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Detection of interannual variability of the spatial distribution of deforestation in Borneo by analyzing the cloud-free daily MODIS satellite-observed green-red vegetation index

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Abstract We examined the interannual variability of the spatial distribution of deforestation in Borneo by analyzing the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-observed daily green-red vegetation index (GRVI) from 2001 to 2013. In coastal regions of Sarawak (Malaysia) and West and Central Kalimantan (Indonesia), deforestation and vegetation plantation establishment by planting oil palm or acacia were detected each year. In recent years, the area of deforestation and vegetation recovery tended to extend into high-elevation hilly areas. These findings suggest that the ecosystem function of carbon fixation may be continuously declining in large areas of Borneo.

Keywords Borneo, Deforestation, Green-red vegetation index, MODIS, Oil palm

Introduction

To accurately evaluate global changes in the carbon balance under rapid climate changes, it is crucial to assess the spatiotemporal variability of tropical ecosystem structure (biomass) and functioning (photosynthesis). The high biodiversity of tropical ecosystems also provides valuable resources (food, timber, and genetic), as well as cultural and educational ecosystem services (SCBD 2010). However, deforestation and forest degradation have changed the land-surface hydrology (Kumagai et al. 2013) and the carbon stock and flux (Adachi et al. 2011) in tropical ecosystems. In insular Southeast Asia, including Indonesia and Malaysia, large areas of the tropical forest have been deforested and converted into oil palm plantations (GEAS 2011; Koh et al. 2011).

Previous studies have detected the spatial distribution of deforestation by analyzing satellite-observed spectral reflectance data (Langner et al. 2007; Koh et al. 2011; Miettinen et al. 2011; Hansen et al. 2013). Few studies, however, have assessed the interannual variability in the spatial distribution of deforestation, although it is basic geographical information for evaluating the spatiotemporal variability of biodiversity and ecosystem structure and functioning. This lack of

assessment may be due to limited chances for observation by satellites with high spatial resolution (1–30 m) and the high rate of cloud contamination in daily-observed satellite data. For example, Nagai et al. (2014) reported that the frequency of satellite observation without cloud contamination is 1–5 days/month during the southwestern monsoon period in Borneo (May to October) and 0–2 days/month in the northeastern monsoon period (November to April).

In this study, we examined the interannual variability in the spatial distribution of deforestation in Borneo from 2001 to 2013 by analyzing the Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) satellite-observed daily green-red vegetation index (GRVI). We then evaluated the characteristics of the spatiotemporal distribution of deforestation in relation to land elevation.

Methods

Our study area was the island of Borneo, including Indonesia and Malaysia. We used the atmospherically corrected MODIS/Terra (morning observations) and MODIS/Aqua (afternoon observations) "Surface Reflectance Daily L2G Global 500 m SIN Grid V005" data products (MOD09GA and MYD09GA; collection 5) for 2001 to 2013. The MOD09GA and MYD09GA products were downloaded from the NASA Land Processes Distributed Active Archive Center (LP DAAC) (https://lpdaac.usgs.gov/data_access/data_pool). We only used the MOD09GA product for 2001 and 2002 because the observation of MODIS/Aqua started in July 2002. We extracted the pixel values in the 500-m surface reflectance bands for red (620–670 nm) and green (545–565 nm) in the MOD09GA and MYD09GA products by using the MODIS Reprojection Tool provided by the LP DAAC (https://lpdaac.usgs.gov/tools). Daily GRVI was calculated by using the following equation (Motohka et al. 2010):

$$\text{GRVI} = (\text{green} - \text{red}) / (\text{green} + \text{red}) \qquad (1)$$

where green and red refer to the reflectance values for each pixel in the corresponding bands. To extract high-quality GRVI data (GRVI_{best}, mainly without cloud contamination), we checked the "Reflectance Data State QA (State 1 km)" values in the MOD09GA and MYD09GA products by using the MODIS Reprojection Tool.

To detect the spatial distribution of deforestation, we calculated the ratio of the number of days (No. days) of $\text{GRVI}_{best} < 0$ to No. days of all GRVI_{best} values for each pixel at a yearly time step. A positive GRVI value indicates that the land was dominated by green leaves, whereas a negative GRVI value indicates that the land was dominated by red and yellow colored leaves or bare soil (Motohka et al. 2010). Here, we assumed that a high ratio of (No. days of $\text{GRVI}_{best} < 0$) / (No. days of all GRVI_{best} values) indicates deforestation (Nagai et al. 2014). We also validated satellite-observed GRVI by performing field studies in a lowland mixed dipterocarp forest in Lambir Hills National Park (LHNP) in Sarawak, Malaysia (4°11'43.71"N, 114°2'25.55"E, 150–200 m above sea level). For a detailed description of the method of GRVI analysis and results of our field studies in LHNP, see Nagai et al. (2014).

