Applied Geography 41 (2013) 168–178

Contents lists available at SciVerse ScienceDirect

Applied Geography

journal homepage: www.elsevier.com/locate/apgeog

The tropical forest in south east Asia: Monitoring and scenario modeling using synthetic aperture radar data

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Keywords:
PALSAR
Land cover change
Deforestation
Scenario analysis
LULUCF
Weights of evidence
Sumatra
REDD+

A B S T R A C T

Tropical forests play a major role in storing large carbon stocks and regulating energy, and water fluxes, but such forest cover is decreasing rapidly in spite of the policy attention on reducing deforestation. High-resolution spatiotemporal maps are unavailable for the forests in majority of the tropical regions in Asia because of the persistent cloud cover and haze cover. Recent advances in radar remote sensing have provided weather-independent data of earth surface, thus offering an opportunity to monitor tropical forest change processes with relatively high spatiotemporal resolutions. In this research, we aim to examine the tropical deforestation process and develop a spatial model to simulate future forest patterns under various scenarios. Riau Province from central Sumatra of Indonesia is selected as the study area; this province has received much attention worldwide because the highest CO_2 emission resulting from tropical deforestation has been recorded. Annual time series PALSAR data from 2007 to 2010 were analyzed for forest mapping and detecting land cover changes. A spatial model was calibrated using the Bayesian method. Modeling parameters were customized for the local subregions that allocate deforestation on the basis of their empirical relationships to physical and socioeconomic drivers. The model generated landscape spatial patterns mirrored the possible locations and extent of deforested areas by 2030 and provided time-series crucial information on forest landscape under various scenarios for future landscape management projects. The results suggested that the current deforestation process is in a critical stage where some subregions may face unprecedented stress on primary forest costing rivers and forest ecosystems by the end of 2020. The perspective views of Riau Province generated by the model highlighted the need for forest/environmental planning controls for the conservation of environmentally sensitive areas.

Introduction

Tropical forests play a major role in storing large amounts of carbon stocks and in regulating energy and water fluxes. These forests are being diminished rapidly despite the attention to policies for reducing deforestation (FAO, 2010; Lambin & Meyfroidt, 2011). As deforestation proceeds, the living planet becomes more vulnerable because of adverse impacts on the environment and overall climate system related to the release of carbon, reduced biodiversity, disturbed water regulation, and impacts on weather patterns. Recently, tropical deforestation has been recognized as the second largest source of greenhouse gas emissions and this trend is expected to continue for the next several years (Harris et al., 2012; IPCC, 2007; Saatchi et al., 2011). To reduce deforestation and forest degradation and to mitigate forest-related GHG emissions, the Reducing Emissions from Deforestation and Forest Degradation (REDD+), an international agreement under the United Nations Framework Convention on Climate Change, is being advanced in several developing countries, including Indonesia (Angelsen, 2008; NORAD, 2011). Successful implementation of this agreement requires regularly updated spatial information on changes in natural forest cover and the development of reference scenarios for projecting deforestation and associated emissions. Therefore, continuous monitoring of tropical deforestation and an understanding of the causal effects will be essential in the future. Examining these effects and envisioning future circumstances of deforestation necessitate logically developed spatial models.

Spatially explicit data on changes in forest cover require investigating such changes, identifying the drivers of the changes, and calibrating deforestation models. In the past, acquisition of spatial

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0143-6228/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apgeog.2013.04.009

data on forest cover was field intensive, making it expensive and difficult to acquire accurate, timely, and consistent data over a large area. However, advances in remote sensing techniques have reduced this limitation and offer vast opportunities to characterize forest cover at reasonable spatiotemporal scales. Tropical regions in Asia mostly covered by clouds, which creates a major barrier to generating spatiotemporally consistent land use/cover maps using optical remote sensing techniques. However, recent progress in improving spatial resolution of synthetic aperture radar (SAR) has significantly reduced this barrier (Hoekman, Vissers, & Wielaard, 2010; Thapa et al., 2013). SAR techniques are particularly useful for monitoring deforestation and forest degradation due to their ability to monitor the earth surface in all weather and solar illumination conditions. Owing to longer wavelengths and shorter frequencies, L-band SAR data enables mapping forest areas because the microwave energy transmitted by the sensor penetrates forest canopies and returns the backscatter representing forest structures. Greater penetration of vegetation and weaker reflection from rough surfaces enable the acquisition of important information for identifying and separating types of forests as well as other land-use types (Shimada & Ohtaki, 2010; Walker, Stickler, Kellndorfer, Kirsch, & Nepstad, 2010). However, the amount of backscattered energy depends on the size and orientation of canopy structural elements (i.e., leaves, branches, and stems), the moisture content of vegetation, and underlying soil conditions.

