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Deforested and drained tropical peatland sites show poorer peat substrate quality and lower microbial biomass and activity than unmanaged swamp forest

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ABSTRACT

Swamp forests on deep tropical peatlands have undergone extensive deforestation and draining for agriculture and plantations, consequently becoming globally significant carbon (C) sources.

To study the effects of land-use change on peat as a biological environment, which directly affects decomposition dynamics and greenhouse gas emissions, we sampled peat from four common land-use types representing different management intensities in Central Kalimantan, Indonesia. The near-pristine *swamp forest* was used to describe unmanaged conditions, and the three other sites in order of increasing management intensity were *reforested*; *degraded*; and *agricultural*. We examined peat substrate quality (total C & nitrogen (N), dissolved organic C (DOC) and N (DON)), organic matter quality characterized by infrared spectroscopy, and microbial biomass and extracellular enzyme activity, to describe both biotic and abiotic conditions in peat.

We found that the peat at altered sites was poorer in quality, i.e. decomposability, as demonstrated by the higher intensity of aromatic and aliphatic compounds, and lower intensity of polysaccharides, and concentration of total N, DOC, and DON compared to the peat in the swamp forest. The observed differences in peat properties can be linked to changes in litter input and decomposition conditions altered after deforestation and draining, as well as increased leaching and fires. The quality of the peat substrate was directly related to its biotic properties, with altered sites generally having lower microbial biomass and enzyme activity. However, irrespective of management intensity or substrate quality, enzyme activity was limited primarily to the first 0–3 cm of the peat profile. Some differences between wet and dry seasons were observed in enzyme activity especially in swamp forest, where the most measured enzyme activities were higher in dry season.

Reforestation 6 years before our measurements had not yet restored enzyme activity in the peat to the level of the swamp forest, although the topmost peat characteristics in the reforested site already resembled those in the swamp forest. This is likely contributed by the limited capacity of the young tree stand to produce litter to support peat formation and restore the quality and structure of the peat, and the chemical weed control performed at the site. Therefore, we conclude that intensive land management, including deforestation and draining, leads to the surface peat becoming poorer biological environment, and it may take long time to restore the peat properties.

1. Introduction

Peatlands in Southeast Asia form globally significant carbon (C) pools comprising 11–14% of C stored in peat (Page et al., 2011). However, since 1990s land-use change, typically deforestation and draining to convert land for agriculture and industry, has occurred extensively. In Peninsular Malaysia, Borneo and Sumatra, only 29% of the original peat swamp forest area still remained forested in 2015,

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while only 6% of the forests lacked clear signs of human impact (Miettinen et al., 2016). The largest remaining swamp forests in Southeast Asia are located in Central Kalimantan, but the increasing demand for land, especially for cultivation, poses a major threat to their existence (Miettinen et al., 2016). Due to land-use change towards drier and more sparsely vegetated systems, altered tropical peatlands are globally significant C sources (IPCC, 2014). In 2015 in Peninsular Malaysia, Borneo and Sumatra, approximately 78% of the total amount of C (146 Mt C yr^{-1}) released in decomposition of peat was from industrial plantations and small holder-farming on peat soils (Miettinen et al., 2017). Net loss from peat carbon store leads to soil surface sinking (surface subsidence) and, for example, oxidative peat decomposition is found to account 72–74% of the progressing peat subsidence in oil palm plantations (Ishikura et al., 2018). Altogether, drained tropical peatlands release approximately 200 Mt of C to the atmosphere per year (Biancalani and Avagyan, 2014; Page and Hooijer, 2016).

Carbon accumulation in soil takes place when the rate of litter deposition exceeds that of decomposition; if this ratio reverses, C is released. Microbial decomposition of organic matter is mediated by extracellular enzymes, each specified to degrade certain compounds. Additionally, microbial population and its composition, as a biotic factor determines the potential decomposition activity and is usually limited by one or more of the abiotic factors. The primary abiotic factor affecting the decomposition rate in peatlands is generally considered to be oxygen availability, which is limited by high water-table level (WT), but also substrate quality, pH, nutrient availability, and especially in boreal latitudes also temperature may further constrain decomposition (Clymo, 1984; Laiho, 2006). Microbial decomposition can accelerate due to WT drawdown improving oxygen availability (e.g., Freeman et al., 2001; Fenner and Freeman, 2011; Ishikura et al., 2017), but it may also be suppressed by drought stress (Kwon et al., 2013; Ishikura et al., 2017). The substrate quality can also be the primary factor limiting decomposition, especially when the substrate is rich in polyphenols and other recalcitrant compounds (Berg, 2000; Straková et al., 2011, 2012; Hoyos-Santillan et al., 2016). Therefore, land-use change that alters both vegetation and draining, and thus influences both the substrate quality and WT, is likely to result in greatly modified environment for decomposers. To promote more sustainable and C-neutral management of tropical peatlands, it is crucial to increase our understanding of how peat decomposability and microbial decomposition activity (i.e. enzyme activity) in peat varies between land management types.

