastern U.S. Coastal Plain (Pennington 2006, Wimberly and Reilly 2006, Henry 2008). In the southeastern United States, the most dominant native habitat types depend on frequent (1- to 3-year interval) prescribed burning for their maintenance (Platt 1999, Glitzenstein et al. 2003), resulting in low-severity fires that may be difficult to detect using remote sensing. Also, vegetation response to burning is generally rapid, with partial recovery of understory pine (*Pinus* spp.) forest vegetation occurring within several weeks of burning (Shepherd 1953). The great majority of prescribed fires in the region are < 100 ha, which is below the size recommended for use of these methods (Key and Benson 2006). Also, proximity to the Gulf of Mexico results in frequent cloud cover that may limit the number of usable Landsat satellite image captures.

The overall goal of this study was to determine the accuracy and bias of NBR and dNBR methodologies for monitoring burned areas in common southeastern U.S. forest cover types and to make recommendations for maximizing their usefulness as monitoring tools in the region. Our approach was to 1) determine most appropriate breakpoints of NBR and dNBR for estimating burned versus unburned areas, 2) use the NBR and dNBR algorithms to estimate burned areas, and 3) validate these estimates using ground-based GPS measurements of burned area.

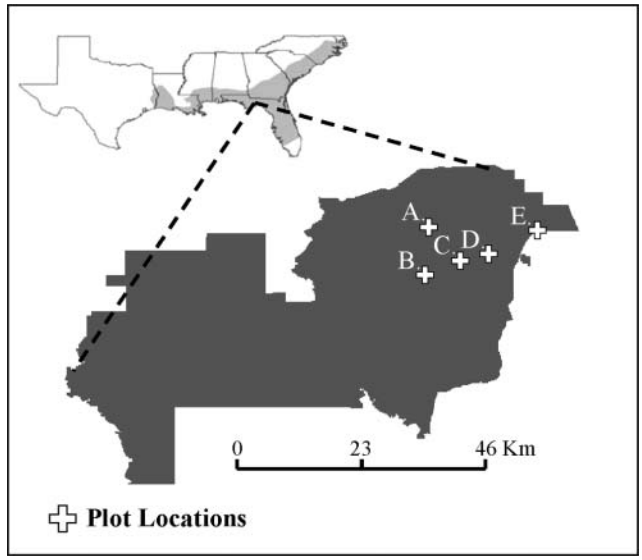

Figure 1. Locations of the surface traced prescribed burns including A. BU231, B. BU304, C. BU302, D. BU228 and BU249, and E. BU254 (see Table 1 for vegetation type, pre-fire image date, burn date, post-fire image date, and post-image days since fire) within the Apalachicola National Forest, Florida (dark gray). The Southeastern Coastal Plain (light gray) has been highlighted to indicate the distribution of flatwoods and sandhills within the southeastern United States.

METHODS

Study Area

The burns validated in this study were on the Apalachicola National Forest in north-central Florida, USA (approximately lat 30°20′N, long 84°21′W). Two plant community types, upland pine sandhills and wet pine flatwoods, were considered in this study. These are two of the most common natural community types remaining throughout much of the eastern portion of the southeastern Coastal Plain from the Mississippi River to North Carolina (Figure 1).

Upland pine sandhills are defined by droughty mineral (sandy) soils that have little organic material (Myers 1990). Dominant plant species are longleaf pine (*Pinus palustris*) and wiregrass (*Aristida stricta*) in frequently burned examples, but turkey oak (*Quercus laevis*), bluejack oak (*Q. incana*), laurel oak (*Q. laurifolia*), post oak (*Q. stellata*), and other hardwood species can be dominant where there is a history of longer fire intervals. Fires are relatively low-intensity surface fires consuming fine fuels consisting of herbaceous vegetation, pine needle litter, and broadleaf litter (Myers 1990).

Wet pine flatwoods have flat topography and periodically flooded organic or sandy soils (Abrahamson and Hartnett 1990). The historic fire return interval is 1–3 years (Glitzenstein et al. 2003). The pine canopy is dominated by longleaf pine or slash pine (*Pinus elliottii*). The understory is either grassy or may be dominated by a variable density of flammable evergreen shrubs, including saw palmetto (*Serenoa repens*), gallberry (*Ilex glabra*), fetterbush (*Lyonia lucida*), and sweet gallberry (*Ilex coriacea*). High rates of woody vegetation productivity and rapid buildup of ground fuels can lead to high-severity surface fires and ground fires where duff is present, especially where fire return intervals are unnaturally long (Sackett 1975).

