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Annual multi-resolution detection of land cover conversion to oil palm in the Peruvian Amazon

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ABSTRACT

Oil palm expansion is a major threat to forest conservation in the tropics. Oil palm can also be a sustainable economic alternative if incentives for expansion outside forests are set in place. Consistent methods to monitor the time and location of oil palm expansion and the area converted from different land covers are essential for the success of such incentives. We developed methods to detect and quantify annual land cover changes associated with oil palm expansion in the Peruvian Amazon between 2001 and 2010 at two spatial scales and for two production modes. At the coarse scale, comprising the whole Peruvian Amazon, we used MODIS data to detect forest conversion to large-scale, industrial oil palm plantations based on metrics characterizing temporal changes in vegetation greenness associated with the conversion. At the fine scale, we used data from the satellite sensors Landsat TM/ETM+ and ALOS-PALSAR to map and quantify the area from different land covers converted into large and small-scale oil palm plantations annually, in a focus area near the city of Pucallpa. Estimates were obtained from the elaboration and further combination of maps representing oil palm plantations by ages in 2010 and non-oil palm land covers in each year between 2001 and 2010. Validation data were obtained in the field and from geospatial information from previous studies. At the coarse scale, MODIS detected deforestation in 73% of training events larger than 50 ha. Detected events added up to 95% of the training areas. Total area converted to oil palm annually was quantified visually by using data from Landsat TM/ETM+ with 96.3% accuracy. At the fine scale, the combination of data from Landsat TM/ETM+ and ALOS-PALSAR identified oil palm expansion in areas larger than 5 ha with 94% accuracy and the year of expansion with an uncertainty of ±1.3 years. This work underscores the need for data from multiple satellite sensors for a comprehensive monitoring of oil palm expansion, considering needs for information not only on the area expanded but also the time of conversion and land cover transitions associated with large- and small-scale plantations.

1. Introduction

Global demand for palm oil has grown exponentially during the last 50 years. Palm oil currently accounts for nearly a third of total edible vegetable oil production (Carter et al., 2007; FAOSTAT, 2012). Most of that demand has been satisfied through increases in harvested area rather than yield, suggesting that pressure on land for oil palm expansion will continue (Kongsager & Reenberg, 2012). Oil palm expansion is recognized as a major driver of tropical deforestation with detrimental consequences for biodiversity and the carbon cycle among other ecosystem services (Fitzherbert et al., 2008; Koh & Ghazoul, 2010; Koh & Wilcove, 2008; Murdiyarso et al., 2010; Wilcove & Koh, 2010). Oil palm plantations are actively promoted as a promising economic alternative among Amazonian countries (Pacheco, 2012). Amazonian countries comprise nearly 60% of the total tropical forest area suitable for oil palm plantations (Persson & Azar, 2010). Increases in palm oil demand, along with incentives for oil palm expansion and the existence of extensive forest areas suitable for oil palm cultivation, raise concerns over the fate of Amazonian forests (Butler & Laurance, 2009; Corley, 2009; Persson & Azar, 2010). Alternatively, oil palm can constitute a sustainable economic activity if incentives for expansion outside forests are set in place (Basiron, 2007; Wicke et al., 2011). The success of such incentives requires reliable methods to monitor the time, location, and land cover changes attributed to oil palm expansion (Kongsager & Reenberg, 2012). Monitoring land cover conversion to oil palm can serve to assess the effectiveness of policy approaches to promote sustainable palm oil production and identify areas where incentives are needed to foster production on already-cleared lands.

The application of remote sensing to detect oil palm expansion is challenging because plantations rapidly develop a dense canopy that makes them spectrally and structurally similar to other land covers, in particular to secondary vegetation (Santos & Messina, 2008) or flooded forests (Morel et al., 2011). In addition, rapid canopy

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closure saturates the satellite signal, reducing the potential to evaluate structural characteristics (Morel et al., 2011; Rosenqvist, 1996). Early attempts for correlating oil palm with satellite information consisted primarily of assessing oil palm age or structural variables such as LAI or biomass from data retrieved from optical or SAR satellite sources, with moderate results (McMorrow, 1995, 2001; Rosenqvist, 1996). Efforts to map oil palm plantations have relied on visual interpretation to either define spectral class thresholds (Thenkabail et al., 2004), assign land cover classes to unsupervised post-classification categories (Koh et al., 2011) or manually digitize reflectance data (Carlson et al., 2012; Miettinen et al., 2012). Recent studies have demonstrated the suitability of using SAR data for oil palm mapping through the application of supervised classification methods (Morel et al., 2011; Santos & Messina, 2008).

Methods for detecting oil palm in previous studies have been predominantly developed in areas covered by large-scale industrial plantations. Industrial plantations are usually operated by private companies, with sufficient access to capital and resources to optimize yields in relatively large areas (Gutierrez-Velez et al., 2011). The detection of large-scale plantations is facilitated by their typical spatial patterns, characterized by cultivation in large homogeneous blocks, usually under optimal management. In contrast, small-scale oil palm plantations are more heterogeneous due to differences in management and spatial configuration (Gutierrez-Velez et al., 2011). Small-scale plantations are typically owned by smallholders with restricted access to capital and land that limits expansion and constraints yields (Gutierrez-Velez et al., 2011). Both industrial and small-scale oil palm plantations are expanding in the tropics (Feintrenie et al., 2010; Vermeulen & Goad, 2006). Therefore, reliable remote sensing methods are imperative for detecting both accurately.

