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Degradation of soil nutrients and slow recovery of biomass following shifting cultivation in the heath forests of Sarawak, Malaysia

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ABSTRACT

Heath forests which are tropical forests on sandy soils are widely distributed in Borneo and provide many ecosystem services, such as carbon storage and non-timber forest products. Over the past several decades, such forests have been disturbed by non-traditional shifting cultivation, which is usually conducted in unsuitable land with short fallow duration. Anthropogenic disturbances in forests growing on sandy soils that have low nutrient retention capacities may promote further reductions in soil fertility. Long-term monitoring of soil nutrients and biomass accumulation is rare in degraded tropical rainforests growing on sandy soils despite the known negative effects of non-traditional shifting cultivation practices on soil fertility, vegetation and biomass recovery, and the growth of trees planted to rehabilitate forests. The objective of the current study was therefore to elucidate changes in soil fertility and biomass recovery potential in degraded forests on sandy soils in Borneo. We monitored soil nutrients and chemical properties in fifty-four 12 × 12 m plots located on different topographical positions along upper and lower slopes. Samples were collected in plots aged 7 and 14 years after abandonment of shifting cultivation. The biomass of secondary forest trees in all plots 12 years after the abandonment was also measured to determine the relationship between biomass accumulation and changes in soil nutrients. We found that soil pH and cation exchange capacity, and the concentrations of most nutrients, including nitrogen, magnesium, and phosphorus, had decreased significantly 7–14 years after abandonment; biomass accumulation in the plots was also limited 12 years after abandonment ($< 0.8\,Mg\,ha^{-1}\,year^{-1}$). These changes in soil traits within the study plots were similar regardless of topographical position, and the changes were not related to the amount of biomass. Soil nutrients in the plots may have leached out as a result of removal of thick root mats in the surface soil, high sand content, and large amounts of rainfall in the area rather than uptake by recovering trees. These results indicate that it may be difficult to recover soil fertility on steep slopes in sandy soil conditions because of high leaching rates and erosion when the soil surface layer is destroyed by shifting cultivation. It is therefore important to carefully manage shifting cultivation practices in tropical forests on sandy soils in Borneo.

1. Introduction

Heath forests which are tropical forests on sandy soils are widely distributed in Borneo and provide many ecosystem services, such as non-timber forest products and wild animals for local communities (Brunig, 2016). In addition, they have large carbon pools (*e.g.*, approximately 100–250 $Mg\,ha^{-1}$ of carbon) and consequently, destruction of these forest ecosystems would have substantial effects on global carbon emissions (Brunig, 1974, 2016; Kenzo et al., 2015; Miyamoto et al., 2016). These forests consist of diverse tree species and generally grow on infertile soil with bleached white sand (Brunig, 1974, 2016; Riswan and Kartawinata, 1991). However, such forests have suffered widespread anthropogenic disturbance, particularly due to shifting cultivation practices, which are common in Borneo (Spencer, 1966; Mertz et al., 2008; Brunig, 2016). Farmers who practiced traditional shifting cultivation generally avoided burning the heath forests prior to cultivation. Yet they were able to obtain sufficient medicinal plants and food for their consumption (Hatch, 1980; Wasli et al., 2009; Brunig,

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2016). Traditional shifting cultivation is an ecologically sustainable and highly efficient agricultural system for low human population density (Christanty, 1986; Kleinman et al., 1996) because a long fallow duration (usually more than 10 years) promotes the recovery of secondary forest biomass and nutrient accumulation, and forest coverage prevents grass domination and soil erosion (Nye and Greenland, 1960; Marten and Vityakon, 1986; Wasli et al., 2009). However, over several recent decades, increases in the local human population from the influx of migrants who practice non-traditional shifting cultivation have expanded cultivation to unsuitable lands, such as tropical heath forests (Primack and Tieh, 1994; Ishizuka et al., 2000a; Ohkubo et al., 2000; Wasli et al., 2009). Non-traditional shifting cultivation on sandy soils is usually not sustainable because the farmers burn the forests and have short fallow periods, typically less than 5 years (Tanaka et al., 2005; Wasli et al., 2009). These practices can cause severe forest degradation characterized by soil erosion, loss of soil fertility, decreases in biomass and species richness, and expansion of *Imperata* grassland (Kleinman et al., 1995; Lawrence et al., 2005; Bruun et al., 2006; Wasli et al., 2009; Lamb, 2010; Yassir et al., 2010). It is important to note that soil degradation inhibits subsequent forest recovery and biomass accumulation (Chazdon, 2003, 2014; Lamb, 2010; Villa et al., 2018).

