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Article

Recovery of Vegetation Canopy after Severe Fire in 2000 at the Black Hills National Forest, South Dakota, USA

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Abstract: Forest fires often result in varying degrees of canopy loss in forested landscapes. The subsequent trajectory of vegetation canopy recovery is important for ecosystem processes because the canopy controls photosynthesis and evapotranspiration. The loss and recovery of a canopy is often measured by leaf area index (LAI) and other vegetation indices that are related to canopy photosynthetic capacity. In this study we used time series imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Terra satellite over the period of 2000–2009 to track the recovery of the vegetation canopy after fire. The Black Hills National Forest, South Dakota, USA experienced an extensive wildfire starting on August 24, 2000 that burned a total area of 33 785 ha, most of which was ponderosa pine forest. The MODIS data show that canopy photosynthetic capacity, as measured by LAI, recovered within 3 years (2001-2003). This recovery was attributed to rapid emergence of understory grass species after the fire event. Satellite-based Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI) at the burned sites also recovered within 3 years (2001-2003). Rapid recovery of LAI, NDVI, and EVI at the burned sites makes it difficult to use these variables for identifying and mapping burned sites several years after the fire event. However, the Land Surface Water Index (LSWI), calculated as a normalized ratio between near infrared and shortwave infrared bands (band 2 and band 6 (1628–1652 nm) in MODIS sensor), was able to identify and track the burned sites over the entire period of 2000–2009. This finding opens a window of opportunity to identify and map disturbances using imagery from those sensors with both NIR and SWIR bands, including Landsat 5 TM (dating back to 1984); furthermore, a longer record of disturbance and recovery helps to improve our understanding of disturbance regimes, simulations of forest succession, and the carbon cycle.

Keywords: conifer forest; MODIS; Landsat; NDVI; EVI; LSWI; forest fire; canopy

1 Introduction

The forest canopy controls photosynthesis and evapotranspiration through the exchange of CO_2 and H_2O between plant leaves and the atmosphere. Forest canopies also determine albedo and the surface energy balance. Forest fires, especially forest crown fires, often result in severe damage to or losses of forest canopy. Forest fires occur extensively and frequently in the world, and in a majority of cases there were no post-fire management activities (e.g., felling dead trees). The natural post-fire recovery process in forested landscapes can be divided into four stages in terms of canopy composition: (i) understory grass and standing dead trees, (ii) shrubs and standing dead trees, (iii) live trees and standing dead trees, and (iv) live trees. Recovery of vegetation canopy and photosynthetic capacity is important and often depends upon many factors including fire severity and pre-fire vegetation condition (Cuevas-Gonzalez *et al*. 2009; Diaz-Delgado *et al*. 2003). Quantifying the loss, recovery rates, and trajectory of vegetation canopy after severe fires is an important issue in forest ecology, as the canopy is one

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of the key determinants for vegetation photosynthetic capacity (Frolking *et al*. 2009).

Satellite imagery from optical sensors has been widely used to map and delineate the spatial extent of forest fires (Cahoon *et al*. 1994; Garcia-Haro *et al*. 2001; George *et al*. 2006; Kasischke and French 1995; Masek *et al*. 2008; Salvador *et al*. 2000), and to track the recovery of vegetation canopy and primary production after fires (Clemente *et al*. 2009; Cuevas-Gonzalez *et al*. 2009; Hicke *et al*. 2003; Idris *et al*. 2005). Most of these studies used imagery from Landsat, NOAA Advanced Very High Resolution Radiometer (AVHRR), SPOT HRV, and Moderate Resolution Imaging Spectroradiometer (MODIS).

Vegetation canopies are often measured by leaf area index (LAI) and vegetation indices calculated from satellite images. The Normalized Difference Vegetation Index (NDVI), calculated as a normalized ratio between red and near infrared (NIR) bands (Tucker 1979), has been widely used to estimate LAI (Myneni *et al*. 2002) and to assess forest disturbance (Masek *et al*. 2008). A number of studies have studied fire disturbance using the Enhanced Vegetation Index (EVI) (Chen *et al*. 2005; Coops *et al*. 2009; Forzieri *et al*. 2010; Xiao *et al*. 2003), which is calculated from red, near infrared, and blue bands (Huete *et al*. 2002). A number of satellite-based studies have used other vegetation indices that incorporate both near infrared and shortwave infrared (SWIR) bands including band 5 (1550–1750 nm) and band 7 (2080–2350 nm) in Landsat TM images, band 6 (1628–1652 nm) and 7 (2105–2155 nm) in MODIS (Cuevas-Gonzalez *et al*. 2009), and band 4 (1580–1750 nm) in SPOT HRV sensor (Chen *et al*. 2002; Jacobson 2010). One of the SWIR-based vegetation indices is the Normalized Burn Ratio (NBR), calculated as the normalized ratio between NIR band and SWIR band from Landsat imagery (band 4 and 7); it was used to evaluate wildfire burn sites in interior Alaska (Epting *et al*. 2005). Another SWIR-based vegetation index is the Land Surface Water Index (LSWI), calculated as the normalized ratio between NIR band and SWIR band (e.g., band 5 in Landsat TM and ETM+, band 6 in MODIS, band 4 in SPOT HRV), and it has been used to track land surface water condition in paddy rice, deciduous forest, and evergreen needleleaf forest (Sakamoto *et al*. 2007; Xiao *et al*. 2002a, 2002b; Xiao *et al*. 2004).

Since its launch on December 18, 1999, the MODIS sensor onboard the Terra satellite has provided continuous observations of the Earth over the period of February 2000 to present. NDVI, EVI, and LSWI data products from the MODIS sensor during 2000–2009 are widely available to the public, and they are related to leaf area index (LAI), chlorophyll content, and water content (Xiao *et al*. 2005b). The extensive and continuous data stream from MODIS provides a unique opportunity to evaluate its potential for tracking the recovery of a vegetation canopy over a decadal time scale after a forest fire.

The Black Hills National Forest, South Dakota, USA (Fig.1), where ponderosa pine (*Pinus ponderosa*) forest dominates, experienced a severe and extensive wildfire that started on August 24, 2000 and burned a total area of 33,785 ha (83 500 acres), or 12% of the Black Hills National Forest (Keyser *et al*. 2010; Lentile *et al*. 2006; Mitchell and Yuan 2010). A previous remote sensing study in the Black Hills National Forest collected ground-based LAI measurements at fourteen sites across a gradient of post-fire severity classes and unburned control sites from June to August in 2002 and 2003, and estimated canopy LAI from NDVI and EVI data derived from Landsat TM

