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Time-series analysis of multi-resolution optical imagery for quantifying forest cover loss in Sumatra and Kalimantan, Indonesia

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ABSTRACT

Monitoring loss of humid tropical forests via remotely sensed imagery is critical for a number of environmental monitoring objectives, including carbon accounting, biodiversity, and climate modeling science applications. Landsat imagery, provided free of charge by the U.S. Geological Survey Center for Earth Resources Observation and Science (USGS/EROS), enables consistent and timely forest cover loss updates from regional to biome scales. The Indonesian islands of Sumatra and Kalimantan are a center of significant forest cover change within the humid tropics with implications for carbon dynamics, biodiversity maintenance and local livelihoods. Sumatra and Kalimantan feature poor observational coverage compared to other centers of humid tropical forest change, such as Mato Grosso, Brazil, due to the lack of ongoing acquisitions from nearby ground stations and the persistence of cloud cover obscuring the land surface. At the same time, forest change in Indonesia is transient and does not always result in deforestation, as cleared forests are rapidly replaced by timber plantations and oil palm estates. Epochal composites, where single best observations are selected over a given time interval and used to quantify change, are one option for monitoring forest change in cloudy regions. However, the frequency of forest cover change in Indonesia confounds the ability of image composite pairs to quantify all change. Transient change occurring between composite periods is often missed and the length of time required for creating a cloud-free composite often obscures change occurring within the composite period itself. In this paper, we analyzed all Landsat 7 imagery with <50% cloud cover and data and products from the Moderate Resolution Imaging Spectroradiometer (MODIS) to quantify forest cover loss for Sumatra and Kalimantan from 2000 to 2005. We demonstrated that time-series approaches examining all good land observations are more accurate in mapping forest cover change in Indonesia than change maps based on image composites. Unlike other time-series analyses employing observations with a consistent periodicity, our study area was characterized by highly unequal observation counts and frequencies due to persistent cloud cover, scan line corrector off (SLC-off) gaps, and the absence of a complete archive. Our method accounts for this variation by generating a generic variable space. We evaluated our results against an independent probability sample-based estimate of gross forest cover loss and expert mapped gross forest cover loss at 64 sample sites. The mapped gross forest cover loss for Sumatra and Kalimantan was 2.86% of the land area, or 2.86 Mha from 2000 to 2005, with the highest concentration having occurred in Riau and Kalimantan Tengah provinces.

1. Introduction

Carbon emissions from deforestation and forest degradation make up the second largest source of anthropogenic carbon emissions after the energy sector (Intergovernmental Panel on Climate Change, 2007). The reducing emissions from deforestation and forest degradation in developing countries (REDD) policy framework aims to reward developing nations for slowing deforestation and forest degradation, which is considered a cost effective way to mitigate anthropogenic greenhouse gas emissions (Gullison et al., 2007). In the context of REDD, Indonesia is of high significance, having the third largest extent of the world's remaining humid tropical forests and a high rate of deforestation (Achard et al., 2002; FAO, 2005; Mayaux et al., 2005; Hansen et al., 2008a, 2009). Besides its importance for climate change mitigation, Indonesia's forests play a critical role for the livelihood of local communities and for the national economy (Forest Watch Indonesia/Global Forest Watch, 2002). Indonesia's forests also harbor high biological diversity and provide diverse ecosystem goods and ecosystem services (Forest Watch Indonesia/Global Forest Watch, 2002).

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Expansion of agriculture and plantations and large fire events have greatly reduced the extent of lowland forest on Sumatra and Kalimantan (Indonesian Borneo) (Mayaux et al., 2005; Curran et al., 2004; Fuller et al., 2004; Gaveau et al., 2009a; Gaveau et al., 2009b; Hansen et al., 2009). However, timely, spatially explicit information on deforestation within Indonesia is lacking, hampering effective forest management and governance (Fuller, 2006; Hansen et al., 2009). Remote sensing approaches using moderate spatial resolution data (defined in Global Observation of Forest and Land Cover Dynamics (2009) as 10–60 m spatial resolution) can map forest cover change accurately and consistently across large regions at lower cost in a timelier manner than approaches using only ground inventory data.

A forest cover change monitoring system that fits the objectives of REDD has not yet been developed for Indonesia. According to the Intergovernmental Panel on Climate Change guidelines (Intergovernmental Panel on Climate Change, 2003, 2006) two inputs are needed to calculate greenhouse gas emissions: activity data in forest areas and emissions factors. Activity data refer to the location and spatial extent of forest cover loss or degradation. Emissions factors refer to emissions of greenhouse gases per unit area of forest cover loss of a specific type (e.g. tons of carbon per hectare of cover loss of a specific forest type). According to Baker et al. (2010) the eventual goal of forest carbon assessment under REDD is to conduct continuous annual national assessments that form a global REDD monitoring system.

