Sensitivity and resistance of soil fertility indicators to land-use changes: New concept and examples from conversion of Indonesian rainforest to plantations

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ABSTRACT

Tropical forest conversion to agricultural land leads to a strong decrease of soil organic carbon (SOC) stocks. While the decrease of the soil C sequestration function is easy to measure, the impacts of SOC losses on soil fertility remain unclear. Especially the assessment of the sensitivity of other fertility indicators as related to ecosystem services suffers from a lack of clear methodology. We developed a new approach to assess the sensitivity of soil fertility indicators and tested it on biological and chemical soil properties affected by rainforest conversion to plantations. The approach is based on (non-)linear regressions between SOC losses and fertility indicators normalized to their level in a natural ecosystem. Biotic indicators (basal respiration, microbial biomass, acid phosphatase), labile SOC pools (dissolved organic carbon and light fraction) and nutrients (total N and available P) were measured in Ah horizons from rainforests, jungle rubber, rubber (Hevea brasiliensis) and oil palm (Elaeis guineensis) plantations located on Sumatra. The negative impact of land-use changes on all measured indicators increased in the following sequence: forest < jungle rubber < rubber < oil palm. The basal respiration, microbial biomass and nutrients were resistant to SOC losses, whereas the light fraction was lost stronger than SOC. Microbial C use efficiency was independent on land use. The resistance of C availability for microorganisms to SOC losses suggests that a decrease of SOC quality was partly compensated by litter input and a relative enrichment by nutrients. However, the relationship between the basal respiration and SOC was non-linear; i.e. negative impact on microbial activity strongly increased with SOC losses. Therefore, a small decrease of C content under oil palm compared to rubber plantations yielded a strong drop in microbial activity. Consequently, management practices mitigating SOC losses in oil palm plantations would strongly increase soil fertility and ecosystem stability. We conclude that the new approach enables quantitatively assessing the sensitivity and resistance of diverse soil functions to land-use changes and can thus be used to assess resilience of agroecosystems with various use intensities.

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1. Introduction

The increase of agricultural land area in the tropics is ongoing mainly at the expense of primary and secondary forests (Gibbs et al., 2010). While tropical deforestation rates are trending to stabilize or to decrease in regions like Brazil, they are still increasing in Indonesia, driven by the international demand for wood-derived products as well as for agricultural land for oil palm and rubber plantations (Abood et al., 2015; Margono et al., 2014). Forest
conversion in general and especially to oil palm and rubber plantations strongly changes ecosystem functioning (Barnes et al., 2014). This results in losses of biodiversity (Barlow et al., 2007), ecosystem services such as water supply (Bruitjnzeel, 2004) and C sequestration in the plant biomass and in the soil (Don et al., 2011; Kotowska et al., 2015). Guillaume et al. (2015) observed up to 70% soil organic carbon (SOC) losses in the topsoil under oil palm and rubber plantations in Indonesia compared to rainforest. Further, SOC losses depended on land-use intensity. Tropical forest conversion to agricultural land also leads to a decrease of biological and chemical indicators of soil fertility (Joergensen, 2010; Kaschuk et al., 2010). Nevertheless, only few studies have included rubber and oil palm plantations, despite the large-scale extension of these land-use types in the last decades (Gatto et al., 2015). In a recent review on the impact of land-use changes on microorganisms in the tropics (Joergensen, 2010), only six studies on rubber and oil palm plantations encompassing two continents were included, and only three of them used forest sites as a baseline to evaluate the plantation’s impact.

The decrease of C sequestered in soils is a major concern because it represents the biggest terrestrial C pool and is in exchange with the biological C cycle and atmospheric CO2. The loss of the C sequestrating function of soils after forest conversion to plantations is measured straightforwardly by comparing SOC stocks among undisturbed (e.g. forest) and agricultural ecosystems. SOC losses are also associated with a decrease of soil quality and fertility and thus, with a soil’s capacity to provide sustainable ecosystem services (Bastida et al., 2008; Lal, 2010; 2006). SOC is considered as an “umbrella” property of soil fertility because SOC decrease is associated with the decrease of most soil properties and functions related to fertility. This includes bulk density, nutrient availability, water penetration and holding capacity, erosion, fertility, and microbial activity (Lal, 2006). For instance, SOC and crop yield are positively correlated in various agricultural systems (Bauer and Black, 1994; Ganzhara, 1998). Nevertheless, the effects of SOC losses due to mineralization or erosion on soil fertility remain unclear because it is difficult to quantify relationships between soil properties and soil functions (Letey et al., 2003).

