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An automated approach for reconstructing recent forest disturbance history using dense Landsat time series stacks

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ABSTRACT

A highly automated algorithm called vegetation change tracker (VCT) has been developed for reconstructing recent forest disturbance history using Landsat time series stacks (LTSS). This algorithm is based on the spectral–temporal properties of land cover and forest change processes, and requires little or no fine tuning for most forests with closed or near close canopy cover. It was found very efficient, taking 2–3 h on average to analyze an LTSS consisting of 12 or more Landsat images using an average desktop PC. This LTSS-VCT approach has been used to examine disturbance patterns with a biennial temporal interval from 1984 to 2006 for many locations across the conterminous U.S. Accuracy assessment over 6 validation sites revealed that overall accuracies of around 80% were achieved for disturbances mapped at individual year level. Average user's and producer's accuracies of the disturbance classes were around 70% and 60% in 5 of the 6 sites, respectively, suggesting that although forest disturbances were typically rare as compared with no-change classes, on average the VCT detected more than half of those disturbances with relatively low levels of false alarms. Field assessment revealed that VCT was able to detect most stand clearing disturbance events, including harvest, fire, and urban development, while some non-stand clearing events such as thinning and selective logging were also mapped in western U.S. The applicability of the LTSS-VCT approach depends on the availability of a temporally adequate supply of Landsat imagery. To ensure that forest disturbance records can be developed continuously in the future, it is necessary to plan and develop observational capabilities today that will allow continuous acquisition of frequent Landsat or Landsat-like observations.

1. Introduction

Forest disturbance and post-disturbance recovery are key processes in the development of forest ecosystems. The landscape pattern of forest age and structure, for example, is shaped in part by the history of disturbance and recovery processes (Peterken, 2001). Understanding these processes over space and time is also crucial to studies of terrestrial and atmospheric carbon, as they are major processes modulating carbon flux between the biosphere and the atmosphere (Hirsch et al., 2004; Law et al., 2004). While North American forests, especially those in the United States, have been proposed as a net carbon sink (Pacala et al., 2001; Liu et al., 2004), estimates of the magnitude of the sink have substantial uncertainties. Reducing such uncertainties requires improved understanding of land use history, especially forest disturbance history (Schimel & Braswell, 1997; Thornton et al., 2002; Houghton, 2003).

The collection of Landsat images acquired through current and previous Landsat missions (Goward et al., 2006) provide a unique data source for reconstructing forest disturbance history for many areas of the globe. With the earliest Landsat images acquired in 1972, this collection makes it possible to document forest changes that have occurred since then, while the fine spatial resolutions of Landsat images provide the spatial details necessary for characterizing many of the changes arising from both natural and anthropogenic disturbances (Townshend & Justice, 1988). Over the past 30+ years, Landsat images have been widely used in land cover and forest change analysis (Goward & Williams, 1997). While the Landsat Record has relatively dense acquisitions in many places of the world, especially in the United States (Goward et al., 2006), largely due to practical reasons, most previous studies characterized land cover change at relatively sparse temporal intervals (Singh, 1989; Lu et al., 2004). For many of the Earth's forests, reestablishment of a new forest stand following a previous disturbance

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can occur in just a few years (e.g. Huang et al., 2009a, Fig. 1). As a result, some of those disturbances can become spectrally undetectable using observations acquired many years apart (Lunetta et al., 2004; Masek et al., 2008).

Within the framework of the North American Carbon Program (NACP), the *North American Forest Dynamics* (NAFD) project is evaluating forest disturbance and regrowth history for the conterminous U.S. by combining Landsat observations and field measurements (Goward et al., 2008). To minimize potential omission errors that may arise from using temporally sparse observations, dense Landsat time series stacks (LTSS) are used in the NAFD study. About 30 LTSS have been assembled during the first phase of NAFD for locations selected across the U.S. (Goward et al., 2008; Huang et al., 2009a).

Two major steps are involved in mapping forest disturbance using LTSS: development of imagery-ready-to-use (IRU) quality LTSS images, and forest disturbance detection. IRU quality LTSS images are defined as having minimum cloud and shadow contaminations and minimum instrument or processing related errors. Such images should also have been corrected geometrically and radiometrically such that they have the highest level of achievable geolocation accuracy and radiometric consistency. Streamlined procedures for producing such IRU quality LTSS images have been developed in a previous study (Huang et al., 2009a).

Over the last few decades of remote sensing history, numerous digital change detection techniques have been developed for use with Landsat and other satellite images (see Singh, 1989; Coppin et al., 2004; Lu et al., 2004 for comprehensive reviews). These existing techniques, however, are mostly bi-temporal in nature, i.e., they can be used to analyze only one collocated image pair at a time. While each LTSS could be divided into a sequence of image pairs and a bi-temporal technique could be used to analyze each image pair, such an approach would be extremely inefficient. Furthermore, bi-temporal techniques cannot take advantage of the rich temporal information contained in LTSS. As will be demonstrated in this study, temporal information is particularly useful for characterizing land cover and change processes. While algorithms capable of analyzing three or more images at a time have also been developed (e.g. Coppin & Bauer, 1996; Cohen et al., 2002; Lunetta et al., 2004), most of them suffer shortcomings similar to those of bi-temporal techniques for analyzing dense satellite observations.