To examine the relationship between the spatial distribution of deforestation and land elevation, we used the ASTER Global Digital Elevation Model, which has a 33.3-m spatial resolution (http://gdem.ersdac.jspacesystems.or.jp).

Results and discussion

In coastal regions of Sarawak (Malaysia) and West and Central Kalimantan (Indonesia), the ratio

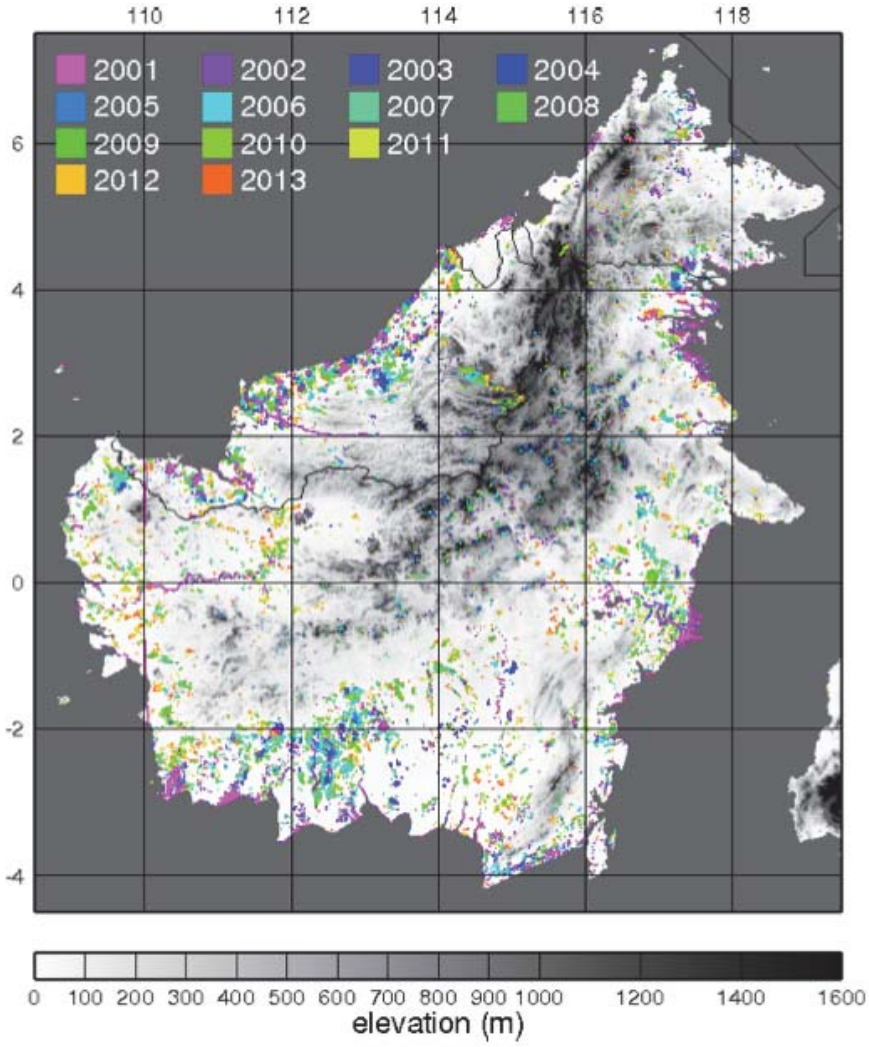

Fig. 1 Spatial distribution of the areas showing (No. days of $GRVI_{best} < 0$) / (No. days of all $GRVI_{best}$ values) of more than 80 % during 2001–2013 in Borneo.

of (No. days of $GRVI_{best} < 0$) / (No. days of all $GRVI_{best}$ values) was high (greater than 80 %) each year (Fig. 1). The spatial distribution of deforestation changed from year to year as a result of deforestation and plantation establishment by planting oil palm or acacia (Nagai et al. 2014). Most of these areas were originally peat swamp forests in Malaysia, and thickets, shrubs, grassland, cultivated perennial crops, and burnt (dry, sparse) vegetation in Indonesia (Stibig et al. 2004). There has been marked carbon loss (stock and flow) due to land-use change from peat swamp forest to oil palm plantations (Hergoualc'h and Verchot 2011; Koh et al. 2011). Adachi et al. (2011) reported that the total biomass and soil carbon of oil palm plantations was about one-third lower than that of rainforest 30 years after planting, based on simulations of a process-based biogeochemical model. Thus, our findings suggest that the ecosystem function of carbon fixation may be declining in large areas of Borneo.