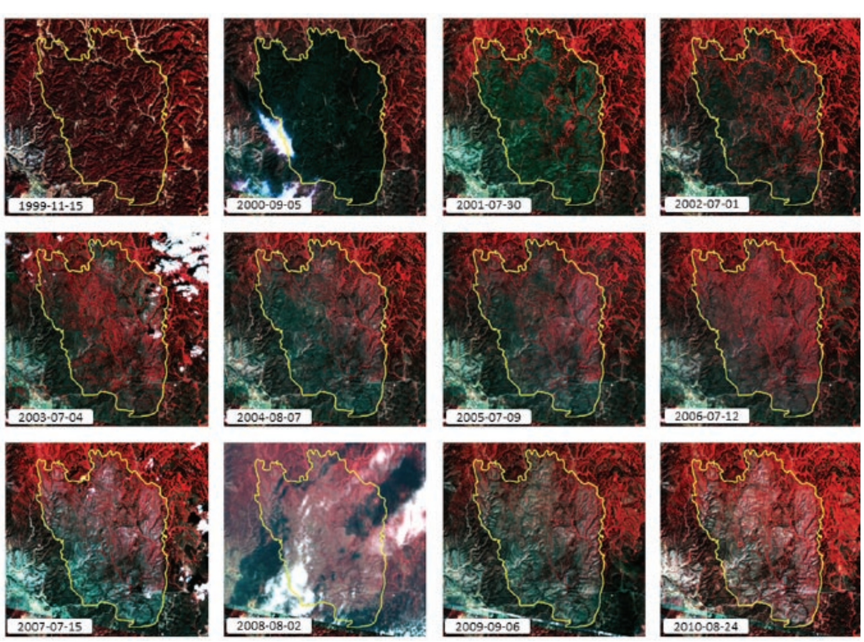

Fig. 1 Landscape characteristics of the Black Hills National Forest, South Dakota, USA, as observed by Landsat 7 ETM+ images in 1999 – 2010. False color composites (NIR, red and green) of Landsat images are used here.

and ETM+ imagery as well as the multi-angle MISR imagery (Pocewicz *et al*. 2007). In this study we acquired and analyzed MODIS imagery and its derived data products over the period of 2000–2009. The objective of this study is twofold: (i) to evaluate time series of three vegetation indices (NDVI, EVI and LSWI) and leaf area index from MODIS imagery for tracking the canopy recovery process during 2000–2009, and (ii) to better understand the recovery rate and trajectory of vegetation canopy recovery in the Black Hills National Forests, as characterized by vegetation indices. In this study we focus on NDVI, EVI, and LSWI because they are widely used to study vegetation phenology, land cover classification, and gross and net primary production.

2 Materials and Methods

2.1 The study area

The Black Hills National Forest is located in South Dakota, USA. Vegetation in the Black Hills is dominated by Pinus ponderosa forests, accompanied by other deciduous broadleaf trees, including *Populus tremuloides* and *Quercus macrocarpa* (Bonnet *et al*. 2005). The study region has a continental climate. According to the ECMWF Atmospheric Reanalysis Data (http://www.ecmwf.int/) over the period of 2000–2009, annual mean temperature in the region varied from 9.2℃ in 2006 to 7℃ in 2009, and annual precipitation varied from 379 mm in 2004 to 764 mm in 2008. Rainfall is abundant in the spring but the summer season is often dry (Fig. 2).

A wildfire in the Black Hills National Forest started on August 24, 2000 and lasted for 8 days; the fire event is often called the Jasper fire. The fire burned a 33 785 ha area dominated by ponderosa pine forests (Fig. 1). Because of complex topography in the forest area (elevation varying from 1800 m to 2200 m) the fire resulted in a mosaic pattern of burned and unburned patches with different levels of forest canopy damage or loss. A number of field studies have examined post-fire dynamics of vegetation in the Black Hills National Forest (Bonnet *et al*. 2005; Keyser *et al*. 2009; Lentile *et al*. 2005; Lentile *et al*. 2006; Mitchell and Yuan 2010), and the severely burned sites are still at the stage consisting of a mixture of grass with standing dead trees (Fig. 3).

We obtained the fire perimeter data (ArcGIS shape file) from the USDA Black Hills National Forest GIS Department, which was generated from field surveys with GPS receivers. We overlaid MODIS images on this fire perimeter data layer (see section 2.3) to delineate the study area for statistical analysis.

2.2 Landsat images

Landsat 5 TM and Landsat 7 ETM+ sensors collect data for six optical spectral bands at 30-m spatial resolution and a 16-day revisit cycle. We searched the Landsat image archive at the US Geological Survey EROS Data Center and downloaded twelve Landsat ETM+ images with little or low cloud cover (Fig. 1). One ETM+ image was acquired before the Jasper fire (November 15, 1999), and the other 11 images were acquired after the fire (one image per year from 2000–2010). Four Landsat images in 1999 – 2002 are from Landsat 7 ETM+, and the other 8 Landsat images in 2004–2010 are from Landsat 5 TM. Landsat 7 was launched on April 15, 1999 but the Scan Line Corrector (SLC) in the ETM instrument failed on May 31, 2003, resulting in a loss of approximately one-fourth of the image data in a Landsat 7 scene. The 12

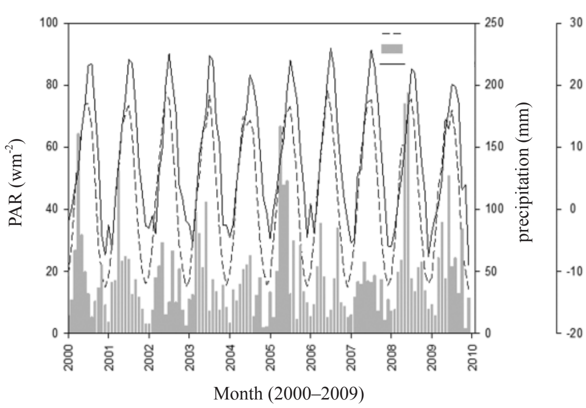

Fig. 2 Seasonal dynamic and annual interannual variation of monthly mean temperature, precipitation and photosynthetic active radiation (PAR) during 2000–2009 at the Black Hills National Forest, South Dakota, USA. Here we used monthly climate data from the ECMWF atmospheric re-analysis data at a spatial resolution of 0.25 degree of latitude and longitude.

Fig. 3 A field photo (7/24/2007) of the burned sites in the Black Hills National Forest Park, South Dakota, USA. It shows a mixture of grass canopy with standing dead trees, 7 years after the fire event in August 2000.

Landsat images we downloaded were co-registered and overlaid with the GIS-based fire perimeter data layer for visual interpretation of the landscape. The Landsat images were also used to assist with the selection of burned and un-burned sites in the MODIS data analysis (Fig. 1).

2.3 MODIS data

The MODIS sensor onboard the NASA Terra and Aqua satellites provide daily observation of the globe. Out of 36 spectral bands in the MODIS sensor, seven bands are primarily designed for the study of vegetation and land surface: blue (459–479 nm), green (545–565 nm), red (620–670 nm), near infrared (841–875 nm, 1230–1250 nm), and shortwave infrared (1628–1652 nm, 2105–2155 nm). The red and NIR1 (841–875 nm) bands have a spatial resolution of 250-m, and the other five bands (blue, green, NIR2, SWIR1, SWIR2 bands) have a spatial resolution of 500-m. The MODIS data are organized in tiles wherein each tile covers approximately 10° by 10° latitude and longitude at the Equator. The Black Hills National Forest is located within the MODIS H10V04 tile. The MODIS Land Science Team provides a suite of standard MODIS data products including surface reflectance, active fire, snow, leaf area index (LAI), the fraction of photosynthetically active radiation absorbed by vegetation (FPAR), and gross and net primary production (http://modis-land.gsfc.nasa.gov/index.htm).

2.3.1 MOD09A1 data and three vegetation indices

The MODIS Land Science Team provides several surface reflectance data products including the 8-day composite MODIS Land Surface Reflectance Product (MOD09A1). Each 8-day composite (MOD09A1) includes estimates of land surface reflectance for the seven spectral bands at 500-m spatial resolution. There are forty-six 8-day composites in a year.

