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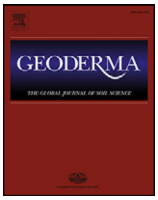

Spatial variability surpasses land-use change effects on soil biochemical properties of converted lowland landscapes in Sumatra, Indonesia

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ABSTRACT

Forest conversion to agriculture can decrease soil nutrient stocks overtime. However, inherent spatial variability in soil biochemical properties in converted landscapes could be high, and may supersede effects of land-use change on soil nutrient changes. Our aims were to assess changes in soil nutrient stocks with land-use change, and to quantify the proportions of spatial variability and land-use change effects on the overall variance of soil nutrient stocks. This study was conducted in Jambi Province, Sumatra, Indonesia in two distinct landscapes defined by the dominant soil texture and type: loam and clay Acrisol soils. In each landscape, four land-use types were examined: lowland forest and rubber interspersed in naturally regenerating forest (referred here as "jungle rubber") as reference land uses and smallholder plantations of rubber and oil palm. In the 0–0.5 m soil depth of the reference land uses, the clay Acrisol had higher total N (660.1 ± 63.8–1074.2 ± 158.8 g N m^{-2}; $P \le 0.05$), exchangeable Ca (24.1 ± 5.7–80.6 ± 22.8 g Ca m^{-2}; $P \le 0.06$), Mg (4.3 ± 0.6–39.2 ± 16.3 g Mg m^{-2}; $P \le 0.02$), K (11.7 ± 0.7–34.7 ± 12.1 g K m^{-2}; $\mathrm{P} \le 0.06$), extractable P (1.1 ± 0.1–2.6 ± 0.1 g P m^{-2}; $P \le 0.001$) and effective cation exchange capacity (ECEC; 11.4 ± 3.1–40.6 ± 11.0 cmol$_c$ kg^{-1}; $P = 0.02$), illustrating that clay content influenced soil fertility in these highly weathered soils. Compared to the reference land uses, the oil palm plantations had higher soil pH (4.2 ± 0.0–4.6 ± 0.1; $P \le 0.04$), base saturation (8.9 ± 1.6–6.5 ± 1.3%; $P \le 0.07$) and extractable P (0.8 ± 0.1–6.1 ± 3.2 g P m^{-2}; $P \le 0.01$) in the top 0.5 m depth, which was probably due to the legacy effect of biomass burning and fertilization. We were unable to detect significant effects of land-use change on other soil biochemical characteristics (i.e., ECEC, stocks of exchangeable bases, soil organic carbon (SOC), total N). Based on variance components analysis, a large proportion of the variance of these parameters was accounted by the variation among replicate plots (26–91%) rather than by land-use types (only 0–6%). Power analysis showed that the optimum number of replicate plots to detect land-use change effects on these parameters ranged from 5 to 7. Our results suggest that spatial variability must be represented in the experimental design in order to detect land-use change effects on soil nutrient changes through stratifying the area of inference (i.e., landscape or region) based on known drivers of soil fertility and determining the optimal number of experimental units.

1. Introduction

Economically important tree-cash crops, such as rubber (*Hevea brasiliensis*) and oil palm (*Elaeis guineensis*), are increasingly replacing Indonesian lowland forests. Previous studies have shown that the greenhouse gas balance—based on carbon (C) losses from oil palm in peat landscapes in Indonesia and Malaysia—incurs large C debts that can only be paid back after >400 years (Fargione et al., 2008). There are very few studies conducted in oil palm on mineral soils in Indonesia, even though mineral soils have far larger areal coverage than peat soils. Recent studies on aboveground C changes from forest conversion to oil palm plantations on highly weathered mineral soils in Jambi Province, Indonesia showed up to 151 Mg C ha^{-1} reduction in aboveground biomass (Kotowska et al., 2015). From a pan-tropic study on highly weathered mineral soils (i.e., Acrisols and Ferralsols) that included Jambi Province, Indonesia, conversion of lowland forests to oil palm and rubber plantations decreases SOC stocks by 40% and 20% in the top 0.1 m depth (van Straaten et al., 2015), respectively, of which the latter is similar to what was found in tropical Yunnan Province, China (de Blécourt et al., 2013). However, none so far has included responses of mineral nutrients to these land-use changes in this particular region.