Remote Sensing of Burned Areas

In order to create dNBR coverages for the fires of interest, two radiometrically corrected Landsat TM 4–5 images, one pre-fire and one post-fire, were obtained from the United States Geological Survey (USGS 2009) for each of the three study seasons, including dormant (November–February), early growing (March–June), and late growing season (July–October), in 2007 and 2008 for a total of 12 images (Table 1). NBR values for each 30-m pixel were calculated using the formula $NBR = (R4 - R7)/(R4 + R7)$, where R4 is the value of Landsat TM band 4 which is sensitive to changes in vegetation, and R7 is Landsat TM band 7 which responds to soil reflectance levels (Key and Benson 2006). Each post-fire image was taken approximately 1 year following the pre-fire image during the same study season to minimize effects of seasonal changes in land cover (Table 1). Post-fire images were taken within 2 months of the date of each burn (except for Burn Unit 254 because a cloud-free

Table 1. Pre-fire image, burn, and post-fire image dates for all examined flatwoods and sandhills areas within the Apalachicola National Forest, Florida. Post-fire image time since fire is the difference in time between the burn and post-fire image dates.

Burn unit	Vegetation type	Pre-fire image date	Burn date	Post-fire image date	Post-fire image time since fire (days)
231	Flatwood	19 Dec 2006	8 Jan 2008	24 Feb 2008	45
304	Flatwood	25 Mar 2007	17 Apr 2008	14 May 2008	27
302	Flatwood	16 Aug 2007	12 Jul 2008	17 Jul 2008	5
248	Sandhill	25 Mar 2007	12 Mar 2008	27 Mar 2008	15
248b	Sandhill	24 Feb 2008	10 Jan 2009	10 Feb 2009	31
249	Sandhill	25 Mar 2007	17 Mar 2008	27 Mar 2008	10
254	Sandhill	16 Aug 2007	25 Jun 2008	19 Sep 2008	86

image was not yet available) to minimize the effects of environmental changes and vegetation regrowth following fire (Holden et al. 2005, Key 2005, Hammill and Bradstock 2006). The dNBR images were composited from the pre-fire and post-fire images within Leica Erdas Imagine Modeler 9.3 (Leica, Quezon City, Philippines) using the algorithm dNBR = (pre-fire NBR − post-fire NBR) × 1,000 to calculate an index of burn severity for each burned area (Key and Benson 2006). Values of dNBR are continuous and dimensionless, ranging from −2,000 to 2,000, with −2,000 indicating regrowth to 2,000 indicating complete burn (Key and Benson 2006).

In order to map burned areas, it is necessary to calculate the values of NBR and dNBR representing breakpoints between different levels of burn severity, including burned versus unburned, for each community type and study season. Although it was only necessary to estimate burned versus unburned areas for the purposes of this study, we found that estimating levels of burn severity assisted in recognizing fire footprints as opposed to other, usually more homogeneous land-use alterations (e.g., timber harvest). Breakpoints were determined by comparing NBR and dNBR values to measurements of burn severity in plots on the ground using the Composite Burn Index (CBI) (Key and Benson 1999), a common method to assess the on-the-ground burn severity after a fire (Cocke et al. 2005, Wimberly and Reilly 2006, Hoy 2007, Allen and Sorbel 2008, Kasischke et al. 2008).

A total of 240 CBI plots were measured on the Apalachicola National Forest. The CBI sample size was dictated by the amount of time available for doing the field work, with an emphasis on gathering approximately equal samples from each combination of community type and season. CBI evaluates the level of change in the vegetation and soil attributable to fire by calculating an overall continuous severity index ranging from 0 to 3, with 0 indicating unburned to 3 indicating maximum fire severity. The overall index is derived by calculating CBI values separately for each of five fuel strata, specifically soil substrate, low vegetation (< 1 m), tall shrubs (1–5 m), intermediate trees, and canopy trees. Each of the five strata has four to five severity variables that are assigned a value of 0 to 3 based on observations following specific criteria (Key and Benson 1999). Severity values are averaged for each stratum, then all strata values are averaged to compute overall plot CBI (Key and Benson 2006). Finally, levels of CBI were nominally classified as unburned (< 0.75), low severity (0.75–1.25), low–moderate severity (1.25–1.75), moderate–high severity (1.75–2.25), or high severity (> 2.25).