In this paper, we evaluate tradeoffs between spatial and temporal resolutions among satellite sensors to determine the area, time and location of oil palm expansion and associated land cover changes between 2001 and 2010 in the Peruvian Amazon at two spatial scales. At the coarse scale we used time series data from MODIS to identify areas of old-growth forest converted to industrial oil palm plantations annually in the whole Peruvian Amazon. At the fine scale, we combine information from Landsat TM/ETM+ and ALOS-PALSAR to map annual oil palm expansion and the associated land cover changes in a focus area near the city of Pucallpa, where both industrial and small-scale plantations operate (Gutierrez-Velez et al., 2011).

The methods described in this paper for the coarse-scale analysis proved useful for quantifying the contribution of high-yield oil palm expansion to deforestation in the Peruvian Amazon in a previous publication (Gutierrez-Velez et al., 2011). The fine-scale analysis described here expands on our previous analyses by developing a method to quantify land use transitions associated with oil palm expansion on an annual basis. Here we compare the performance of the coarse and fine methods and discuss spatial, temporal, and categorical trade-offs between the two approaches on the detection of oil palm expansion.

2. Methods

2.1. Study areas

The study takes place at two spatial scales (Fig. 1). The coarse-scale analysis comprises the Peruvian Amazon, covering an area of 939,204 km^2. By 2000, the total protected area in the Peruvian Amazon was 7.3% while deforestation corresponded to 8% of the territory (MINAM, 2009). Major forest types are classified as lowland and highland vegetation. Lowland forests include seasonally flooded vegetation and *terra-firme* forests. Highland forests are located in dissected hills and mountains toward the west, limiting to the Andean region (IIAP, 2004). The boundaries of the area were obtained by overlaying a map of the Amazon basin (Costa et al., 2003) with the country limits of Peru (IIAP-GRSM, 2005).

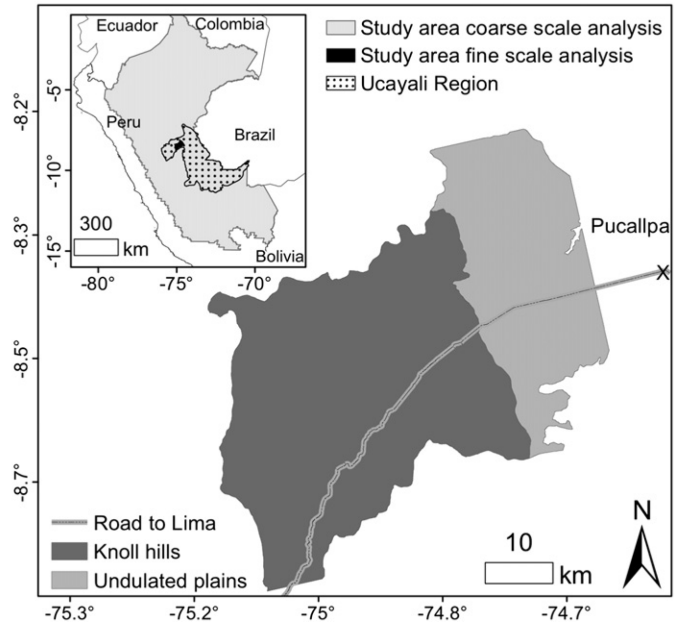

Fig. 1. Study areas for the coarse and fine scale analyses.

We restricted our analysis to areas suitable for oil palm plantations. Suitability was based on environmental conditions favorable for oil palm growth. Oil palm grows well in non-flooded and well drained soils located below 700 m altitude and slopes lower than 12%. Areas with precipitation between 1700 and 4000 mm yr^{-1} and annual temperature between 22 and 32 °C are considered suitable for oil palm plantations (Raygada-Zambrano, 2005; Saenz-Mejia, 2006). We selected the area for further analysis based on the criteria for non-flooded areas, slope and altitude because the study area does not pose any restriction for oil palm growth in terms of precipitation or temperature. Elevation and slope were calculated from an SRTM digital elevation model at 250 m resolution (Jarvis et al., 2008) (Table 1). We used SRTM data at 250 m resolution to keep consistency with the resolution of the input data from MODIS used for oil palm detection and the final resolution of the coarse scale analysis (232 m). SRTM data is also available at 90 m resolution but the gains in detail from using finer SRTM resolution data will likely be lost after resampling the data to the MODIS resolution. Flooded areas were removed from the analysis by using the wetland map from Melack and Hess (2011).

The study area for the fine-scale analysis is located in the Ucayali region between the Aguaytia and Ucayali rivers near the city of Pucallpa. It comprises a total area of 2158 km^2 corresponding to 0.2% of the extent of the Peruvian Amazon. The terrain is mostly composed by undulated plains and knoll hills that do not pose restrictions for oil palm plantations in terms of flooding, soil drainage, or slope (GOREU-IIAP, 2003). We also included some areas with moderately marginal slopes for oil palm (15–25%) because we found oil palm expanding in those areas in our fieldwork. The study area is located in one of the most dynamic deforestation hotspots in the Peruvian Amazon (Oliveira et al., 2007) where both large- and small-scale oil palm plantations are expanding actively (Gutierrez-Velez et al., 2011). Elevations oscillate between 150 and 250 m. Annual mean temperature is 25 °C, fluctuating between 21 and 32 °C. Precipitation ranges between 1500 and 2500 mm/yr. The precipitation cycle is bimodal with a longer and drier season between June and August and a shorter and less intense one between December and January (Barbaran-Garcia, 2000; Fujisaka et al., 2000).