In this study we downloaded MOD09A1 data (Collection 5) in 2000–2009 from the US Geological Survey EROS Data Center. We calculated three vegetation indices: NDVI (Tucker 1979), EVI (Huete *et al*. 1997), and LSWI (Xiao *et al*. 2002a), using blue, red, NIR1 (841–875 nm) and SWIR1 (1628–1652 nm) spectral bands. The resultant vegetation indices are available at the Earth Observation and Modeling Facility website (http://www.eomf.ou.edu). NDVI, LSWI, and EVI are related to leaf area index, canopy chlorophyll, and water contents, remote period and "respictively" (Xiao *et al*. 2005b).

$$NDVI = \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + \rho_{red}} \tag{1}$$

$$EVI = 2.5 \times \frac{\rho_{nir} - \rho_{red}}{\rho_{nir} + 6 \times \rho_{red} - 7.5 \times \rho_{blue} + 1} \tag{2}$$

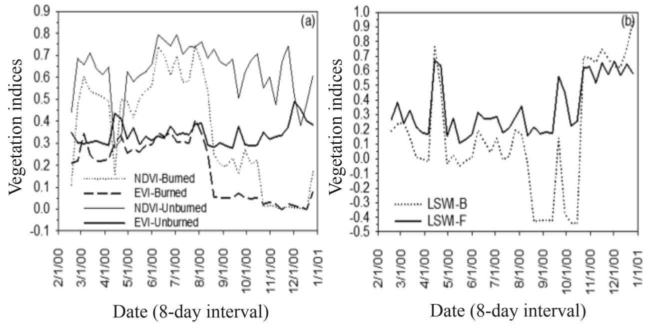

Fig. 4 Seasonal dynamics of three vegetation indices (NDVI, EVI and LSWI) at a burned site (43.8639oN, 103.8912°W) and an unburned site (43.7668°N, 103.7038°W) in 2000 at the Black Hills National Forest, South Dakota, USA. Three vegetation indices were derived from the 8-day MODIS surface reflectance data at 500-m resolution (MOD09A1). We use un-filtered data in the figure to illustrate the quality of data.

$$LSWI = \frac{\rho_{nir} - \rho_{swir}}{\rho_{nir} + \rho_{swir}} \tag{3}$$

The MOD09A1 data files (Collection 5, http://modis-sr.ltdri.org/) provide data quality flags that indicate the presence of clouds, cloud shadows, aerosols (climatology and high) and pixels adjacent to clouds. We treated those observations with the above-mentioned quality flags as bad observations and exclude them from statistical data analysis. Observations with snow cover are identified using the MODIS snow algorithm, which is primarily based on the Normalized Difference Snow Index (NDSI) (Hall *et al*. 2002). In addition, we also treated those observations with blue band value > 0.20 as bad observations (mostly due to atmospheric aerosols) and exclude them from statistical data analysis (Xiao *et al*. 2005a).

2.3.2 MOD15A2 LAI/FPAR data product

The MODIS Science Team provides the data of leaf area

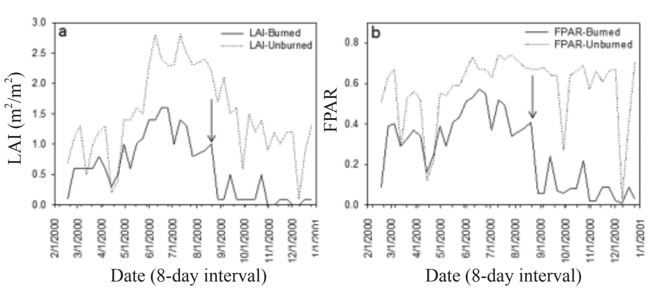

Fig. 5 Seasonal dynamics of LAI (a) and FPAR (b) at a burned site (43.8639°N, 103.8912°W) and an unburned site (43.7668°N, 103.7038°W) in 2000 at the Black Hills National Forest, South Dakota, USA. The LAI/FPAR data were from the 8-day MODIS LAI/FPAR at 1-km resolution (MOD15A2). We use un-filtered data in the figure to illustrate the quality of data.

index (LAI, m^2/m^2) and the fraction of photosynthetically active radiation (FPAR, 400–700 nm) absorbed by vegetation canopy at 8-day temporal resolution and 1-km spatial resolution, which is called as MOD15A2 (Myneni *et al*. 2002). The LAI and FPAR data products are derived from daily MODIS data through the inversion of a radiative transfer model, with an NDVI-LAI regression model as a back-up calculation method. Many studies have demonstrated that LAI is closely related to NDVI (Myneni and Williams 1994).

We downloaded the MOD15A2 dataset (Collection 5) over the period of 2000–2009 from the US Geological Survey EROS Data Center. We generated monthly composites of LAI and FPAR from the 8-day composite MOD15A2 datasets by selecting the maximum values of LAI and FPAR in each month at individual pixels. Based on the seasonality of vegetation at the sites we chose July as the reference month for inter-annual comparison of LAI and FPAR data over the period of 2000–2009. We overlaid the GIS-based fire perimeter boundary map in 2000 to the 8-day composite (MOD15A2 dataset) and the monthly composite LAI and FPAR datasets, and retrieved LAI and FPAR time series data from these datasets. We calculated the frequency distribution (a bin size 0.5 m^2/m^2) of LAI for those MODIS pixels within the fire perimeter area in 2000. In this study, the time series LAI and FPAR data over 2000–2009 were used to quantify and track the losses and recovery rates of LAI and FPAR after the 2000 fire in the Black Hills National Forest, South Dakota, USA.

3 Results

3.1 Loss of canopy photosynthetic capacity after the wildfire in August 2000

Forests in the Black Hills National Forest are dominated by ponderosa pine, an evergreen needleleaf tree. Fig. 4 shows the seasonal dynamics of three vegetation indices (NDVI, EVI and LSWI) at a burned site and an unburned site in 2000. In the unburned forest site (Ponderosa pine forest) NDVI values in 2000 were in the range of 0.6–0.8 throughout a year. The burned site had similar range of NDVI values during February to August 2000, but its NDVI values dropped to 0.2 after the fire starting on 8/24/2000 (Fig. 4a). EVI values in the unburned site were in the range of 0.3 throughout the year 2000 (Fig. 4a). EVI values in the burned site were similar to the unburned site during February to August 2000, but dropped to 0.05 after the fire. LSWI values in the unburned site remained above 0.0 throughout the year (Fig. 4b). High LSWI values in the winter season are attributed to snow cover on the ground. During the plant growing season, LSWI values in the unburned site varied between 0.1 and 0.3 (Fig. 4b). LSWI values in the burned site had similar dynamics as NDVI and EVI, and dropped to below -0.4 after the fire in August 2000.

Fig. 5 shows the seasonal dynamics of leaf area index (LAI) and the fraction of photosynthetically active radiation (FPAR) at a burned site and an unburned site in 2000 as estimated by MODIS LAI/FPAR data product (MOD15A2). At the burned site, LAI values were approximately 1.5 m^2/m^2 in mid-June 2000, but dropped close to 0 after the fire event (Fig. 5a), substantially lower than LAI values (0.5 m^2/m^2) in spring 2000. At the unburned site, LAI values had a strong seasonal dynamic and varied within a range of ~1.4 m^2/m^2 in early spring, 2.8 m^2/m^2 in early summer, and 1.4 m^2/m^2 in late fall (Fig. 5a). The fraction of photosynthetically active radiation absorbed by vegetation canopy (FPAR) at the burned site also dropped from 0.5 in mid-June to 0.05 after the fire event in 2000 (Fig. 5b). In comparison, FPAR at the unburned site has only a slight temporal variation during the plant growing season (Fig. 5b).