To improve the efficiency of land cover change analysis using LTSS, Kennedy et al. (2007) developed a trajectory-based change detection algorithm. This algorithm takes all images in an LTSS into consideration, and uses idealized temporal trajectory of spectral values to detect and characterize changes. Here we develop a different change detection algorithm called vegetation change tracker (VCT) for mapping forest change using LTSS. This algorithm is similar to the trajectory-based change detection algorithm of Kennedy et al. (2007) in that changes are detected through simultaneous analysis of all images in an LTSS. But the mechanisms based on which changes are detected are different. The VCT is based on the spectral–temporal characteristics of land cover and forest change processes. It consists of two major steps. In the first step, each image in an LTSS is analyzed to create masks and to calculate spectral indices that are measures of forest likelihood. Once this step is complete for all images in that LTSS, the derived indices and masks are analyzed in a time series analysis step to map disturbances. A brief description of the VCT algorithm has been provided before (Huang et al., 2009b). Some key components of the first step have also been detailed previously (Huang et al., 2008; in press). The purpose of this paper is to provide a detailed, coherent description of all components of the VCT and to assess the disturbance products derived using this algorithm.

The VCT has been used to produce disturbance products for the sites where LTSS were assembled during the first phase of the NAFD project (Goward et al., 2008; Huang et al., 2009a). Biennial disturbance products have also been produced using this approach for Mississippi (Li et al., in press) and Alabama (Li et al., 2009) as part of an effort to update a vegetation database developed through the LANDFIRE project (Rollins, 2009). Those disturbance products have been evaluated using multiple approaches, including ground-based assessment, visual assessment, designed-based accuracy assessment and assessment using field survey data collected through the Forest Inventory and Analysis (FIA) program of the USDA Forest Service. Mainly for page limit considerations, only a summary of the results derived from field based assessment, visual evaluation, and design-based accuracy assessment is provided in this paper. Full details on the design-based accuracy assessment and assessment using FIA field survey data will be provided in a follow-up paper (Thomas, in preparation).

Because the VCT algorithm is designed for use with LTSS, a brief review of the LTSS concept and the procedures for developing LTSS is deemed necessary here, although details on those procedures have been provided previously (Huang et al., 2009a). Following this review Section 3 provides a detailed description of the VCT algorithm. Assessments of VCT disturbance products are provided in Section 4, followed by a summary and discussions on the properties of the VCT algorithm and its requirement on satellite observations.

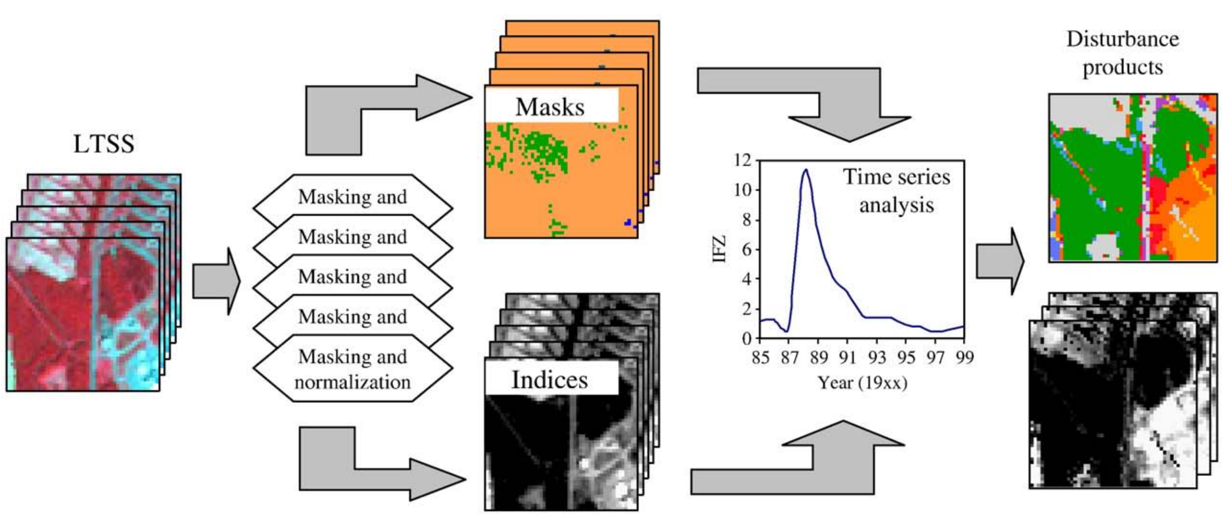

Fig. 1. Overall data flow and processes of the VCT algorithm.