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Mapping burned areas using dense time-series of Landsat data

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ABSTRACT

Complete and accurate burned area data are needed to document patterns of fires, to quantify relationships between the patterns and drivers of fire occurrence, and to assess the impacts of fires on human and natural systems. Unfortunately, in many areas existing fire occurrence datasets are known to be incomplete. Consequently, the need to systematically collect burned area information has been recognized by the United Nations Framework Convention on Climate Change and the Intergovernmental Panel on Climate Change, which have both called for the production of essential climate variables (ECVs), including information about burned area. In this paper, we present an algorithm that identifies burned areas in dense time-series of Landsat data to produce the Landsat Burned Area Essential Climate Variable (BAECV) products. The algorithm uses gradient boosted regression models to generate burn probability surfaces using band values and spectral indices from individual Landsat scenes, lagged reference conditions, and change metrics between the scene and reference predictors. Burn classifications are generated from the burn probability surfaces using pixel-level thresholding in combination with a region growing process. The algorithm can be applied anywhere Landsat and training data are available. For this study, BAECV products were generated for the conterminous United States from 1984 through 2015. These products consist of pixel-level burn probabilities for each Landsat scene, in addition to, annual composites including: the maximum burn probability and a burn classification. We compared the BAECV burn classification products to the existing Global Fire Emissions Database (GFED; 1997–2015) and Monitoring Trends in Burn Severity (MTBS; 1984–2013) data. We found that the BAECV products mapped 36% more burned area than the GFED and 116% more burned area than MTBS. Differences between the BAECV products and the GFED were especially high in the West and East where the BAECV products mapped 32% and 88% more burned area, respectively. However, the BAECV products found less burned area than the GFED in regions with frequent agricultural fires. Compared to the MTBS data, the BAECV products identified 31% more burned area in the West, 312% more in the Great Plains, and 233% more in the East. Most pixels in the MTBS data were detected by the BAECV, regardless of burn severity. The BAECV products document patterns of fire similar to those in the GFED but also showed patterns of fire that are not well characterized by the existing MTBS data. We anticipate the BAECV products will be useful to studies that seek to understand past patterns of fire occurrence, the drivers that created them, and the impacts fires have on natural and human systems.

1. Introduction

Accurate and complete data on fire locations and burned areas (prescribed and wild) are needed for a variety of applications including quantifying trends and patterns of fire occurrence (Abatzoglou and Williams, 2016; Dennison et al., 2014; Giglio et al., 2013; Westerling et al., 2006); characterizing drivers of past fire occurrence and projecting future potential patterns of fires (Bachelet et al., 2003; Hawbaker et al., 2013; Krawchuk et al., 2009; Parisien and Moritz, 2009; Riley et al., 2013); and assessing the impacts of fires on a range of natural and social systems (French et al., 2014; Shakesby and Doerr, 2006; van der Werf et al., 2010; Williams et al., 2016). Many of these applications require

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consistent fire data collected over long time periods to determine if changes in fire occurrence and fire impacts are related to shifts in climate, land-use/land-cover change, policy and management, and other drivers.

Recognizing the importance of fires, especially for understanding climate change and its impacts, the Global Climate Observing System (GCOS) included fire disturbance, specifically burned area, in their list of 13 terrestrial essential climate variables (ECVs) that are technically and economically feasible for systematic observation (Food and Agriculture Organization of the United Nations, 2008). These are being developed in response to calls from the United Nations Framework Convention on Climate Change, Intergovernmental Panel on Climate Change (Global Climate Observing System, 2004), as well as calls from the European Space Agency's Climate Change Initiative, the National Research Council, and the Landsat Science Team to systematically observe atmosphere, ocean, and land characteristics (Hollmann et al., 2013; National Research Council, 2001; Roy et al., 2014; Wulder et al., 2012).

Remote sensing is critical to the development of ECVs because satellite images and the products derived from them can provide a basis for long-term systematic data collection to monitor changes in the land surface that either influence or are influenced by climate. Monitoring active fires and burned areas, in particular, is feasible with remote sensing because of the thermal and spectral changes induced by fires. Coarse-resolution sensors equipped with spectral and thermal bands, such as the Advanced Very High Resolution Radiometer (AVHRR), can effectively map subpixel heat sources (Dozier, 1981; Matson and Dozier, 1981) and applications for spatially-extensive active fire detection with AVHRR data were realized (Flannigan and Vonder Haar, 1986; Malingreau et al., 1985; Matson et al., 1987) and extended to other sensors such as the Geostationary Operational Environmental Satellite Visible Infrared Spin Scan Radiometer Atmospheric Sounder (Prins and Menzel, 1992; Prins and Menzel, 1994), the Defense Meteorological Satellite Program Operational Linescan System (Elvidge et al., 1996), the Moderate Resolution Imaging Spectroradiometer (MODIS) (Giglio et al., 2003), the Visible Infrared Imaging Radiometer Suite (VIIRS) (Giglio et al., 2000), and even moderate-resolution sensors like the Landsat Thermal Infrared Sensor (Schroeder et al., 2015). In addition to identifying actively burning fires, spectral changes visible in the temporally rich data provided by coarse-resolution sensors allowed for burned area detection, although the approaches varied depending on the spectral bands specific to individual sensors (Eva and Lambin, 1998; Kasischke and French, 1995; Roy et al., 2005). Other approaches combined spectral change analysis with hot spot detection, to help distinguish burned areas from other types of change (Alonso-Canas and Chuvieco, 2015; Fraser et al., 2000; Giglio et al., 2009; Li et al., 1997). Many of the existing coarse resolution global active fire and burned area algorithms and products provide the types of data identified in the GCOS ECV definitions (Alonso-Canas and Chuvieco, 2015; Global Climate Observing System, 2004) and have been combined to produce operational products monitoring burned areas and emissions such as the Global Fire Emissions Database (GFED; Giglio et al., 2013; Randerson et al., 2012; van der Werf et al., 2010).