Estimates of NBR and dNBR breakpoints corresponding to levels of burn severity were made using sigmoidal curve equations in Sigma Plot 8.0 (Systat, San Jose, CA). The CBI value served as the dependent variable and NBR or dNBR as the independent variable. Fifteen separate regression analyses were run for combinations of vegetation type and season with 13–96 ($\bar{x} = 57$) CBI plot estimates per combination. The best-fit line equations allowed determination of NBR or dNBR values corresponding to the CBI values representing burn-severity breakpoints. Although the dNBR–CBI curve has been previously fitted with a second-order polynomial equation (van Wagtendonk et al. 2004), we determined that sigmoidal curve models provided the best fit for data examined in this study.

After each NBR and dNBR image was imported into ArcGIS 9.3 (ESRI, Redlands, CA), the ArcGIS Spatial Analyst Extension was used to classify the image into severity images with two classes (burned or unburned) using the corresponding breakpoints as defined for each season and vegetation type. This raster image was converted to a polygon shapefile. The area of each burned polygon was then calculated and summed for the burn unit.

Surface Measurement of Burned Areas

In 2008 and 2009, we mapped boundaries between burned and unburned areas on foot within the six prescribed burn units in the Apalachicola National Forest (Figures 2, 3) using Trimble Geoexplorer XT handheld GPS units (Trimble, Sunnyvale, CA). The number of units sampled was limited by the large size of the blocks typically containing long and complex burn edges around wet areas. Burned area was mapped within 3 months of each burn. When tracing burned areas, we attempted to stay within 2 m of the burned/unburned boundary. All burned or unburned patches greater than approximately 15 m × 15 m were mapped. Mapping involved approximately 140 man-hours. GPS data were converted to shapefiles using GPS Pathfinder Office 4.0 (Trimble) and used to hand-digitize polygons representing the burned areas.

Burn Mapping Data and Interpretation

Specific goals of analyses were to 1) describe the spatial accuracy of polygons in estimating burned area and 2) identify consistent directional bias and variance in estimates of burned area. In order to assess the spatial accuracy of