The impacts of fires are likely to vary over space due

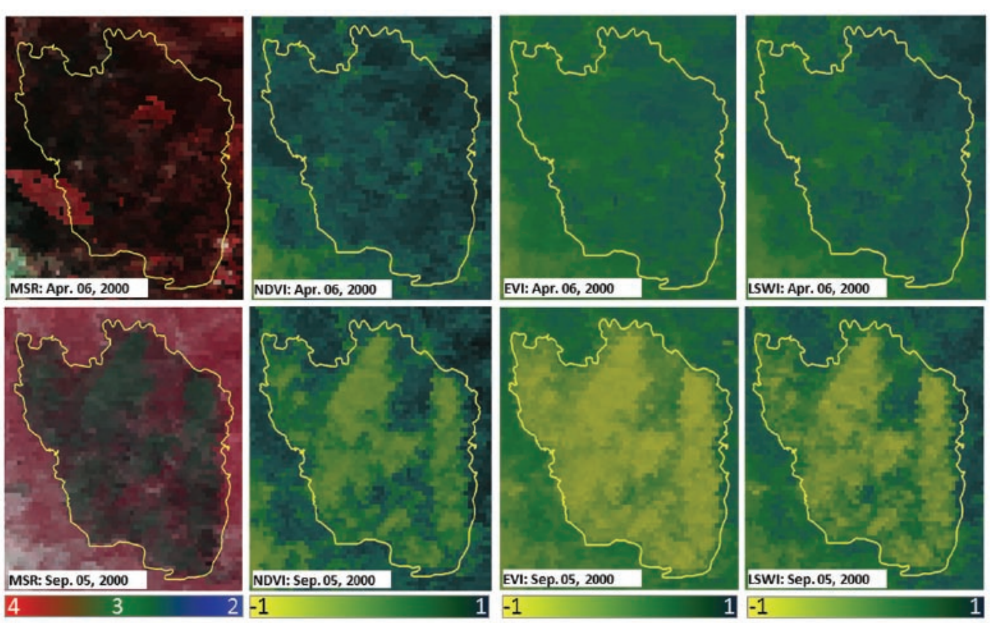

Fig. 6 Spatial distribution of surface reflectance and three vegetation indices on April 6, 2000 (before the fire) and September 5, 2000 (after the fire) in the Black Hills National Forest, South Dakota, USA.

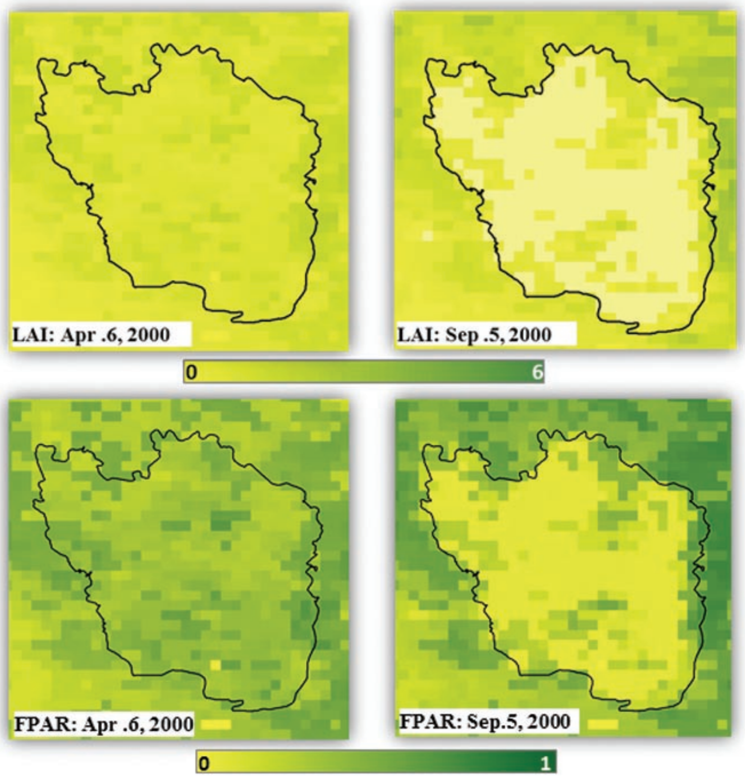

Fig. 7 Spatial distribution of leaf area index and FPAR on April 6, 2000 (before the fire) and September 5, 2000 (after the fire) in the Black Hills National Forest, South Dakota, USA.

to meso-scale topography and landscape characteristics. Consequently the loss of canopy photosynthesis capacity may also vary over space. Fig. 6 compares the spatial variations of surface reflectance and three vegetation indices on April 6, 2000 (before the fire) and September 5, 2000 (after the fire). The fire resulted in substantial drops of NDVI, EVI and LSWI values at the burned sites. Spatially, the decreases of EVI at the burned sites were much more evenly distributed than NDVI and LSWI (Fig. 6).

Fig. 7 compares the spatial variations of leaf area index and FPAR on April 6, 2000 (before the fire) and September 5, 2000 (after the fire). The majority of MODIS pixels had LAI values in the range of 1.0–1.5 m^2/m^2 on April 6, 2000 but dropped to below 0.5 m^2/m^2 on September 5, 2000, clearly showing the losses of forest canopy due to the fire event. FPAR values also had similar large changes between April 6, 2000 (before the fire) and September

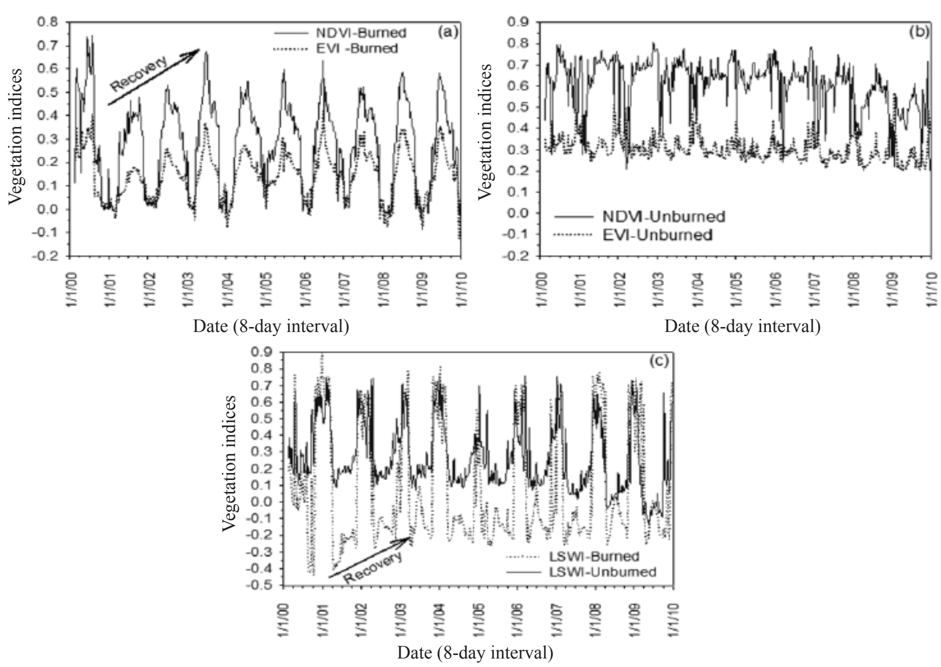

Fig. 8 Seasonal dynamics and interannual variation of three vegetation indices during 2000–2009 at a burned site (43.8639°N, 103.8912°W) and an unburned site (43.7668°N, 103.7038°W) in the Black Hills National Forest, South Dakota, USA. (a) NDVI and EVI at the burned site, (b) NDVI and EVI at the unburned site, and (c) LSWI at the burned and unburned site. We use un-filtered data in the figure to illustrate the quality of data.

