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Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and carbon stocks

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ABSTRACT

Ecosystem services provided by tropical peat swamp forests, such as carbon (C) storage and water regulation, are under threat due to encroachment and replacement of these natural forests by drainage-based agriculture, commonly oil palm plantation. This study aims to quantify how the chemical and physical properties of peat change during land conversion to oil palm. This will be addressed by comparing four separate stages of conversion; namely, secondary peat swamp forests, recently deeply drained secondary forests, cleared and recently planted oil palm, and mature oil palm plantation in North Selangor, Malaysia. Results indicate accelerated peat decomposition in surface peats of mature oil palm plantations due to the lowered water table and altered litter inputs associated with this land-use change. Surface organic matter content and peat C stocks at secondary forest sites were higher than at mature oil palm sites (e.g. C stocks were 975 ± 151 and 497 ± 157 Mg ha^{-1} at secondary forest and mature oil palm sites, respectively). Land conversion altered peat physical properties such as shear strength, bulk density and porosity, with mirrored changes above and below the water table. Our findings suggest close links between the organic matter and C content and peat physical properties through the entire depth of the peat profile. We have demonstrated that conversion from secondary peat swamp forest to mature oil palm plantation may seriously compromise C storage and, through its impact on peat physical properties, the water holding capacity in these peatlands.

1. Introduction

Ombrotrophic tropical peat swamp forests are unique ecosystems covering 247,778 km^2 in SE Asia and 441,025 km^2 globally (Page et al., 2011). Areas of diverse tropical rainforest perched on rich deposits of preserved organic matter are made possible by substantial rainfall, coupled with suitable topography and geology, which results in waterlogging. The anoxic and acidic conditions retard microbial decay (Andriesse, 1988; Page et al., 2006; Yule and Gomez, 2009) resulting in peat accumulation as inputs of litter from the vegetation are greater than decomposition rates (Jauhiainen et al., 2008).

These unique systems are valuable resources, contributing a multitude of ecosystem services. Above ground, tropical rainforests maintain areas of high biodiversity by providing habitats for a variety of species, many of which are endemic (Posa et al., 2011; Keddy et al., 2009). Below ground, the sequestration of atmospheric carbon is interwoven into the fabric of the ecosystem (Jauhiainen et al., 2008). An estimated 42,000 megatons of ancient carbon is stored in 12% of the total land area of Southeast Asia alone, making this one of the largest stores of terrestrial carbon on Earth (Wetlands International, 2014). Peat soil structure is responsible for ecosystem processes by controlling hydrology, which regulates hydrological features within the catchment. For example, its high organic matter content and low bulk density allows peat to acts as a water reservoir, mitigating extreme conditions such as floods and droughts (Huat et al., 2011; Wösten et al., 2008).

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Land use change over the past century has been a key driver of peatland degradation, with conversion to agriculture and forestry, and peat extraction sites, leading to artificially lowered water tables (Haddaway et al., 2014). Limitations in understanding how peatland systems function has led to land degradation, which, for example has caused uncontrollable burning of over a million hectares of Indonesian peat during 1996, resulting from excessive land use change by the Mega Rice Project (Page et al., 2002). Land conversion to agricultural oil palm plantation represents one of the primary threats to Malaysia's peat swamp forests (Koh et al., 2011). However, knowledge of the impact of the different land conversion stages involved in the establishment of oil palm plantations, in terms of decomposition, C stocks and peat physical properties, is extremely limited as most previous work has focused on binary comparison of intact forest and mature oil palm plantations.

Drainage of peat swamp forests to support oil palm production intensifies peat degradation as the thickness of the oxygenated zone of decay (acrotelm) is increased. This enhances rapid aerobic microbial decay compared to anaerobic decomposition which predominates within the anoxic zone below the water table (Anshari et al., 2010). In addition to lowered water tables, deforestation removes complex vegetation structures and replaces them with a monoculture of oil palm trees, which deposit far less biomass, limiting organic matter inputs (Anshari et al., 2010). The combination of decreased biomass input and reduced preservation of deposited biomass has caused large-scale peat degradation resulting in high atmospheric CO_2 emissions (Hooijer et al., 2012; Couwenberg et al., 2010).

A greater degree of peat decomposition results in loss of structure as fresh litter is first broken down to fibrous hemic peat, and then, following sustained decomposition, to sapric peat (Wüst et al., 2003). The progressing decomposition process alters the organic components and chemistry due to loss of carbon and conversion of readily decomposable materials, such as polysaccharides, celluloses and hemicelluloses, with only more recalcitrant compounds such as lignin and humic substances remaining (Andriesse, 1988; Broder et al., 2012; Kuhry and Vitt, 1996; Yonebayashi et al., 1994). Degradation of physical properties occurs through subsidence as the open pore structure created by the fibrous, woody material collapses due to oxidation, shrinkage and compression, reducing total porosity and increasing bulk density as more solid material is concentrated per unit volume (Wösten et al., 1997; Quinton and Marsh, 2000). As a consequence of degradation, percolation of water down the peat profile slows, decreasing hydraulic conductivity (Firdaus et al., 2010). Water storage characteristics are also altered by decomposition as the water holding capacity is lowered and water retention increases, with implications for both the water content and gas flux rates within the peatlands (Boelter, 1964).