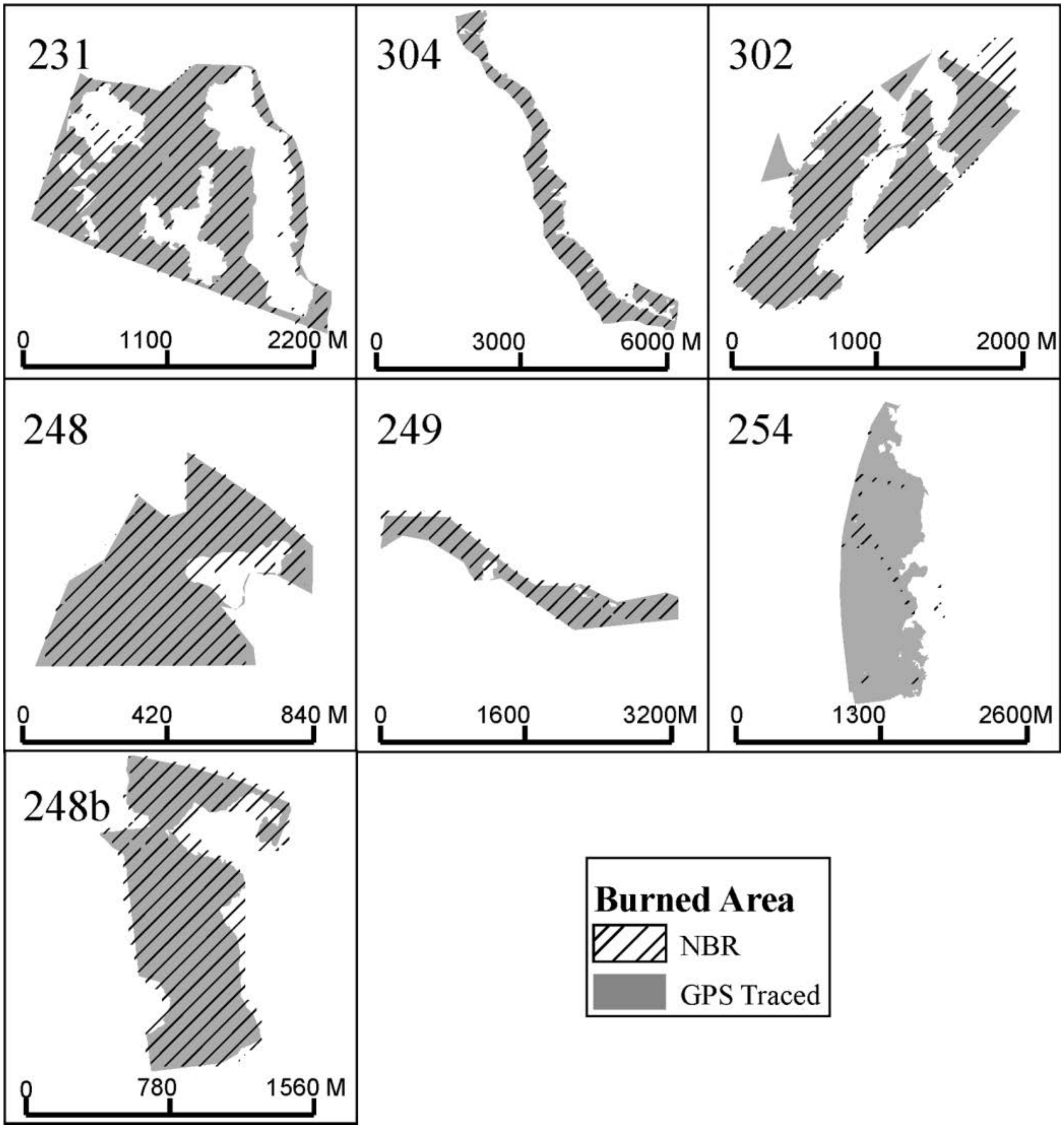

Figure 2. A comparison of GPS and Normalized Burn Ratio (NBR) burn mapping methods used to trace the extent of seven burned areas (Figure 1) within all prescribed burns monitored from 2006 to 2008 within the Apalachicola National Forest, Florida. Unburned areas within the burned areas are indicated by their lack of color.

estimates of burned area, remote sensing errors of commission (unburned areas interpreted as burned) and errors of omission (burned areas interpreted as unburned) were calculated for each burn. Polygons representing areas of commission and omission were generated in ArcGIS 9.3 (ESRI, Redlands, CA) using the X-Tools Pro Erase Features extension 5.2 (Data East, Novosibirsk, Russia) by overlaying GPS-measured polygons and remotely sensed polygons. Errors of commission, omission, and bias (commission – omission, positive or negative) were reported as a percent error relative to the ground-based measurement of burned area.

We used paired *t*-tests (SPSS 15.0; SPSS, Chicago, IL) to compare remotely estimated (NBR or dNBR) burned areas with those measured on the ground, using the seven burn units as replicates, to test for consistent bias in estimates of

