Forest Ecology and Management 393 (2017) 63–73

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Characterizing degradation of palm swamp peatlands from space and on the ground: An exploratory study in the Peruvian Amazon

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ARTICLE INFO

Article history:
Received 4 October 2016
Accepted 12 March 2017
Available online 23 March 2017

Keywords:
Aguajal
CO_2
Mauritia flexuosa
Tropical peatland
Land cover classification
Remote sensing
Satellite data

ABSTRACT

Peru has the fourth largest area of peatlands in the Tropics. Its most representative land cover on peat is a *Mauritia flexuosa* dominated palm swamp (thereafter called dense PS), which has been under human pressure over decades due to the high demand for the *M. flexuosa* fruit often collected by cutting down the entire palm. Degradation of these carbon dense forests can substantially affect emissions of greenhouse gases and contribute to climate change. The first objective of this research was to assess the impact of dense PS degradation on forest structure and biomass carbon stocks. The second one was to explore the potential of mapping the distribution of dense PS with different degradation levels using remote sensing data and methods. Biomass stocks were measured in 0.25 ha plots established in areas of dense PS with low (n = 2 plots), medium (n = 2) and high degradation (n = 4). We combined field and remote sensing data from the satellites Landsat TM and ALOS/PALSAR to discriminate between areas typifying dense PS with low, medium and high degradation and *terra firme*, *restinga* and mixed PS (not *M. flexuosa* dominated) forests. For this we used a Random Forest machine learning classification algorithm. Results suggest a shift in forest composition from palm to woody tree dominated forest following degradation. We also found that human intervention in dense PS translates into significant reductions in tree carbon stocks with initial (above and below-ground) biomass stocks (135.4 ± 4.8 Mg C ha^{-1}) decreased by 11 and 17% following medium and high degradation. The remote sensing analysis indicates a high separability between dense PS with low degradation from all other categories. Dense PS with medium and high degradation were highly separable from most categories except for *restinga* forests and mixed PS. Results also showed that data from both active and passive remote sensing sensors are important for the mapping of dense PS degradation. Overall land cover classification accuracy was high (91%). Results from this pilot analysis are encouraging to further explore the use of remote sensing data and methods for monitoring dense PS degradation at broader scales in the Peruvian Amazon. Providing precise estimates on the spatial extent of dense PS degradation and on biomass and peat derived emissions is required for assessing national emissions from forest degradation in Peru and is essential for supporting initiatives aiming at reducing degradation activities.

1. Introduction

Peatlands store large amounts of carbon (C) in their soil. According to recent estimates, the C stored in global tropical peat soils is equivalent to about 40% of the total C stored in woody vegetation in the entire tropics (Page et al., 2011; Baccini et al., 2012). The luxuriant tropical rainforests living on rich C deposits also store substantial amounts of C in their biomass. (Murdiyarso et al., 2009). Tropical peatlands are estimated to cover an area between 368,500 and 441,025 km^2 representing 8–11% of global peatland area (Yu et al., 2010; Page et al., 2011). Indonesia, Democratic Republic of Congo, Northern Republic of Congo and Peru are the countries with the largest areas of peatland in the tropics (Page et al., 2011; Dargie et al., 2017). Peru harbors lowland peatlands in the Amazon basin as well as highland peatlands in the Andes (Román-Cuesta et al., 2011; Draper et al., 2014). In lowlands, Draper et al. (2014) estimated peatland areas of 35,600 km^2 in the Pastaza-Marañon basin and Householder et al. (2012) 294 km^2 in the floodplain of the river Madre de Dios; for a total of 35,894 km^2.

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http://dx.doi.org/10.1016/j.foreco.2017.03.016
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While in Indonesia the majority of peatlands are ombrotrophic domes (Jaenicke et al., 2008) supporting the growth of a variety of swamp forest types (Brady, 1997; Laumonier, 1997), both minerotrophic and ombrotrophic peatlands are found in the Peruvian Amazon basin. The distinction between minerotrophic and ombrotrophic environments is based on the origin of water and nutrient supply; from streams and ground-water in the first case, from precipitation in the second one. The different water regimes and associated nutrient status led to a diversity of ecosystem types: pole forest peatlands, palm swamp peatlands (locally known as 'aguajales') and opened peatlands made up of herbaceous communities with or without dispersed palms (Lähteenoja et al., 2009a; Lähteenoja and Roucoux, 2010; Lähteenoja and Page, 2011; Householder et al., 2012). Pole forests were described by Draper et al. (2014) and Kelly et al. (2014) as being low stature with thin-stemmed trees and excluding many species. Palm swamps (PS) are the main peatland ecosystem type in the Peruvian Amazon basin (Draper et al., 2014). These palm dominated forests are classified as dense and mixed PS (IIAP, 2004; Freitas et al., 2006; González-B. and Rial, 2013). Dense PS formations are permanently flooded depressions which lie parallel to the river bed between ridges. The substratum is clayey, and retains rainfall. River water enters the depressions only at the time of highest flooding (Kahn and Mejia, 1990). Dense PS are dominated by the *Mauritia flexuosa* (or 'aguaje') palm. Mixed PS are partially exposed to seasonal flooding of nearby rivers (IIAP, 2004). Unlike dense PS, mixed PS are not dominated by *M. flexuosa*, they are formed by communities of *M. flexuosa* associated with other palms or trees (*Ficus* sp. or *Coussapoa* sp.). Permanently flooded dense PS seem to grow on peat soil exclusively whereas seasonally flooded mixed PS are observed to grow both on peat (Freitas et al., 2006) and mineral soils (this study, and field observations).