Knowledge on peat chemical and physical properties, as affected by the stages of land conversion for oil palm cultivation, is necessary to develop effective peatland management, and in the instance of degraded peatlands, restoration plans (Jauhiainen et al., 2008; GEC, Global Environment Centre, 2014), thus conserving valuable ecosystem services. Land-use change in tropical peatlands is commonly discussed from the perspective of carbon emissions, with a very limited literature associated with peatland properties, and even fewer studies associated with multiple stages of conversion. This study determines how peat chemical and physical properties are altered during land conversion to oil palm. To achieve this we tested the following hypothesis: Land-use change of secondary peat swamp forests by drainage, clearance of forest and planting of oil palm, and finally establishment of mature oil palm plantations, which involve lowering of the water table and altered litter inputs, will accelerate peat decomposition and reduce C storage in tropical peatlands. As a consequence of land-use change to oil palm plantation, we predict greater peat humification and loss of carbohydrates and carboxyl compounds relative to recalcitrant aromatic structures reflecting enhanced microbial decomposition in drained surface peat layers. We expect this enhanced decomposition to result in (i) peat subsidence and lower C stocks in mature oil palm plantations compared to secondary forest sites and areas under the initial stages of conversion and (ii) highest shear strength and bulk densities, but the lowest porosity at oil palm sites.

2. Study sites

Prior to gaining reserve status in 1990 (Kumari, 1996), North Selangor Peat Swamp Forest (NSPSF) was a stateland forest, subject to uncontrolled deforestation. As a result forest cover varies in quality and ca. 500 km of drainage ditches originally cut for timber transport remain as a legacy, however, these have filled in over-time and are now only ca. 80 cm deep with no measureable water movements (Evers SE, unpublished data). However, the forest sites chosen for this study had not been targeted for logging in approximately 40 years and as such are in areas of relatively high canopy density (trees >25 m, canopy coverage >80%; GEC, Global Environment Centre, 2014). In addition, drainage schemes implemented for irrigation of Tanjung Karang rice paddies near the coast have further contributed to the alteration of peatland hydrology. As such, water storage and retention in NSPSF has been found to be severely diminished (Rahim and Yusop, 1999). Together, these disturbances have resulted in secondary mixed swamp forests. It is also important to note that some degraded areas of the NSPSF are being restored under a new integrated management plan (GEC, Global Environment Centre, 2014) aiming to restore ecosystem services by raising water tables through drain blocking, fire management and replanting with native tree species. The tropical peat swamp forest sites were chosen in areas with as little anthropogenic impact as possible and away from old drainage ditches. None of the areas used in this study has been affected by fire.

During the early Holocene, the area was likely colonised by extensive mangrove systems, but these diminished after the last Holocene interglacial marine incursion when the fresh water peatland vegetation started to take hold, resulting in the deposition of acidic peat up to 5 m deep, overlaying grey marine clay (Yule and Gomez, 2009). The area receives an average rainfall of over 2000 mm per year, with the driest month in June measuring 76 to 191 mm and the wettest month in November measuring 185 to 414 mm (Sim and Balamurugam, 1990; Yusop, 2002). Average shaded air temperature recorded was 28.5 °C, with an average monthly relative humidity of 77.2% (Hahn-Schilling, 1994).

The study site of NSPSF is situated on a flat coastal plain about 10 km inland on the west coast of Peninsular Malaysia (Fig. 1), (Yule and Gomez, 2009). This tropical ombrotrophic peat swamp covers 73,592 ha and includes 50,106 ha of the Sungai Karang Forest Reserve to the north and 23,486 ha of the Raja Musa Forest Reserve to the south (Ahmed, 2014). The main tree species found in the areas are: *Macaranga pruinosa*, *Campnospermacoriaceum*, *Blumeodendron tokbrai*, *Shorea platycarpa*, *Parartocarpus venenosus*, *Ixora grandiflora*, *Pternandra galeata*, *Crytostachys sp.*, *and Pandanus atrocarpus* (Yule and Gomez, 2009). Four land conversion classes were selected, with five replicate sites for each, to represent the stages involved in the process of conversion (ranging from secondary forest to mature oil palm):

Stage 1. Historically drained secondary forest sites – prior to conversion, secondary peat swamp forests where water tables are close to or at the surface for a large part of the year (Evers SE pers obs; GEC, Global Environment Centre, 2014), maximum water table draw down during drought periods are ca. 50–60 cm below the surface. At the time of sampling water tables were at the surface at all forest sites. The historically drained secondary forest sites are subsequently denoted “forest” sites for simplicity.

Stage 2. Recently deeply drained forest sites – extensive drainage of secondary peat swamp forests where large drainage ditches (2–3 m wide and ca. 2 m deep) have been dug every few hundred meters in order to lower the water table, but trees and understory vegetation have not been removed i.e. the forest structure is comparable to