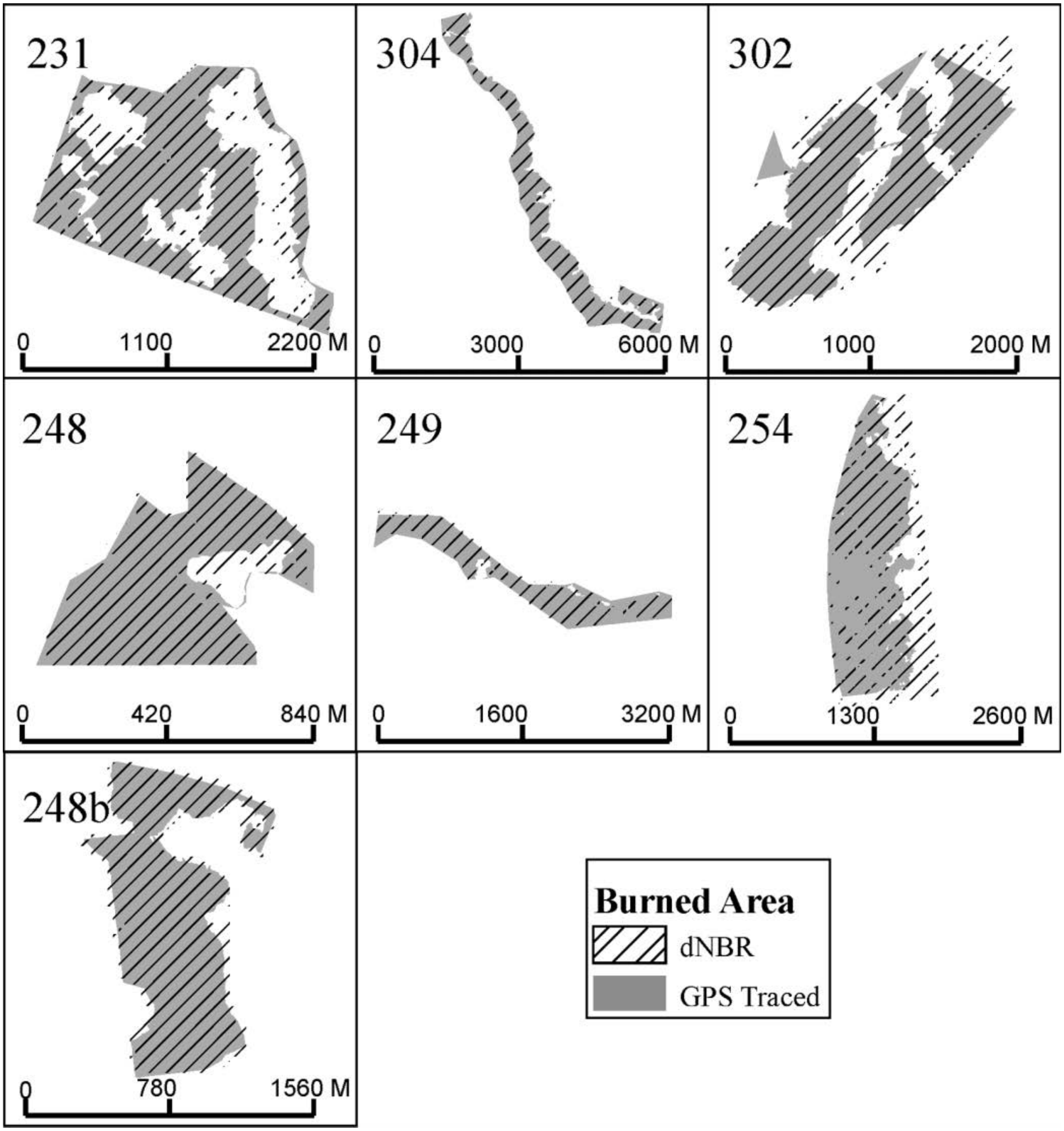

Figure 3. A comparison of GPS traced and differenced Normalized Burn Ratio (dNBR) burn mapping methods to trace the extent of all seven mapped burned areas (Figure 1) within the Apalachicola National Forest, Florida, 2006–2008. Unburned areas within burned areas are indicated by white.

burned area. Homogeneity of variance was confirmed using Levene's test (SPSS). The mean, standard deviation, and standard error of the bias among the seven burns were also reported. To determine whether or not the NBR versus dNBR differed consistently in their estimates of burned area, paired *t*-tests were performed to compare NBR and dNBR percent bias using the seven burn units as replicates (SPSS).

Imagery may become less reliable at mapping burned areas as vegetation has time to recover (Key 2005). To determine the effect of post-fire time until image capture on dNBR and NBR percent errors of omission, commission, and bias in burned area estimates, separate Pearson correlation tests were performed (SPSS). Differences between vegetation types (flatwoods, sandhills) were also considered, but not statistically tested, because of the small sample sizes (three and four burn units, respectively).

RESULTS

Comparison of remote estimates with ground measurements of burned area revealed errors of commission ranging from 1 to 44% ($\bar{x} = 15.7\%$, SE = 3.3%) and errors of omission ranging from 2 to 93% ($\bar{x} = 17.8\%$, SE = 7.1%) considering both remote sensing methods together (Table 2). Flatwoods had higher average errors of commission than sandhills and sandhills had higher average errors of omission than flatwoods (Table 2).