Information provided by the relatively few studies conducted in Indonesia illustrates that conversion of montane forests on less weathered, fertile soils to agricultural land uses in Central Sulawesi

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decreases soil fertility (Dechert et al., 2004). Conversion of lowland forests on highly weathered soils to rubber and oil palm plantations in Jambi Province increases soil pH, attributed primarily to the legacy effect of ashes from biomass burning during conversion, as well as soil N availability due to fertilization (Allen et al., 2015; van Straaten et al., 2015). However, fertilizer application in converted land-use systems mitigates only short-term nutrient shortage (Ngoze et al., 2008). The ultimate result with years of continuous cultivation after forest conversion is a decrease in soil nutrient levels and cycling (e.g., nitrogen; Corre et al., 2006; Davidson et al., 2007). Of the limited number of studies that focus on tropical land-use conversion and soil nutrient changes, most quantifications were restricted to the topsoil. A majority of previous studies quantified soil nutrient stocks and their changes within the top 0.3 or 0.4 m of soil (e.g., Dechert et al., 2004; Ngoze et al., 2008) although there are indications of SOC changes at soil depths ≥0.5 m (van Straaten et al., 2015; Veldkamp et al., 2003) and nutrient leaching losses at depths ≥1 m (Dechert et al., 2005) with land-use conversion.

At the landscape scale, soil texture is the main driver of spatial variation in soil fertility in highly weathered Ferralsol soils in the Brazilian Amazon (Silver et al., 2000; Sotta et al., 2008). Clay soils are known to have higher nutrient ion availability, higher water holding capacity and higher SOC stocks, total N stocks and soil-N cycling rates than coarser-textured soils. Thus, in our study region in Jambi, Indonesia, which is dominated by highly weathered Acrisol soils, it is important to consider the systematic spatial pattern of soil texture at a landscape scale when investigating the extent of nutrient changes from land-use conversion. A recent study conducted in the same lowland landscapes as our present study found that SOC stock losses from forest conversion to oil palm and rubber plantations are firstly hinged on the initial levels of SOC in the reference land use (i.e., forest) and secondly controlled by the clay contents of the soil (van Straaten et al., 2015). Forest soils with higher SOC are more susceptible to SOC losses while SOC stabilization is influenced by clay content.

On the other hand, land-use change effects on soil nutrient levels may be overshadowed by spatial variability. Since soil biochemical properties have inherently high spatial variability (Parkin, 1993; Pennock and Corre, 2001; Powers and Schlesinger, 2002), the spatial characterization (e.g., representing the spatial pattern within a landscape) and the number of soil samples taken to represent an experimental unit (i.e., replicate plot) are aspects that are often not addressed in quantifying changes in soil nutrient stocks due to land-use change. Recent studies on soil nutrient stocks and soil nutrient cycling in tropical forests conducted at the landscape scale based their experimental designs on the spatially-systematic occurrence of principal drivers of the measured processes (e.g., soil group or degree of soil development (de Koning et al., 2003; Hall and Matson, 2003), soil texture within a broad soil group (Silver et al., 2000; Sotta et al., 2008), topography within a landscape (Wolf et al., 2011), chronosequence (de Blécourt et al., 2013) or elevation gradient (Arnold et al., 2009; Baldos et al., 2015; Powers and Schlesinger, 2002)). These studies' experimental designs are often nested, similar to what we employed in our present study. Our study region is delineated into landscapes of distinct soil texture within a broad soil group; each landscape is represented by replicate plots which are randomly selected to represent each land-use type; and each replicate plot is represented by subplots that are randomly chosen for measurements of soil biochemical characteristics (Allen et al., 2015). Important advantages of a nested experimental design are not only to represent the spatial driver (i.e., soil texture) on soil nutrients at the scale of investigation (i.e., landscape scale), but also to quantify the variations accounted by the different spatial components of the experimental design (i.e., subplots, replicate plots, land uses and landscapes).