In spite of the impressive efforts made to monitor fire activity and burned area with coarse-resolution sensors, many shortcomings remain. Fires obscured by clouds, fires with short-lived thermal signatures, and small fires may not be identified (Hawbaker et al., 2008; Morisette et al., 2005; Schroeder et al., 2008). Detection errors remain high for many global coarse-resolution products; Padilla et al. (2015) found that commission errors for burned area ranged between 42% and 94%, and omission errors for burned area ranged between 68% and 93%, depending on the sensor used. Additionally, the short time series provided by coarse-resolution sensors (other than AVHRR) are inadequate when trying to quantify relationships between patterns of climate and fire occurrence because they span a limited range of climate variability, potentially over emphasizing the importance of extreme years (Hawbaker et al., 2013; Hawbaker and Zhu, 2012; Westerling et al., 2011).

Moderate-resolution sensors such as the Landsat Multispectral Scanner System (MSS) and Thematic Mapper (TM) have also been used to remotely sense burned areas. Initial efforts used Landsat pre- and post-fire images to map pre-fire vegetation, burned area extent, and severity (Chuvieco and Congalton, 1988; Hall et al., 1980; Jakubauskas et al., 1990; Koutsias and Karteris, 1998). Subsequent efforts focused on identifying burned areas within single scenes (Koutsias and Karteris, 2000; Kushla and Ripple, 1998), extracting within-fire heterogeneity, severity, mortality, and carbon loss (Michalek et al., 2000; Miller and Yool, 2002; Patterson and Yool, 1998; Rogan and Yool, 2001). The moderate resolution of Landsat sensors also allowed for the development of burned area detection algorithms using spatial contagion metrics and region-growing approaches to incorporate the spatial patterns of spectral reflectance among neighboring pixels, in addition to the pixel-level spectral data to identify burned areas; helping to reduce omission errors (Bastarrika et al., 2011; Chuvieco et al., 2002; Goodwin and Collett, 2014; Koutsias, 2003; Stroppiana et al., 2012). The results of these approaches provide data products with the spatial and temporal resolution relevant to fire ecology and management and have laid the foundation for operational programs monitoring patterns of severity and area burned by large fires in the United States (Eidenshink et al., 2007).

Since the opening of the Landsat archive (Wulder et al., 2012), change detection approaches for moderate-resolution data have evolved to incorporate the temporal depth of the data available in the Landsat archive by subdividing annual time series of spectral responses into piecewise segments, and then using the changes between segments and characteristics of segments to delineate disturbances, such as the Vegetation Change Tracker (VCT; Huang et al., 2010) and the Landsat-based detection of Trends in Disturbance and Recovery (LandTrendr; Kennedy et al., 2010) algorithms. More recent approaches have analyzed the time series as a whole (Hansen et al., 2014) or decomposed dense time series data to distinguish seasonality from long-term trends for change detection using both MODIS (Verbesselt et al., 2010) and Landsat data (Brooks et al., 2014; Zhu and Woodcock, 2014b). These methods detect change, but require additional attribution to characterize the specific type of change (Kennedy et al., 2015; Liang et al., 2014; Zhao et al., 2015). The methods cited above have largely focused on detection of stand-replacing forest disturbances, or in the case of fires, those that result in long-lasting changes in spectral reflectance visible in annual Landsat time series stacks (e.g. stand-replacing forest fires, Huang et al., 2010; Kennedy et al., 2010).

Fire-specific change detection algorithms making use of the full temporal depth of the Landsat archive are also emerging. For example, Goodwin and Collett (2014) combined a change-detection algorithm with a region-growing algorithm to identify contiguous areas of change and then classified which areas of change were caused by fires in Queensland Australia, using all available Landsat data from 1986 through 2013. Similarly, Boschetti et al. (2015) used weekly composites of Landsat 7 data from 2002 to identify areas with spectral change and then combined them with MODIS active fire data to separate burned areas in predominantly forested regions in the western U.S. These two studies demonstrated that burned areas can be mapped with automated approaches over large spatial extents using moderate-resolution data. However, the need for consistently collected burned area data covering large spatial (national, continental, and global scales) and temporal (30 or more years) extents has not been met.

In this paper, we present an algorithm to identify burned areas in Landsat satellite images, compare its outputs with existing burned area dataset, and discuss how those outputs or products provide novel information about patterns of fire occurrence in the conterminous United States (CONUS). The first objective of this study was to develop a new algorithm to identify burned areas in satellite imagery; henceforth referred to as the Landsat Burned Area Essential Climate Variable (BAECV) algorithm. The second objective of this study was to produce a publicly available Landsat-based burned area product from 1984