Differences between remotely sensed estimates of burned area and surface measurements were not significant (NBR: $t = -0.291$, df = 6, $P = 0.781$; dNBR: $t = -0.427$, df = 6, $P = 0.685$). Based on average bias, both the NBR and the dNBR methods slightly underestimated the area of burn severity with habitat types combined (−4.7% bias using NBR, −0.4% bias using dNBR [Table 2; Figure 4]). Direction of bias differed between habitat types. Specifically, area burned in flatwoods was overestimated and area burned in sandhills underestimated, reflecting errors of commission and omission reported above. Although average bias was small, there was great variation in the accuracy of remotely sensed estimates among burns (Table 2; Figure 4).

Post-fire time until image capture had a significant positive effect on error of omission for both NBR and dNBR ($R^2 = 0.769$, $P = 0.009$, df = 7 and $R^2 = 0.614$, $P = 0.037$, df = 7, respectively) but not on error of commission. For NBR, this trend of increasing error of omission translated into an overall significant effect of time since burn on bias ($R^2 = 0.711$, $P = 0.017$, df = 7).

DISCUSSION

The results demonstrate the usefulness of dNBR and NBR remote sensing methods for estimating burned area in southeastern U.S. ecosystems, as long as certain limitations are taken into consideration. Although the errors of commission or omission were large on certain burns, they were comparable to results from the western United States where the method was developed (e.g., Holden et al. 2005, Shapiro-Miller et al. 2007). The method also showed very little bias in estimating the cumulative burned area for multiple burns. Thus, the method is promising for monitoring total burned area within large landscapes with many relatively small fires, as is typical in the southeastern United States.

Key factors to consider for maximizing the accuracy of the method are time between the burn and post-burn image

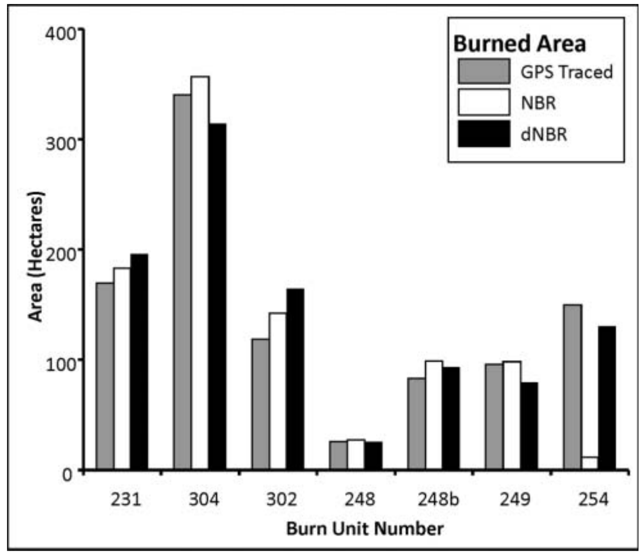

Figure 4. A comparison of GPS traced, Normalized Burn Ratio (NBR), and differenced Normalized Burn Ratio (dNBR) area estimates (ha), for each of the seven prescribed burn units monitored within the Apalachicola National Forest, Florida, 2006–2008.

Table 2. Commission error (CE), omission error (OE), and average bias (AB) between actual burned area (GPSed) and burned areas estimated by the Normalized Burn Ratio (NBR) or differenced Normalized Burn Ratio (dNBR) within the Apalachicola National Forest, Florida. Burned areas have been subdivided into their respective vegetation types by season of burn. Mean values, SD, and SE were calculated for both vegetation types and all data.

			NBR (%)			dNBR (%)		
Burn unit	Vegetation	Season	CE	OE	AB	CE	OE	AB
231	Flatwoods	Dormant	16	8	+8	9	24	−15
304	Flatwoods	Early growing	10	5	+5	6	13	−7
302	Flatwoods	Late growing	27	7	+20	44	6	+38
$\bar{x}$	Flatwoods		18	7	+11	19	14	+5
SD	Flatwoods		9	2	8	21	9	29
SE	Flatwoods		3	1	3	5	3	5
248b	Sandhill	Dormant	21	2	+19	13	2	+11
248	Sandhill	Early growing	9	4	+5	8	8	0
249	Sandhill	Early growing	14	12	+2	5	22	−17
254	Sandhill	Late growing	1	93	−92	30	43	−13
$\bar{x}$	Sandhill		11	28	−17	14	19	−5
SD	Sandhill		8	44	51	11	18	13
SE	Sandhill		3	7	7	3	4	4
$\bar{x}$	All		15	19	−5	16	17	−1
SD	All		8	33	39	14	14	20
SE	All		3	13	15	6	6	7