Soil fertility cannot be measured directly because the commonly used crop yield reflects only one of many soil functions and services. Therefore, soil fertility is classically assessed by selecting and interpreting changes of properties or processes recognized as important for fertility, i.e. using them as indicators of soil fertility (Askari and Holden, 2014). Maximal or optimal levels of biological, chemical or physical soil properties are specific for each natural or agricultural system. Consequently, in order to evaluate the impact of land-use changes, indicators must be compared to a baseline level from undisturbed environments or from specific sustainable management practices (Gil-Sotres et al., 2005). Moreover, various soil properties and functions are not similarly affected by land-use changes. This calls for determining the sensitivity or the resistance of fertility indicators to land-use changes in order to identify which functions are at risk and to target appropriate management practices. For this purpose, determining the sensitivity of indicators to SOC losses is especially appropriate because SOC is (i) correlated with most soil fertility indicators, (ii) easily measurable and (iii) directly affected by management practices.

Biological soil properties and SOC labile pools are in general more sensitive to land-use or management changes than physical or chemical soil properties (Bastida et al., 2008; Raiesi and Beheshti, 2015; Sharma et al., 2011). For instance, microbial biomass, basal respiration, extracellular enzymes activities, SOC light fraction or dissolved organic carbon (DOC) decreased generally faster after land-use changes than the total SOC (Bolinder et al., 1999; Kandeler et al., 1999; Powlson et al., 1987; Sparling, 1992). Microbial activity is a main indicators reflecting soil fertility because microorganisms favors plant growth by driving all C and nutrient cycles and depends strongly on C content (Anderson and Domsch, 1989). Microbial activity, however, depends not only on the total amount of SOC but also on its availability for microorganisms, e.g. the proportion of labile SOC pools (von Lititzow et al., 2006) or the nutrient content (Cleveland et al., 2006). For instance, microbial activities measured based on basal respiration during incubation of free particulate organic matter, the light fraction or the water- or K2SO4-soluble C were higher than the basal respiration of the bulk soil (Alvarez et al., 1998; Haile-Mariam et al., 2008; Mueller et al., 2014; Wagai et al., 2013; Wang et al., 2003). Thus, the basal respiration reported per unit of SOC is an indicator of C availability. Using ratios of single indicators, further indices were developed reflecting microbial community functioning or SOC functions in the soil (Anderson, 2003). Among them, the metabolic quotient (qCO2) (basal respiration to microbial biomass ratio) is one of the most widely used and reflects the carbon-use efficiency of microbial communities (Anderson and Domsch, 1990). The microbial quotient (microbial biomass to soil SOC ratio) was suggested to reflect the soil function of supporting microbial growth (Insam and Domsch, 1988).

Sun-ray plots or radar plots provide quick overviews of the sensitivity of all indicators (Bloom et al., 2006; Schloter et al., 2003), but do not quantitatively assess differences in their sensitivity. Changes after site conversion of indices based on the ratios of two soil properties reflect differences in the sensitivity of these two properties, i.e. one variable change more or less than the other. However, because comparisons are made between groups (land-use types) and not along a continuous and quantitative variable, it is not possible to determine the type of relationship between these properties. Linear and non-linear relationships among soil properties or functions have completely different ecological meaning and implications for management practices. On the one hand, a linear relationship between the decrease of SOC and of a soil property or function implies that SOC losses have the same effect at any C content whenever the property or function is sensitive, resistant or proportionally decreases with SOC losses (Fig. 1). On the other hand, a non-linear relationship implies that the effect of SOC losses depends on the C content. The same absolute SOC loss has a higher negative impact at low C than at high C content for indicators being resistant, or vice versa for indicators being sensitive.

We hypothesized that (1) SOC losses in plantations are associated with a strong decrease of soil fertility indicators. Furthermore, (2) the indicators do not necessarily decrease proportionally with SOC losses but could be more resistance or more sensitive than SOC to land-use change (Fig. 1). Finally, (3) the indicators’ sensitivity varies depending on the SOC loss intensity. Therefore, the study objectives were to (1) quantify the changes in soil fertility indicators following SOC losses after forest conversion to oil palm and rubber plantations, (2) relate C availability with biological and chemical indicators of soil fertility and (3) provide a comprehensive approach to assess the sensitivity of these (and other) fertility indicators to SOC losses.

2. Materials and methods

2.1. Study sites

Study sites were located in Jambi Province (Sumatra, Indonesia) under a humid tropical climate (27°C; 2400 mm year−1; 112–259 mm month−1) with a drier season lasting from May to September. A space-for-time substitution approach was used to assess the impact of rainforest conversion on soil fertility indicators. The experimental design includes natural lowland tropical rainforest as reference site and three land-use types dominating on Sumatra: (1) jungle rubber, (2) rubber plantation and (3) oil
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