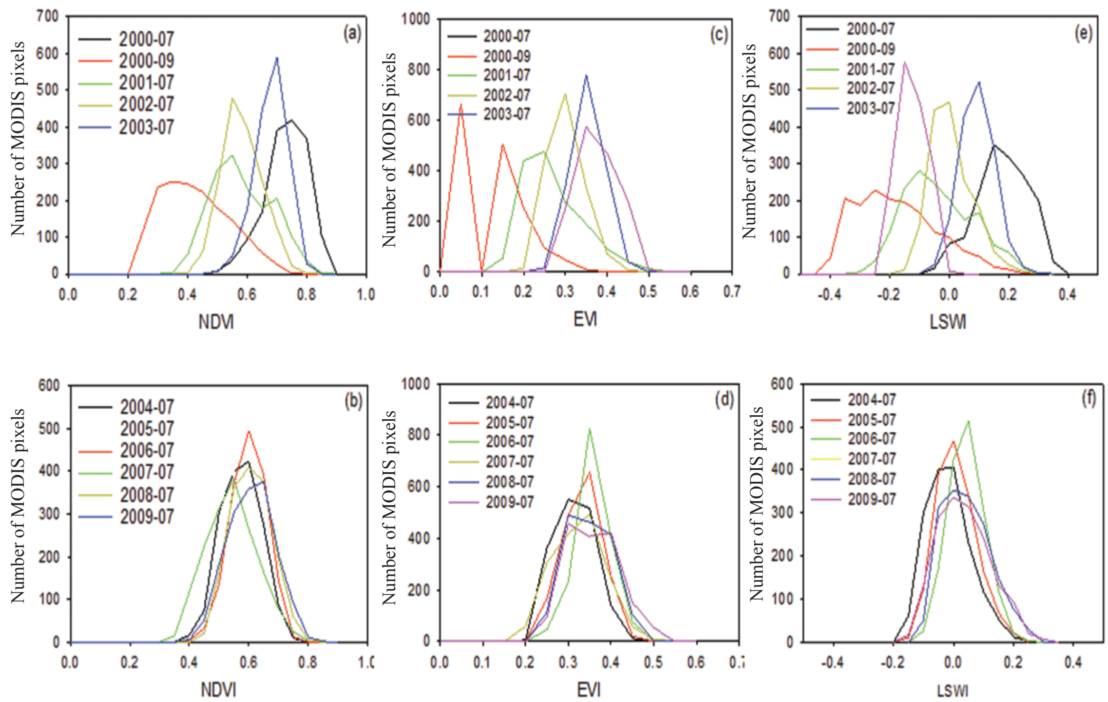

Fig. 9 The histogram of three vegetation indices (NDVI, EVI, and LSWI) in July over the period of 2000–2009 within the Jasper fire area, the Black Hills National Forest, South Dakota, USA. (a and b) —NDVI, (c and d)—EVI and (e and f) —LSWI.

5, 2000 (after the fire). The significant contrast between the fire-impacted area and non-fire neighbors makes it relatively easy for identifying and mapping fire scars using time series of MODIS images (Fig. 7).

3.2 Recovery of canopy photosynthetic capacity during 2000–2009

Fig. 8 shows seasonal dynamics and interannual variations of three vegetation indices over the period of 2000–2009 at a burned site and an unburned site in the Black Hills National Forest, South Dakota. At the burned site NDVI in mid-summer increased from ~0.4 in 2001 (1st year after the fire in 2000) to ~0.6 in 2003 (3rd year after the fire in 2000), and then remained at a similar level (with slight fluctuation) during 2004–2009 (Fig. 8a). Similarly, EVI in mid-summer also increased from ~0.15 in 2001 to ~0.3 in 2003, and then remained at this level with minor fluctuation through 2009. Both NDVI and EVI at the burned site had a strong seasonal dynamic during 2001–2009, a typical feature of grass vegetation (Fig. 8a). In comparison, when excluding those snow-affected observations in the winter season, the unburned site had relatively high values of NDVI and EVI throughout a year, a typical feature of evergreen forests. The time series data of NDVI and EVI suggested that the burned site recovered in 3 years, and it became relatively difficult to identify a burned site after 3 years using NDVI and EVI data alone.

At the burned site, LSWI in mid-summer increased from –0.2 in 2001 to slightly below 0.0 in 2003 and remained below 0.0 throughout 2004–2009 (Fig. 8c). Negative

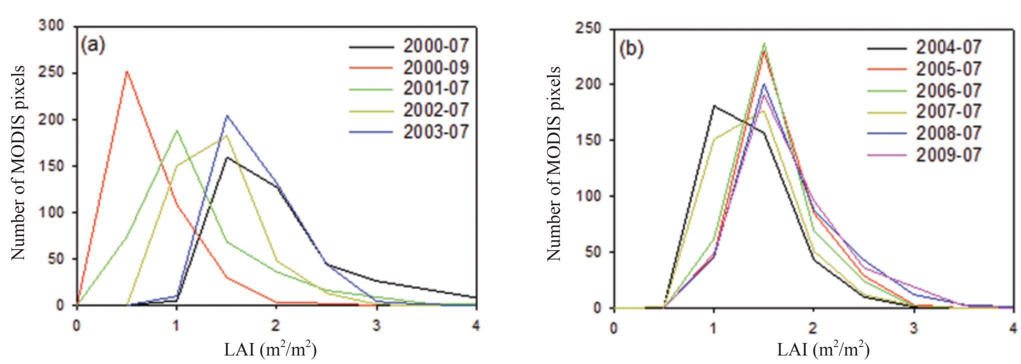

Fig. 10 The histogram of leaf area index in July over the period of 2000–2009 within the Jasper fire area, the Black Hills National Forest, South Dakota, USA, (a) 2000–2003, and (b) 2004–2009.

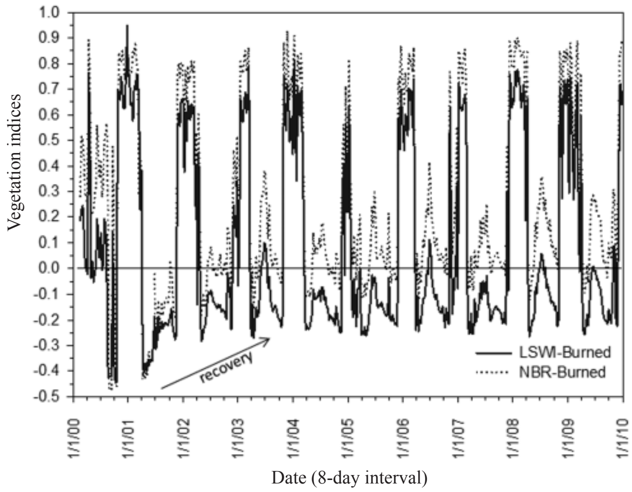

Fig. 11 Seasonal dynamics and inter-annual variation of Land Surface Water Index (LSWI) and Normalized Burn Ratio (NBR) over the period of 2000–2009 at a burned site (43.8639°N, 103.8912°W) in the Black Hills National Forest, South Dakota, USA. LSWI and NBR data are from the same MODIS pixel (a burned site) as Fig. 4. We use un-filtered data in the figure to illustrate the quality of data.