Previous studies examining spatial patterns of SOC stocks have illustrated that SOC in tropical forests in southern China, Laos and Costa Rica is greatly influenced by small-scale variation, and that a majority of the overall variance on SOC stocks can be accounted by the spatial components within a landscape (i.e., elevation, Powers and Schlesinger, 2002; slope gradient, Chaplot et al., 2010; land-use age, de Blecourt, 2013). Additionally, examining soil nutrient stocks in a nested spatial design can be a useful tool in evaluating whether estimates can be extrapolated over large spatial areas (Powers and Schlesinger, 2002).

The aims of this study were to 1) assess changes in soil nutrient stocks down to 2 m depth with land-use change and 2) determine the proportions of spatial variability and land-use change effects on the overall variance of soil nutrient contents. We measured soil biochemical characteristics and soil nutrient stocks in lowland forest and jungle rubber, as reference land uses, and in converted smallholder rubber and oil palm plantations, all located within two texturally different lowland Acrisol soils in Jambi Province, Sumatra, Indonesia. We hypothesized firstly that soil nutrient stocks in the reference land uses will be higher in the clay than the loam Acrisol soils, and secondly that if effects of land-use change are detectable, soil nutrient stocks will be highest in the reference land uses, lowest in the unfertilized converted land use (rubber) and intermediate in the fertilized converted land use (oil palm). Thirdly, we hypothesized that in cases where land-use change effects on soil biochemical characteristics are statistically not detectable, the proportions of the overall variance of soil biochemical characteristics will be highest between landscapes, followed by among replicate plots within landscapes and least by among subplots within replicate plots. In this study, we provide much-needed background information on soil nutrient contents down to 2 m depth in the dwindling Indonesian lowland forests, and how they are influenced by land-use conversion as well as spatial variations of soil biochemical characteristics in commonly converted lowland landscapes.

2. Materials and methods

2.1. Study sites and experimental design

Our study region in Jambi Province, Sumatra, Indonesia was delineated into two distinct lowland landscapes (Fig. A.1), based on the dominant soil type and texture (i.e., clay Acrisol and loam Acrisol soils). The loam Acrisol soil landscape was located south of Jambi city (1°55′40″S, 103°15′33″ E and elevation of 70 ± 4 m above sea level, asl) and the clay Acrisol soil landscape was located west of Jambi city (2°0′57″S, 102°45′12″ E and elevation of 75 ± 4 m asl; Fig. A.1). The mean annual temperature in Jambi is 26.7 ± 1.0 °C and the mean annual precipitation is 2235 ± 385 mm (1991–2011; climate station at the Jambi Sultan Thaha airport of the Meteorological, Climatological and Geophysical Agency).

Four common land-use types were examined: mixed Dipterocarp (Kotowska et al., 2015) lowland forest and rubber interspersed in naturally regenerating secondary forest or jungle rubber as reference land uses, and smallholder monoculture plantations of rubber and oil palm (Table A.1). We considered the forest and jungle rubber as reference land uses, because the rubber and oil palm plantations were established on logged and/or burned forest or jungle rubber sites (Euler, 2015) and the jungle rubber sites were closer in proximity to the monoculture plantations compared to the forest sites (Fig. A.1). In each landscape, four replicate plots per land-use type were selected ($n = 32$) and each replicate plot was 50 m × 50 m with a minimum distance of 200 m between plots (Fig. A.1). A full description of the study design can be found in Drescher et al. (2016). Management practices in these smallholder monoculture plantations are described by Allen et al. (2015). In short, oil palm plantations represented typical smallholder-managed land uses with fertilization (varying between 48 and 138 kg N ha^{-1} $year^{-1}$, , 21–38 kg P ha^{-1} $year^{-1}$ and 40–157 kg K ha^{-1} $year^{-1}$ with NPK complete and KCl fertilizers), liming (200 kg dolomite $(CaMg(CO_3)_2)$ ha^{-1}-$year^{-1}$) and weeding (herbicides) during our study period in 2013, whereas the rubber plantations represented the less managed land use having weeding but without any soil amendments during 2013.