capture, vegetation type, and landscape changes that have occurred between the pre- and post-fire images. The positive relationship between errors of omission and time-since-fire is presumably because of increased growth of vegetation obscuring the division between burned and unburned areas (Hammill and Bradstock 2006), which is naturally most rapid during the growing season. During this period, images used in mapping burned areas should be taken within 2–8 weeks post-fire (Key 2005), i.e., after browning of woody vegetation and before significant recovery of vegetation. However, the availability of clear images within the needed time frame sometimes can be limiting because of cloud cover. By viewing Landsat images provided through the GloVis framework (USGS 2009), we found that over the 10-year period from 1999 to 2008 there were viable cloud-free images available for eight months of the year on average. January, May, June, July, and August were the most difficult months to obtain an image, with less than a 40% probability of obtaining at least one viable image. In contrast, February, March, April, September, October, November, and December had at least a 60% probability of obtaining at least one clear image.

Differences in the direction and magnitude of errors and bias between flatwoods and sandhills are attributable to their specific vegetation characteristics. Sandhill fuels are dominated by herbaceous vegetation on droughty soils, resulting in relatively low-severity fires that are more difficult to detect and more likely to cause errors of omission. Flatwoods measurements may have been complicated by their characteristic embedded areas of hardwood depression swamps and sandy ridges which might be best interpreted with different breakpoints (White et al. 1996). Flatwoods are also more likely to have hydrological changes that translate into differences in reflectance that are not attributable to fire. Error due to hydrological variation was especially evident in Burn Unit 302, where heavy rain just prior to the pre-burn image capture and relatively dry conditions in the post-fire image capture apparently translated into a high error of commission using dNBR (44%).

Landscape changes apart from fire that occur between the pre- and post-fire image captures can lead to incorrect burned area classification when using dNBR (Key 2005). Such changes can result from timber harvesting, land clearing, agricultural activities, fluctuations in hydrology, severe storms, and other events. When the spatial areas of these other landscape changes are known, they can be excluded from calculations of burned area. Otherwise, the NBR method is recommended because it detects recently burned environments without reference to pre-fire vegetation conditions.

MANAGEMENT IMPLICATIONS

Remote sensing NBR and dNBR methods of assessing burn severity within the southeastern United States provide a low-cost and relatively unbiased way of monitoring total burned area within a given region. Although existing fire monitoring programs using the studied methods are currently restricted to fires >200 ha, we found that fires ≥ 10 ha can be monitored as effectively, keeping in mind the limitations and guidelines presented in this and other studies. To meet the need for accurate burn monitoring within the southeastern United States, we envision a system using our described methods to monitor wildfires and prescribed burns at the state or regional levels at a cost limited to employing a small number of technicians, given that Landsat TM images are available free of charge (USGS 2009). Wildfire incident reports and prescribed fire authorizations, which are required and archived in most southeastern states, could be used to provide the location, approximate size, and date of burn, which would assist greatly in identifying areas of focus for applying the NBR and dNBR methods. Follow-up visits, additional measurement of CBI plots, and provision of ground-measured burned area maps from certain agencies and landholders on a subset of burn locations could be used to continue refinement and validation of the method. Providing reliable estimates of burned area at the state and regional levels would significantly improve assessments of wildfire risk, habitat management goals, and air pollution emissions from fire.

ACKNOWLEDGMENTS

We would like to thank S. Aicher, N. Benson, J. Bowen, D. Brownlie, K. Gordon, M. Housh, J. Isbell, C. Noble, J. Noble, D. Ohlen, T. Terhune, E. Watkins, and G. Wyche for their valuable assistance in this project. We would especially like to thank the Apalachicola National Forest (U.S. Department of Agriculture Forest Service) and Okefenokee National Wildlife Refuge (U.S. Department of Interior Fish and Wildlife Service) for allowing us to access burned areas and providing logistical support. This project was supported by Joint Fire Science Program Grant No. 06-2-1-31 and Tall Timbers Research Station.

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