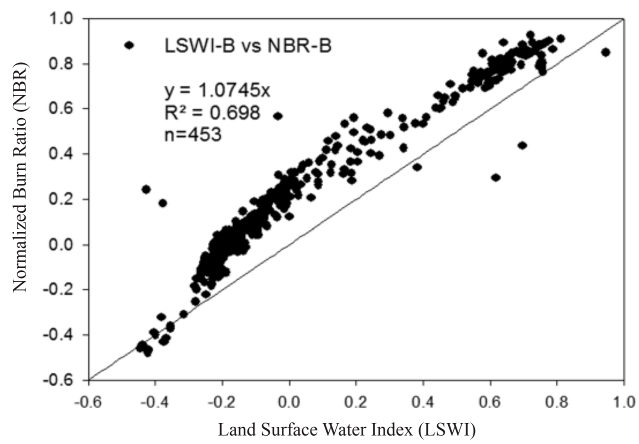

Fig. 12 The quantitative relationship between Land Surface Water Index (LSWI) and Normalized Burn Ratio (NBR) over the period of 2000–2009 at a burned site (43.8639°N, 103.8912°W) in the Black Hills National Forest, South Dakota, USA. LSWI and NBR data are from the same MODIS pixel (a burned site) as Fig. 4.

LSWI values indicate that the burned site, as observed by satellite, is a mix of dead trees and green grasses. In comparison, LSWI values at the unburned site remained positive (>0.0) from 2000–2009 (Fig. 8c). The negative LSWI values within the plant growing season during 2001–2009 at the burned site and positive LSWI values at the unburned site indicates that the LSWI time series data can be used to identify the burned site 9 years after the fire.

We calculated the frequency distribution of three vegetation indices in July 2000 (before the fire) and in September 2000 (after the fire) within the Jasper fire affected area (Fig. 9). The histograms of NDVI had a clear shift from July 2000 to September 2000 (Fig. 9a-b), consistent with the time series NDVI data from an individual pixel in 2000 (Fig. 4). Both LSWI and EVI histograms also had substantial shifts from July 2000 to September 2000 (Fig. 9c-f).

The histograms of NDVI, EVI, and LSWI in mid-summer (July) during 2001–2003 clearly show the recovery process at the Jasper fire sites. The median values of these histograms suggest that the NDVI had the fastest recovery rate during 2001–2003, followed by EVI and LSWI (Fig. 9a-f). These three vegetation indices fluctuated over the period 2004–2009, which represented the responses of grasses to interannual weather and climate variations (Fig. 2).

It is interesting to note that approximately half of the MODIS pixels within the fire affected area still had negative LSWI values in July of 2009, which indicated that much of the land surface is still a mixture of standing dead trees and grass canopy (Fig. 3). Conversely, those MODIS pixels with positive LSWI values in July of 2009 suggest that recovery in some fire-impacted areas have reached the stage of a vegetation canopy with small or little amounts of standing dead trees exposed to satellite sensors. With such a capacity to distinguish two recovery stages, specifically (i) grass canopy mixed with standing dead trees and (ii) vegetation canopy dominated by live trees, the LSWI time series data appear to be useful indicator for identifying fire-affected areas over at least 9 years.

We also calculated the frequency distribution of LAI in July 2000 and September 2000 within the fire-affected areas using the MOD15A2 (LAI/FPAR) data product. Fig. 10 shows a substantial decrease of LAI from ~1.5 m^2/m^2 in July 2000 to ~0.5 m^2/m^2 in September 2000 (Fig. 10a). LAI increased from ~1.0 m^2/m^2 in 2001 to ~1.5 m^2/m^2 in 2003 and fluctuated again during 2004–2009, ranging from low values in 2004 (1.1 m^2/m^2) and 2007 (1.3 m^2/m^2) to high values in 2005, 2006, 2008–2009 (~1.5 m^2/m^2; Fig. 10b). LAI at the burned sites recovered within 3-years, and there was no significant difference in LAI between the forest canopy (July 2000; Fig. 10a) and the grass canopy (2004–2009; Fig. 10b).

4 Discussion

Since the launch of the MODIS sensor onboard the Terra satellite in 1999, MODIS imagery have been widely used to map active fires and fire scars (Giglio *et al*. 2003; Justice *et al*. 2002; Roy *et al*. 2002; Roy *et al*. 2006). A few studies have used MODIS imagery to document forest recovery after disturbance at individual sites (Chen *et al*. 2005; Lucas *et al*. 2002). In this study we examined the canopy recovery process after a wildfire in 2000 in the ponderosa pine forest dominated Black Hills National Forest using remotely sensed data from MODIS for 2000–2009.

Leaf area index is an important biophysical parameter for tracking canopy recovery rates and trajectory after disturbance. The results from this study show that leaf area index at the burned sites in the Black Hills National Forest, as estimated by the MODIS LAI/FPAR product, recovered rapidly and reached pre-fire levels within 3 years. These results suggest that LAI data in mid-summer is not a useful indicator to identify or detect fire-affected areas after 3 years in the Black Hills National Forest where evergreen ponderosa pine forest dominates. Rapid recovery of leaf area index has also been observed after other types of disturbances. For example, gaps generated by the conventional forest logging in the eastern Amazon were filled with secondary plant species within 0.5 to 3.5 years (Asner *et al*. 2004a, 2004b).

A number of remote sensing studies tracked canopy recovery after disturbance using either surface reflectance (Lucas *et al*. 2002) or vegetation indices (Diaz-Delgado *et al*. 2003; Epting *et al*. 2005). Masek *et al*. used Landsat image archives in 1990 and 2000 to identify and map disturbance and recovery of forests in North America, and found that approximately 30%–60% of forest disturbance cannot be mapped due to the long interval between image acquisition dates (1990 versus 2000),when temporal changes in a Tasseled-Cap "Disturbance Index" was used (Masek *et al*. 2008). This is clearly attributed to rapid recovery of leaf area index at the disturbance sites by early successional species (mostly grass species). Note that early successional species often have higher foliage nitrogen content and chlorophyll content than late successional species, which substantially affects reflectance in visible and near infrared bands. The results from this study show that NDVI and EVI data values recovered rapidly in the first three years (2001–2003) and then fluctuated with inter-annual variation of climate during the period of 2004–2009, a typical dynamic of grass canopies. The results suggest that majority of the burned sties in the Black Hills National Forest remain in the recovery stage of grass canopy and standing dead trees by 2009.