Mature swamp forest with closed canopy, high biomass (Sulistiyanto, 2004), relatively cool and unvarying temperatures on the ground (Brady, 1997; Jaya, 2007) and usually moist peat up to the surface encloses abundant organic substrate resources and good environment for decomposition. In the unmanaged swamp forests, high amount of leaf litter is deposited and also mainly decomposed on the peat surface (Sulistiyanto, 2004; Yule and Gomez, 2009; Hoyos-Santillan et al., 2015). Woody litters; roots, trunks and branches, are more resistant to decomposition and partly deposited below the WT, and therefore have a higher importance in peat formation in swamp forests (Wüst et al., 2008; Hoyos-Santillan et al., 2015). The woody peat formed in swamp forests has a lignin concentration of up to 72% of dry mass (Andriesse, 1988; Könönen et al., 2016). Swamp forests are ombrotrophic ecosystems (i.e., rain fed), and cycling of the limited nutrient pools within the system is tight. Most of the nutrients are released from litter during decomposition at or close to the peat surface, and rapidly bound again to microbial and plant biomass (Page et al., 1999). Therefore, nutrients are most concentrated in the surface peat (Page et al., 1999; Andriesse, 1988; Lampela et al., 2014). The slow water runoff in comparison to the amount of water received in precipitation maintains a WT close to the peat surface. The forest floor is partly waterlogged in wet seasons (Lampela et al., 2014). In dry seasons, aerobic decomposition processes are possible in the surface peat above the WT, yet, the shading of the tree canopy reduces ground temperature and loss of water from peat by evaporation. The high WT, highest litter inputs at the peat surface especially of the easily decomposed leaf litter, and the highest availability of nutrients in the surface peat all mean that the highest microbial biomass and activity is likely restricted to the very surface layers in the unmanaged swamp forests. Yet, the fluctuation of WT between the wet and dry seasons can be high, and the impacts of this fluctuation on the biomass and activity of the microbial community has not yet been quantified for swamp forests.

Cultivation on peatlands requires removal of the original vegetation, i.e. deforestation, and draining, which ensures sufficient aeration of the rooting zone necessary for the growth of most crop plants. Permanent draining also leads to consolidation of the peat, improving its bearing capacity and thus enabling the use of cultivation machinery. Deforestation reduces the litter deposition rate, as the volume of vegetation in all subsequent land management types (small-holder farms, plantations, and abandoned areas that often develop to fern-covered shrub lands) is typically much smaller than in swamp forest (Sulistiyanto, 2004; Hoscilo et al., 2011; Blackham et al., 2014; Yule et al., 2016). Although the stand biomass in mature oil palm and acacia plantations may be relatively high, harvesting and other intensive management practices (slash-and-burn, weeding, tilling) reduce litter deposition (Hertel et al., 2009; Smith et al., 2012). The reduced litter deposition may be one of the most important parameters influencing peat C-dynamics as it reduces the potential for C-accumulation, irrespective of potential changes in decomposition rates. It may also cause the intuitively paradoxal soil respiration patterns observed in some comparative studies, with the highest respiration coming from the large mass of litter decomposing in unmanaged swamp forests, and clearly lower rates observed for sites under intensive land management (Hirano et al., 2014; Jauhiainen et al., 2016b).

Draining enables aerobic decomposition deeper in the peat profile, consequently leading to C loss from deeper layers in peat (Evans et al., 2014; Hirano et al., 2014; Jauhiainen et al., 2016a). Together the enhanced draining and replacing of the swamp forest vegetation with no or patchy vegetation cover further lead to high peat surface temperatures due to the direct solar radiation reaching to and being absorbed by the dark, bare soil surface (Jauhiainen et al., 2014). High surface peat temperatures may cause drought stress thereby suppressing microbial decomposition activity (Kwon et al., 2013). Removal of the original vegetation cover and draining also upsets the tight nutrient cycle between litter and live vegetation and may exacerbate the loss of nutrients, as it is known to increase the export of dissolved organic carbon (DOC) (Page et al., 1999; Anshari et al., 2010; Moore et al., 2013). DOC and nutrient leaching often take place in tandem (Nieminen et al., 2015). The impoverishment of already nutrient-poor peat increases the need for fertilization for productive cultivation (Andriesse, 1988). Poor soil quality for cultivation may also lead to the abandonment of the deforested and drained degraded areas, where recurrent wildfires enhance the impoverishment of peat by preventing regrowth of vegetation (Page and Hooijer, 2016).

Altered WT and litter deposition rates, progressing peat decomposition, and fire occurrence all modify peat properties in complex manners, and determine the quality of the peat as a biological environment for decomposers. However, relatively little is still known about peat as a biological environment in the tropics. Differences in substrate quality, climate and WT regime may lead to different patterns from the northern peatlands, where the peat is primarily formed by *Sphagnum* mosses and *Carex* sedges. This study aims to provide insight into the factors regulating decomposition in swamp forests subject to differing land management intensities. To do so, we studied peat substrate quality (total C & nitrogen (N), DOC & DON, and organic matter quality characterized by infrared spectroscopy) as well as microbial biomass and extracellular enzyme activity under the varying environmental conditions of different land-use types in Central Kalimantan, Indonesia.

We hypothesized that: (i) deforested and drained sites have lower