In tropical rainforests, once forest is burned and/or removed, the soil nutrient cycle changes drastically (Jordan, 1985; Kleinman et al., 1995; Malmer et al., 1998; Giardina et al., 2000). The destruction of surface soils by non-traditional shifting cultivation can also accelerate leaching of soil nutrients because tropical forests, especially those on sandy soils, generally have thick litter layers and a thick root mat that helps prevent leaching and severe erosion (Brunig, 1974; Jordan, 1985; Ishizuka et al., 1998; Kenzo et al., 2015). Stark and Jordan (1978) reported that thick root mats on sandy soils in an Amazonian tropical rainforest can sequester 99% of the dissolved nutrients available in the soil before they leach downward to the mineral layer. Short-term (approximately 1–2 years) soil nutrient dynamics following shifting cultivation have been reported in several tropical regions, including South America, Africa, and Southeast Asia (Nye and Greenland, 1964; Christanty, 1986; Andriesse and Schelhaas, 1987; Giardina et al., 2000; Kendawang et al., 2004, 2005; Ying et al., 2018). However, with the exception of chronosequence studies (Kleinman et al., 1996; Lawrence, 2005; Wasli et al., 2009; Sarkar et al., 2015; Villa et al., 2018), medium- and long-term monitoring of soil elements in single sites has rarely been reported. In general, concentrations of most soil nutrients, such as calcium, magnesium, and phosphorus, increase rapidly after burning as they are abundant in ash (Nakano and Syahbuddin, 1989; Kleinman et al., 1995; Thomaz et al., 2014). Because these elements are crucial for the synthesis of leaf chlorophyll, root development, and reproduction, the high concentrations of wood ash promote the growth and yield of crops in the year following burning (Kendawang et al., 2004, 2005). However, after being added to the soil surface, most of these nutrients are largely lost within a few months mainly through leaching and they then gradually decrease further over the fallow period (Sanchez, 1976; Andriesse and Schelhaas, 1987; Villa et al., 2018). This gradual reduction in soil nutrients over the fallow period results from absorption by fast-growing secondary forest trees (Kleinman et al., 1995; Ohta et al., 2000; Hattori et al., 2013). After the secondary forest matures, soil nutrients may gradually recover (Kleinman et al., 1995). One chronosequence study in a Mexican tropical montane cloud forest showed that soil nutrient contents, such as exchangeable calcium, magnesium, and potassium, decrease once during the first 0–45 years and then gradually increase with forest recovery until 100 years following abandonment (Bautista-Cruz and del Castillo, 2005).

Soil nutrient dynamics can be greatly affected by soil texture (Ohta and Effendi, 1992; Ohta et al., 1993; Silver et al., 2000; McGrath, et al., 2001; Kendawang et al., 2004, 2005; Paz et al., 2016), with topography and/or the growth rate of regrowing vegetation as important secondary influences (Johnson et al., 2001; Brearley et al., 2004; Hattori et al., 2013). In clayey soils, large quantities of nutrients derived from ash are retained in the soils because the variable negative charges in clay strongly bind the nutrients to the clay particles (Jordan, 1985) and prevent them from being leached away by rainwater. In contrast, due to the low nutrient retention capacity caused by a decreased negative charge, with a small number of broken bonds around the edge of the silica-alumina units in sand particles (Yong and Warkentin, 2012), the nutrients added to sandy soils from ash are quickly washed away by rainwater before the regrowing vegetation can absorb them. Topography and biomass also have large effects on soil nutrients. Decreases in clay soil nutrient concentrations in Borneo were higher on upper slopes where the biomass growth rate was elevated than on lower slopes (Hattori et al., 2013). This decrease in concentrations on upper slopes may have resulted from leaching and/or nutrient uptake by the large vegetation biomass. However, the long-term changes in soil fertility and biomass accumulation in degraded tropical rainforests on sandy soils after shifting cultivation in Borneo is unclear (Mukul and Herbohn, 2016), as much of the published work focused on the short-term effects of shifting cultivation on clayey soils over a maximum of 2 years (Nye and Greenland, 1964; Andriesse and Schelhaas, 1987; Giardina et al., 2000; Kendawang et al., 2004, 2005). The effects of topography and how the rate of secondary forest regrowth affects soil fertility is also largely unexplored. To address the research gaps, we evaluate how shifting cultivation in tropical forest on sandy soils has affected soil fertility and biomass recovery on upper, middle and lower slope positions over a medium to long term time frame.

We hypothesize that soil fertility on abandoned land decreases over time due to poor nutrient retention by the sandy soils in the wet tropics. In addition, we examined the effects of topography and biomass accumulation in secondary forest trees after abandonment because these factors influence soil nutrient dynamics (Jordan, 1985; Blanco and Lal, 2008). To test our hypotheses, we monitored soil chemical properties at different topographical positions 7 and 14 years after the abandonment of shifting cultivation practices in a typical tropical degraded forest on sandy soil in Sarawak, Malaysia. The key objectives of this research were to (1) determine how soil conditions change 7–14 years following the abandonment of shifting cultivation and (2) evaluate the extent to which environmental factors, such as topography and soil texture, affect nutrient loss and aboveground biomass (AGB) accumulation.

2. Materials and methods

2.1. Study site

This study was conducted at the Bakam Experimental Reserve in Sarawak, Malaysia (04°16′N, 113°60′E; Figs. 1 and 2). This region has a humid tropical climate and no clear dry season, with an average annual air temperature of 25 °C and an annual rainfall of 2900 mm (Kendawang et al., 2007). The study site had a total area of 243.9 ha and was located in an area of lowland hills with a relatively steep slope (about 90 m above sea level).

The soil parent materials in the study site are interlayered sandstone, shale, and/or lignite derived from sedimentary rocks of the Lower Miri and Takau Formations developed during the Tertiary period (Wilford, 1960; Nagarajan et al., 2017). Most of the outcropping rocks of the Lower Miri Formation are arenaceous however, intercalated beds of shale appear locally in some areas. The Takau Formation consists of a succession of massive soft sandstones and soft lignitic clays. Baillie (1971) reported that it was not possible to distinguish between the two formations in a soil survey because of the deep weathering and lithological similarity of the rocks. Most of the soils in the study area are classified as typic dystrudepts or typic udorthents (Soil survey staff, 1999; Kendawang et al., 2005).

The site has been repeatedly degraded by anthropogenic activities such as logging and shifting cultivation (Baillie, 1971; Ohkubo et al., 2000). Logging was conducted from 1960 to 1985. From 1985 to 1991, fires were started by humans in the forests along major logging roads,