In addition to reflectance and vegetation indices from visible and near infrared bands, several studies examined the potential of shortwave infrared (SWIR) bands to track canopy growth, for example band 7 (2080 nm–2350 nm) in Landsat imagery and band 7 (2105 nm–2155 nm) in MODIS imagery (Epting *et al*. 2005; Roy *et al*. 2006; Soverel *et al*. 2010). The Normalized Burn Ratio (NBR), calculated as the normalized ratio between near infrared (NIR) and mid-infrared (MIR) from Landsat imagery (band 4 and 7), was used to evaluate wildfire burn sites in interior Alaska (Epting *et al*. 2005). The NBR was evaluated across 14 fires in the Sierra Nevada mountain range of California (Miller and Thode 2007) and is now used by US federal land management agencies to map fire severity due to wildland fire (Miller *et al*. 2009). Roy *et al*. also assessed the reliability of NBR as an index of fire severity using Landsat images and MODIS images (Roy *et al*. 2006). In this study we used Land Surface Water Index (LSWI), which is calculated as a normalized ratio between NIR and SWIR bands, for example, band 2 (841–876 nm) and band 6 (1628–1652 nm) in MODIS, and band 4 (760–900 nm) and band 5 (1550 nm–1750 nm) in Landsat. Both LSWI and NBR values have a range of –1 to +1. To compare LSWI and NBR values, we calculated NBR at the burned site (the same site shown in Fig. 4) from MOD09A1 data in 2000–2009 (Fig. 11). LSWI and NBR have very similar seasonality (Fig. 11). NBR values increased rapidly in 2001–2003 and fluctuated during 2004–2009 (Fig. 11). The majority of NBR values during the plant growing season in 2004–2009 were positive (>0.0). Both LSWI and NBR indices are correlated with each other to a large degree (linear correlation coefficient $r = 0.70$; Fig. 12). Note that LSWI values within the plant growing season over the period of 2001–2009 at the burned sites remain negative (Fig. 8, 9), and negative LSWI values generally corresponds a mixture of grass canopy with standing dead trees at the burned sites (Fig. 3). In comparison to positive LSWI values before the wildfire occurred in August 2000, negative LSWI values in 2009 provides a qualitative indicator that forest fire disturbance at the ponderosa pine forest sites is still detectable after 9 years. Therefore, LSWI may be used as another complementary index to track fire disturbance and post-fire recovery, in addition to NBR.

In summary, this study and several previous studies (Asner *et al*. 2004b; Frolking *et al*. 2009; Masek *et al*. 2008) have shown that forest disturbance in temperate and tropical zones is often difficult to detect and map after several years when using reflectance data and vegetation indices from visible and near infrared bands. However, the results from this study have clearly demonstrated that a time series of LSWI data from MODIS during 2000 – 2009 is able to detect and map forest disturbance 9 years after a major fire event at the Black Hills National Forest. Note that Landsat 5 Thematic Mapper (TM) has much longer records (dated back to 1984) than do MODIS sensors. Therefore, a time series of Landsat 5 TM (and Landsat 7 ETM+) imagery can be used to calculate LSWI and further evaluate the potential of LSWI in detecting and mapping forest disturbance over a period of 26 years (1984–2010). This will lead to better quantification of disturbance regimes and recovery processes at the landscape, regional to global scales.

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References

Asner G P, M Keller, R Pereira, J C Zweede and J N M Silva. 2004a. Canopy damage and recovery after selective logging in Amazonia: Field and satellite studies. *Ecological Applications*, 14:S280–S298.

Asner G P, M Keller and J N M Silva. 2004b. Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. *Global Change Biology*, 10:765–783.

Bonnet V H, A W Schoettle and W D Shepperd. 2005. Postfire environmental conditions influence the spatial pattern of regeneration for Pinus ponderosa. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, 35:37–47.

Cahoon D R, B J Stocks, J S Levine, W R Cofer and J M Pierson. 1994. Satellite Analysis of the Severe 1987 Forest-Fires in Northern China and Southeastern Siberia. *Journal of Geophysical Research-Atmospheres*, 99:18627–18638.

Chen J M, G Pavlic, L Brown, J Cihlar, S G Leblanc, H P White, R J Hall, D R Peddle, D J King, J A Trofymow, E Swift, J Van der Sanden and P K E Pellikka. 2002. Derivation and validation of Canada-wide coarse-resolution leaf area index maps using high-resolution satellite imagery and ground measurements. *Remote Sensing of Environment*, 80:165–184.

Chen X, L Vierling, D Deering and A Conley. 2005. Monitoring boreal forest leaf area index across a Siberian burn chronosequence: a MODIS validation study. *International Journal of Remote Sensing*, 26:5433–5451.

Clemente R H, R M N Cerrillo and I Z Gitas. 2009. Monitoring post-fire regeneration in Mediterranean ecosystems by employing multitemporal satellite imagery. *Int J Wildland Fire*, 18:648–658.

Coops N C, M A Wulder and D Iwanicka. 2009. Large area monitoring with a MODIS-based Disturbance Index (DI) sensitive to annual and seasonal variations. *Remote Sensing of Environment*, 113:1250–1261.

Cuevas-Gonzalez M, F Gerard, H Balzter and D Riano. 2009. Analysing forest recovery after wildfire disturbance in boreal Siberia using remotely sensed vegetation indices. *Global Change Biology*, 15:561–577.

Diaz-Delgado R, F Llorett and X Pons. 2003. Influence of fire severity on plant regeneration by means of remote sensing imagery. *International Journal of Remote Sensing*, 24:1751–1763.

Epting J, D Verbyla and B Sorbel. 2005. Evaluation of remotely sensed indices for assessing burn severity in interior Alaska using Landsat TM and ETM+. *Remote Sensing of Environment*, 96:328–339.

Forzieri G, F Castelli and E R Vivoni. 2010. A Predictive Multidimensional Model for Vegetation Anomalies Derived From Remote-Sensing Observations. *Ieee Transactions on Geoscience and Remote Sensing*, 48:1729–1741.

Frolking S, M W Palace, D B Clark, J Q Chambers, H H Shugart and G C Hurtt. 2009. Forest disturbance and recovery: A general review in the context of spaceborne remote sensing of impacts on aboveground biomass and canopy structure. *Journal of Geophysical Research-Biogeosciences*, 114:–.

Garcia-Haro F J, M A Gilabert and J Melia. 2001. Monitoring fire-affected areas using Thematic Mapper data. *International Journal of Remote Sensing*, 22:533–549.

George C, C Rowland, F Gerard and H Balzter. 2006. Retrospective mapping of burnt areas in Central Siberia using a modification of the normalised difference water index. *Remote Sensing of Environment*, 104:346–359.

Giglio L, J Descloitres, C O Justice and Y J Kaufman. 2003. An enhanced contextual fire detection algorithm for MODIS. *Remote Sensing of Environment*, 87:273–282.

Hall, D.K., G.A. Riggs, V.V. Salomonson, N.E. DiGirolamo, and K.J. Bayr. 2002. MODIS snow-cover products. *Remote Sensing of Environment*. 83:181–194.

Hicke J A, G P Asner, E S Kasischke, N H F French, J T Randerson, G J Collatz, B J Stocks, C J Tucker, S O Los and C B Field. 2003. Postfire response of North American boreal forest net primary productivity analyzed with satellite observations. *Global Change Biology*, 9:1145–1157.

Huete A, K Didan, T Miura, E P Rodriguez, Gao X and L G Ferreira. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 83:195–213.

Huete A R, Liu H Q, K Batchily and W vanLeeuwen. 1997. A comparison of vegetation indices over a global set of TM images for EOS-MODIS. *Remote Sensing of Environment*, 59:440–451.

Idris M H, K Kuraji and M Suzuki. 2005. Evaluating vegetation recovery following large-scale forest fires in Borneo and northeastern China using multi-temporal NOAA/AVHRR images. *Journal of Forest Research*, 10:101–111.

Jacobson C R. 2010. Use of linguistic estimates and vegetation indices to assess post-fire vegetation regrowth in woodland areas. *Int J Wildland Fire*, 19:94–103.

Justice C O, L Giglio, S Korontzi, J Owens, J T Morisette, D Roy, J Descloitres, S Alleaume, F Petitcolin and Y Kaufman. 2002. The MODIS fire products. *Remote Sensing of Environment*, 83:244–262.