Tropical peatlands are subject to increasing pressures that threaten the stability of the stored C pools, especially in Indonesia where large amounts of greenhouse gases (GHG) have been released as a consequence mainly of agricultural expansion and fires (van der Werf et al., 2008; Koh et al., 2011; Gaveau et al., 2014; Hergoualc'h and Verchot, 2014). Peruvian lowland peatlands are found to be under less pressure than Indonesian ones although logging, oil and gas prospection, gold mining, agriculture, grazing and settlements are becoming increasingly frequent (Lähteenoja et al., 2012; Janovec et al., 2013). Peatlands in tropical montane cloud forests in the Peruvian Andes have also been shown to experience extensive fire pressure (Román-Cuesta et al., 2011). PS have been the subject of heavy degradation over the past decades due to the high local and regional demand for the *M. flexuosa* fruit and the 'suri' larva, which grows inside the trunk of dead palms and is an important source of protein for rural residents (Padoch, 1988; Penn, 2008; Horn et al., 2012). Despite the existence of viable sustainable harvesting techniques, the collection of *M. flexuosa* fruits is extensively performed by cutting the entire palm (Appendix 1). This degradation of PS compromises the renewal of *M. flexuosa* populations and causes genetic degradation because *M. flexuosa* extractors usually select the females with the best quality and biggest fructifications (Penn, 2008). Degradation leads to a change in the sex ratio of palms with a decrease in female densities (Horn et al., 2012); it also constitutes a threat to a variety of mammal species that depend on them (Penn, 2008).

Forest degradation can contribute substantially to national emissions however these emissions are generally disregarded as they are more technically challenging to measure than emissions from deforestation (Pearson et al., 2017). The use of satellite data for monitoring degradation implies identifying often-subtle differences in reflectance between conserved and degraded forest. In addition degradation patches are generally small compared with clearings which difficults their identification (Miettinen et al., 2014; Shimabukuro et al., 2014).

Remote sensing efforts on peatlands in the Peruvian Amazon include the work by Lähteenoja et al. (2012) who developed a map discriminating different types of peatland forests, wetlands and other land covers in the Pastaza-Marañon basin through an unspecified supervised classification of Landsat images based on field observations. However no classification accuracy assessment was performed. More recently, Draper et al. (2014) used data from the satellite sensors Landsat, ALOS-PALSAR and SRTM along with ground referencing points of known classes to map the spatial distribution of peatlands also in the Pastaza-Marañon foreland. Classification was performed using a supervised, support vector machine method. Land cover classes considered were pole forests, PS and open peatlands as well as four non peat-forming categories (*terra firme* forests or occasionally flooded forests, seasonally flooded forests, open water and urban areas). The overall classification accuracy was 95%.

Attempts at mapping peat forest degradation has been limited to Indonesia. Miettinen et al. (2012), Miettinen and Liew (2010a) and Miettinen and Liew (2010b) visually interpreted time series of optical data from Landsat and SPOT satellites to assess degradation in Sumatra and Kalimantan. Hereafter, Englhart et al. (2013) combined optical and lidar data to assess changes in aboveground biomass between 2007 and 2011 in central Kalimantan. Medium and high resolution data from Landsat and RapidEye sensors were used to identify unaffected, selectively logged, and burned forests while lidar data were correlated with field biomass measurements.

Despite the importance of accounting greenhouse gas emissions from forest degradation, very limited monitoring or research has been conducted on degradation of Peruvian lowland peatlands. In particular there is to date no assessment on the impact that over-harvesting of *M. flexuosa* in dense PS can have on forest structure and functions. Previous attempts to classify and map peatland ecosystems in the Peruvian Amazon (Lähteenoja et al., 2012; Draper et al., 2014) have set aside past and on-going degradation activities in dense PS. To evaluate and map the extent of degradation it is essential to develop new methods suitable for dense PS. With this work we intend to provide a first and preliminary quantification of the impact of dense PS degradation on forest structure, composition and biomass C stocks. We also explore the potential of remote sensing data from the satellites Landsat and ALOS-PALSAR to distinguish areas of dense PS from other land covers and to further discriminate these areas under different levels of degradation using satellite and field data from one single year.

2. Materials and methods

2.1. Study area

The case study was conducted in the Peruvian Amazon, Region of *Loreto*, in the watersheds of the *Marañon* and *Ucayali* rivers (Fig. 1). The site is located 90–130 m above sea level and has mean annual air temperature and precipitation of 26 °C and 3100 mm. The study encompassed an area of 351,324 ha which included the *Pacaya-Samiria* National reserve in the *Yanayacu-Pucate* watershed. This watershed is part of the *Pastaza-Marañon* basin, the most extensive continuous wetland area of the Peruvian Amazon (Räsänen et al., 1992). The selected area offered the opportunity to measure dense PS with different levels of degradation from low and medium degradation inside the *Pacaya-Samiria* reserve (Gonzales Davila et al., 2007) to high degradation outside the reserve, in particular near the *Tigre* river where *M. flexuosa* fruit has been extracted intensively since the 80s (Padoch, 1988; Penn et al., 2008).