Remote sensing techniques have made it possible to map the history of forest land cover and analyze dynamics of forest change regardless of geographic size, but spatial modeling of deforestation is necessary for understanding the complex process of forest cover change; because the spatial modeling provides important abstract information about the future, and enables testing the implications of different forest policies. Various spatial models have been developed from different perspectives to improve representation of dynamic process of deforestation in the cellular automata (CA) modeling environment by differentiating the probabilistic functions. For instance, logistic regression (Chowdhury, 2006; Echeverria, Coomes, Hall, & Newton, 2008), genetic algorithm (Soares-Filho, Rodrigues, & Follador, 2013; Venema, Calamai, & Fieguth, 2005), weight of evidence (Maeda et al., 2011; Soares-Filho et al., 2010), and artificial neural network (Khoi & Murayama, 2011; Mas, Puig, Palacio, & Sosa-López, 2004) methods have been discussed in the contemporary literature. The spatial models described in these works simulate changes in forest cover based on previous and surrounding states and on biophysical and socioeconomic driving factors. The focus of most of these models is to investigate deforestation, understand the driving factors, simulate the dynamic processes of forest conversion, and expedite understandings of the associated environmental impacts so that measures to control deforestation can be formulated.

Understanding the dynamic process of deforestation in a region depends greatly on time–space relationships. This dynamic process consists of a complex interaction between several components, such as physiography, socioeconomic factors, and forest management policies. Such complex interaction between changes in forest cover and the various components, often called drivers, can be addressed smoothly in CA with the weights of evidence (WofE) modeling framework. CA is a simple grid-based system in which forest cover changes can be represented in grid cells. CA-based models have been demonstrated to be effective platforms for simulating dynamic spatial interactions among biophysical and socioeconomic factors associated with land-use and land-cover changes. The WofE method is based on Bayes' rule of probability with an assumption of conditional independence (Thapa, 2012). It has been used widely for different applications, originally for modeling geologic phenomena (Bonham-Carter, 1994) and later for modeling changes in land use and land cover (Maeda et al., 2011; Soares-Filho, Cerqueira, & Pennachin, 2002; Thapa, Shimada, Motohka, Watanabe, & Shiraishi, 2011). The WofE method is robust in its handling of categorical and continuous spatial data, such as land cover maps and distance maps, respectively. This method concerns the favorability of detecting a certain event, for example, a land change event from forest to non-forest, in relation to potential evidences that may be topographic or socioeconomic types of drivers. The model is in log-linear form, which allows the weights from the evidential themes be added while developing a probability map that can be easily implemented in the CA modeling environment.

Riau Province in western Indonesia has recently received worldwide attention owing to forest-related carbon emissions. The province lost 583 thousand hectares (ha) of natural forest in dry and peat-swamp areas and led in CO_2 emissions (812 megatons) the other provinces in the country during 2000–2005 (MoFor, 2008). Alarming deforestation has threatened forest carbon stocks, peat drainage, and biodiversity in the province. The goal of this research is to examine the deforestation process and develop a spatial model to simulate spatial patterns of forest cover under "what-if" scenarios to provide a basis for forest management in the province. The CA model was calibrated using the WofE method and four scenarios (business as usual, forest regeneration, forest conservation, and forest concession) were examined. Time-series phased-array L-band synthetic aperture radar (PALSAR) data were analyzed for time-series mapping of the forest cover.

Study area and database

Geography of Riau Province, Indonesia

Riau Province is located in central Sumatra, Indonesia (Fig. 1). It is within the geographic region of 1°7′24″ S to 2°32′36″ N latitude and 100°1′30″ to 103°48′39″ E longitude. The province has varied topography, including peat-swamp areas, basins, hillocks, mountains, rivers, and the coasts (east–south to north). It spans about 9 million ha with varying elevations up to 1200 m. The area has a mostly cloudy and hazy atmosphere throughout the year. The province consists of 12 administrative subregions (districts): Bengkalis, Indragiri Hilir, Indragiri Hulu, Kampar, Dumai, Pekanbaru, Singingi, Pelalawan, Rokan Hilir, Rokan Hulu, Siak, and Meranti. Occupying 15% of the landscape, Indragiri Hilir is the largest subregion, whereas Pekanbaru, headquarters of the province, is the smallest with only 0.7% of the provincial territory. Currently, 5.54 million people live in the province (BPS, 2010). Being a major source of pulp and paper, oilpalm, and petroleum products, the province is of great economic importance for Indonesia. The forest landscape has become the major source of land for industrial plantations in recent years. The province has lost more than 35% of its forest since 1985 and is ranked to the most highly deforested province in Sumatra (Uryu et al., 2010).

Spatial data preparation

Owing to the persistent cloudy and hazy conditions that exist throughout the year in the study area, SAR data are an ultimate choice for monitoring and assessing changes in forest cover. PALSAR, a SAR sensor on the Advanced Land Observing Satellite (ALOS), systematically acquired a large amount of data covering Earth's surface through the five-year period of 2006–2011 (Rosenqvist, Shimada, Ito, & Watanabe, 2007). This L-band sensor, designed with a long operating wavelength (23.6 cm), was appropriate for tropical forest monitoring because of its high sensitivity to forest structure and moisture characteristics (Shimada, 2011). We used PALSAR mosaic data products that were radiometrically