Among nations with tropical forests, only Brazil and India have operational remote sensing-based forest monitoring systems in place (Forest Survey of India, 2004; INPE, 2010). The Brazilian National Institute for Space Research (INPE) provides annual wall-to-wall deforestation maps of the Brazilian Legal Amazon (INPE, 2010). Most of the deforestation in the Brazilian Legal Amazon takes place well south of the equator where a seasonally cloud-free window allows the acquisition of cloud-free Landsat imagery by a local ground station (INPE, 2010). Compared with Brazil, optical remote sensing-based deforestation monitoring in Indonesia is more challenging due to persistent cloud cover (Hansen et al., 2009). Current mapping of forest cover and change in Indonesia is carried out by the Ministry of Forestry of Indonesia. Landsat images with low cloud cover have been photo-interpreted to map forest cover and change between 1985 and 1998, using best available single-date image inputs per epoch. The most recent country-wide map of deforestation was published in 1998, but data gaps due to clouds reduce the reliability of deforestation estimates (Government of Indonesia/World Bank 2000, Ministry of Forestry Indonesia, 2003a). Chances for obtaining cloud-free optical imagery are low as Indonesia's forests are located in an aseasonal, persistently cloudy zone near the equator (Roy et al., 2006; Trigg et al., 2006; Ju and Roy, 2008; Hansen et al., 2009). Public access to Landsat data for Indonesia is confined to the imagery in the U.S. Geological Survey Center for Earth Resources Observation and Science (USGS/EROS) archive. The USGS/EROS data holding includes few Landsat 5 images and multiple Landsat 7 images for each year and location. The Landsat 7 images have been acquired under the long-term acquisition plan (Arvidson et al., 2006), which does not cover all of the 23 annual overpasses of the sensor for Indonesia.

Assembling cloud-free observations from multiple images into composites has been suggested to overcome cloud contamination in forest monitoring applications (Olthof et al., 2004; Hansen et al., 2008b; Huang et al., 2010). Another reason to create composites is to fill scan gaps in Landsat 7 images. Images were acquired in Scan Line Corrector-off mode (SLC-off) after May 2003 due to the permanent failure of the scan line corrector. SLC-off images are characterized by track-parallel data gaps that render 22% of each image unusable (Storey et al., 2005; Maxwell et al., 2007). Landsat 7 composites have been provided as part of the Global Land Survey 2005 dataset for areas where Landsat 5 images were not available. The composites combined up to three SLC-off images with low cloud cover per path/row that were acquired around 2005 (Gutman et al., 2008). Yet, Lindquist's et al. (2008) study in the Congo Basin showed that, for persistently cloudy regions, a large number of images may be needed to reduce data gaps to a level that allows meaningful analysis of humid tropical forest cover change. An automated compositing approach that identifies and assembles good observations of the land surface from a large number of Landsat images into cloud-free composites has been realized for the Congo basin (Hansen et al., 2008b). In their implementation, Landsat data acquired between 1984 and 2003 were assembled into two epochal 1990 and 2000 composites. The term "epochal" refers to a time period. For example the 2000 epochal composite consisted of images acquired between 1996 and 2003. Forest cover change between the 1990 and 2000 epochal composites was automatically mapped using decision tree algorithms (Hansen et al., 2008b).

Most change detection methods using moderate spatial resolution data estimate change between images acquired on two anniversary dates (Coppin and Bauer, 1996; Mas, 1999; Lu et al., 2004; Coppin et al., 2004). Among studies using multiple years of imagery for change detection, many have applied a sequence of two-date (bi-temporal) comparisons rather than analyzing the entire record at once (Roberts et al., 1998; Salvador et al., 2000; Almeida and Shimabukuro, 2002; Cohen et al., 2002; Haertel et al., 2004; Lunetta et al., 2004). Previous studies using multiple years of cloud-free Landsat data in less cloudy parts of the world showed that regrowth of trees rapidly masked the spectral signature of forest clear cuts (Lunetta et al., 2004; Healey et al., 2005; Wulder et al., 2005; Kennedy et al., 2007). If forest clear cutting followed by regrowth had occurred a few years prior to the acquisition of a second image, the regrowth areas were indistinguishable from mature forest in the subtropical South-East of the USA (Lunetta et al., 2004). Timber and oil palm plantations are an increasingly important land use in the tropics and have been widely promoted in Indonesia (Forest Watch Indonesia/Global Forest Watch, 2002). Large scale conversion of natural forest to plantations and harvesting cycles of such plantations, followed by regrowth, may be difficult to map using gap-free composites, as multiple years of imagery may have to be assembled to obtain sufficient cloud free observations (Lindquist et al., 2008). The observation frequency of gap-free composites may be too low to capture the rapidly fading signature of clear cutting events.

In order to overcome this limitation of infrequent bi-temporal comparisons, simultaneous analysis of entire image stacks is required. An overview of such approaches for both coarse and high spatial resolution imagery can be found in Kennedy et al. (2007). Two recent examples include Kennedy et al. (2007), Huang et al. (2009, 2010), who mapped forest disturbance in the temperate zone of North America using dense time-series stacks of near cloud-free Landsat imagery. Kennedy et al. (2007) used curve fitting techniques to search for idealized temporal signatures of disturbance, while Huang et al. (2010) used thresholds of consecutive high and low forest probability observations. Advantages of their simultaneous analysis of time-series image stacks include: improved signal to noise ratio, identification of transient change, and identification of different change trajectories. Unlike the temperate zone of North America, where dense stacks of annual cloud-free Landsat images are feasible because of limited cloud cover, and because every image is acquired, Sumatra and Kalimantan are characterized by more persistent cloud cover and fewer images are acquired (Ju and Roy, 2008). The resulting data limitations lead to gaps for any given year and highly variable observation counts over time. This paper presents a new approach that accounts for these conditions, employing a per pixel time-series analysis that