At elevations from 20 to 120 m, the area (km^2) with a high ratio of (No. days of $GRVI_{best} < 0$) / (No. days of all $GRVI_{best}$ values) has increased since 2007 (Fig. 2). This means that the

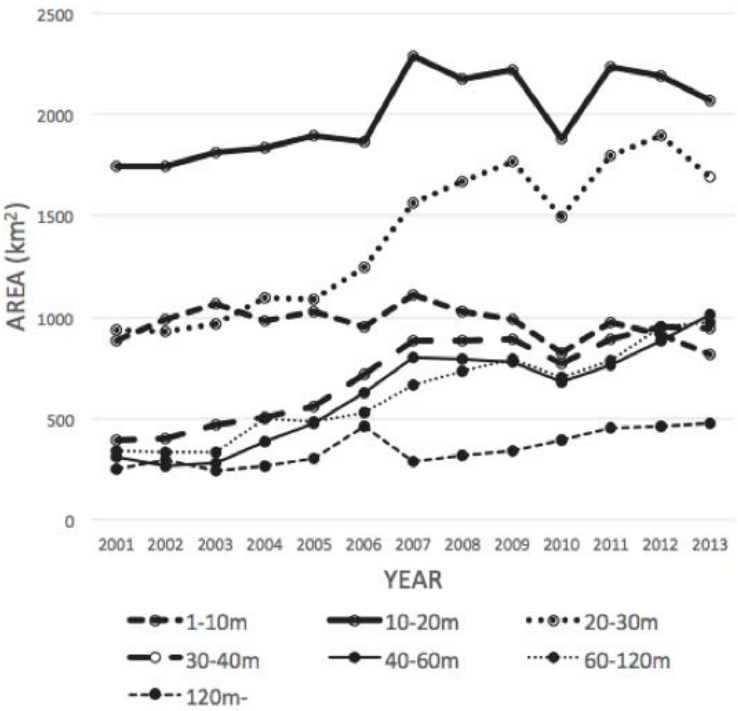

Fig. 2 Interannual variability of the area in Borneo that showed (No. days of $GRVI_{best} < 0$) / (No. days of all $GRVI_{best}$ values) of more than 80%, categorized by land elevation.

deforestation and vegetation recovery by planting oil palm extended into high-elevation hilly areas that are relatively difficult to access. Demand for palm oil products has increased with economic growth in developing countries. GEAS (2011) predicted that global demand for palm oil would increase two-fold by 2020. Compared with Borneo (except for Sabah in Malaysia), the ratio of oil-palm-harvested area to country area is 8- to 40-fold higher on the Malay Peninsula and in Sumatra in Indonesia (Fitzherbert et al. 2008). In 2006, the production quantity of oil palm from Indonesia sharply exceeded that from Malaysia, although both countries have increased the production quantity since the 1970s (FAOSTAT; http://faostat.fao.org). In the near future, especially in Indonesia, the deforestation and vegetation recovery by planting oil palm may gradually extend into high-elevation hilly areas in inland West and Central Kalimantan. In contrast, deforestation and vegetation recovery may gradually reach a steady state in coastal regions of Sarawak (Malaysia) because of depletion of the forests to be felled. The only observed vegetation changes will be the cycle of clear felling and replanting of oil palms at 25- to 30-year intervals (Wahid et al. 2005; GEAS 2011).

Here we show that the analysis of cloud-free satellite-observed daily GRVI is useful for detecting interannual variability in the spatial distribution of deforestation at a coarse spatial resolution (500 m). The recently launched Advanced Himawari Imager on the Himawari-8 next-generation geostationary meteorological satellite may help us to develop our approach owing to its high frequency of observation (every 10 min), although the spatial resolution of spectral reflectance is inferior to that of MODIS (1 km). Further studies will also be required to estimate the interannual variability of the carbon stock and flows in tropical ecosystems by using a

process-based biogeochemical model incorporating the interannual variability of the spatial distribution of deforestation.

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