Kasischke E S and N H F French. 1995. Locating and Estimating the Areal Extent of Wildfires in Alaskan Boreal Forests Using Multiple-Season Avhrr Ndvi Composite Data. *Remote Sensing of Environment*, 51:263–275.

Keyser T L, F W Smith and W D Shepperd. 2009. Short-term impact of post-fire salvage logging on regeneration, hazardous fuel accumulation, and understorey development in ponderosa pine forests of the Black Hills, SD, USA. *Int J Wildland Fire*, 18:451–458.

Keyser T L, F W Smith and W D Shepperd. 2010. Growth Response of Pinus ponderosa following a Mixed-Severity Wildfire in the Black Hills, South Dakota. *West J Appl For*., 25:49–54.

Lentile L B, F W Smith and W D Shepperd. 2005. Patch structure, fire-scar formation, and tree regeneration in a large mixed-severity fire in the South Dakota Black Hills, USA. *Canadian Journal of Forest Research-Revue Canadienne De Recherche Forestiere*, 35:2875–2885.

Lentile L B, F W Smith and W D Shepperd. 2006. Influence of topography and forest structure on patterns of mixed severity fire in ponderosa pine forests of the South Dakota Black Hills, USA. *Int J Wildland Fire*, 15:557–566.

Lucas R M, X M Xiao, S Hagen and S Frolking. 2002. Evaluating TERRA-1 MODIS data for discrimination of tropical secondary forest regeneration stages in the Brazilian Legal Amazon. *Geophysical Research Letters*, 29:art. no.–1200.

Masek J G, C Q Huang, R Wolfe, W Cohen, F Hall, J Kutler and P Nelson. 2008. North American forest disturbance mapped from a decadal Landsat record. *Remote Sensing of Environment*, 112:2914–2926.

Miller J D, E E Knapp, C H Key, C N Skinner, C J Isbell, R M Creasy and J W Sherlock. 2009. Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. *Remote Sensing of Environmen*t, 113:645–656.

Miller J D and A E Thode. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). *Remote Sensing of Environment*, 109:66–80.

Mitchell M and F Yuan. 2010. Assessing Forest Fire and Vegetation Recovery in the Black Hills, South Dakota. *Giscience & Remote Sensing*, 47:276–299.

Myneni R B, S Hoffman, Y Knyazikhin, J L Privette, J Glassy, Y Tian, Y Wang, X Song, Y Zhang, G R Smith, A Lotsch, M Friedl, J T Morisette, P Votava, R R Nemani and S W Running. 2002. Global products of vegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment*, 83:214–231.

Myneni R B and D L Williams. 1994. On the Relationship between Fapar and NDVI. *Remote Sensing of Environment*, 49:200–211.

Pocewicz A, L A Vierling, L B Lentile and R Smith. 2007. View angle effects on relationships between MISR vegetation indices and leaf area index in a recently burned ponderosa pine forest. *Remote Sensing of Environment,* 107:322–333.

Roy D P, P E Lewis and C O Justice. 2002. Burned area mapping using multi-temporal moderate spatial resolution data - a bi-directional reflectance model-based expectation approach. *Remote Sensing of Environment,* 83:263–286.

Roy D R, L Boschetti and S N Trigg. 2006. Remote sensing of fire severity: Assesing the performance of the normalized Burn ratio. *Ieee Geoscience and Remote Sensing Letters,* 3:112–116.

Sakamoto T, N Van Nguyen, A Kotera, H Ohno, N Ishitsuka and M Yokozawa. 2007. Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. *Remote Sensing of Environment,* 109:295–313.

Salvador R, J Valeriano, X Pons and R Diaz-Delgado. 2000. A semi-automatic methodology to detect fire scars in shrubs and evergreen forests with Landsat MSS time series. *International Journal of Remote Sensing*, 21:655–671.

Soverel N O, D D B Perrakis and N C Coops. 2010. Estimating burn severity from Landsat dNBR and RdNBR indices across western Canada. *Remote Sensing of Environment*, 114:1896–1909.

Tucker C J. 1979. Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. *Remote Sensing of Environment*, 8:127–150.

Xiao X, S Boles, S Frolking, W Salas, B Moore, C Li, L He and R Zhao. 2002a. Observation of flooding and rice transplanting of paddy rice fields at the site to landscape scales in China using VEGETATION sensor data. *International Journal of Remote Sensing*, 23:3009–3022.

Xiao X, S Boles, J Liu, D Zhuang and M Liu. 2002b. Characterization of forest types in Northeastern China, using multi-temporal SPOT-4 VEGETATION sensor data. *Remote Sensing of Environment*, 82:335–348.

Xiao X M, S Boles, J Y Liu, D F Zhuang, S Frolking, C S Li, W Salas and B Moore. 2005a. Mapping paddy rice agriculture in southern China using multi-temporal MODIS images. *Remote Sensing of Environment,* 95:480–492.

Xiao X M, B Braswell, Q Y Zhang, S Boles, S Frolking and B Moore. 2003. Sensitivity of vegetation indices to atmospheric aerosols: continental-scale observations in Northern Asia. *Remote Sensing of Environment*, 84:385–392.

Xiao X M, D Hollinger, J Aber, M Goltz, E A Davidson, Q Y Zhang and B Moore. 2004. Satellite-based modeling of gross primary production in an evergreen needleleaf forest. *Remote Sensing of Environment*, 89:519–534.

Xiao X M, Q Y Zhang, D Hollinger, J Aber and B Moore. 2005b. Modeling gross primary production of an evergreen needleleaf forest using MODIS and climate data. *Ecological Applications*, 15:954–969.

美国南达科他州Black Hills国家森林公园2000年森林火灾后植被恢复过程研究

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摘要：森林火灾在景观上往往造成不同程度的森林冠层损失，而冠层影响光合作用和蒸散，因此刻画灾后森林冠层恢复的轨迹对于了解生态系统过程具有重要意义。森林冠层的损失和恢复通常采用叶面积指数(LAI)或其它能够反映冠层光合能力的植被指数进行表征。本研究中，我们采用Terra卫星搭载的中分辨率成像光谱仪（MODIS）的长时间序列影像（2000–2009年）来重建火灾后森林冠层恢复的过程。以美国南达科他州布莱克山国家森林公园（The Black Hills National Forest, South Dakota）为例，该地区在2000年8月24日经历了一次大的自然火灾，烧毁了近33 785 ha森林，其中大部分是美国黄松林。基于LAI的研究表明，植被冠层光合能力在3年内（2001−2003年）基本恢复，这主要来自于林下未烧毁草地在灾后的快速生长；火烧迹地的NDVI和EVI在这3年内也呈现恢复的态势。可见，LAI、NDVI和EVI在火灾几年之后便难以有效地识别火烧迹地。然而，陆地表面水分指数(基于近红外和短波红外波段的遥感标准化指数，简称LSWI)，能够有效地识别和追踪火烧迹地至今的整个过程(2000−2009年)。这一研究结果也使得采用其它具有近红外和短波红外波段的传感器研究森林火灾迹地恢复和干扰过程成为可能，其中包括Landsat 5 TM影像（可追溯至1984年）。更长时间序列的数据对于研究森林火灾灾后生态系统干扰和恢复过程、森林演替模拟以及碳循环具有重要的支撑作用，LSWI指标证明能够有效地刻画这一过程。

关键词：针叶林；MODIS；Landsat；NDVI；EVI；LSWI；森林火灾；冠层