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Long-term water regime differentiates changes in decomposition and microbial properties in tropical peat soils exposed to the short-term drought

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ABSTRACT

Tropical peatlands function as substantial carbon sinks, but are susceptible to the impact of global climate changes (especially drought) and drainage. The effects of drought and drainage on tropical peatlands have been investigated separately, but the combined effects of these 2 factors have not been examined in depth. To understand how tropical peat soils are decomposed by a short-term drought event differently with drainage history (pristine, intermediate, and drained), we collected peat soils from 3sites with distinct water regimes and performed a 28-day dry incubation. We found that the activities of 5 hydrolase enzymes decreased significantly at all sites, but those of 2 oxidase enzymes increased after the incubation. In conjunction with these alterations in extracellular enzyme activities, peat soil from a high water regime (pristine) released dissolved organic carbon (DOC) with high aromaticity, while that from a low water regime (intermediate and drained) released labile forms of DOC. This implies the initial quality and composition of peat soil, which is caused by the long-term water regime, influence the form of DOC released under drought conditions. Microbial (bacteria, archaea, and fungi) community structures of all sites shifted significantly during the drought incubation, and bacterial and fungal community structures in the soil from the high water regime were distinct even after the drought event, indicating they are more resistant to drastic hydrological changes. Gene copy numbers of bacteria and archaea decreased significantly, but that of fungi in soil with the low water regime increased considerably after the drought incubation. The increased fungal abundance in soils from sites with a low water table could partially explain the larger amount of carbon dioxide released from these soils. Overall, peat soil from sites with low water tables released large amounts of carbon dioxide, methane and dissolved carbon, and the microbial community structure at these sites was more affected by the drought incubation. These results suggest that the lowered water level in tropical peatlands is more vulnerable to drought event and will release more amounts of CO_2, CH_4, and DOC compared to pristine peatlands as a result of differences in enhanced oxidative enzyme activities, and microbial respiration of which varied with the long-term water regime history.

1. Introduction

Tropical peatlands cover only 0.25% of the terrestrial land surface (441,025 km^2), yet they contain 3% of total terrestrial carbon (88.599 Gt) (Page et al., 2011). The disproportionately high carbon content of tropical peat soils is partly due to the slow decomposition rates in anaerobic and acidic soil conditions that inhibit microbial activity. Although high temperatures result in greater rates of microbial soil respiration (Bond-Lamberty and Thomson, 2010; Dillon et al., 2010), peatlands in tropical regions are a net sink for carbon because high temperatures facilitate higher rates of primary productivity than those found in boreal or temperate zones. Carbon sequestration rates in northern peatlands range from 8 to 61 g C m^{-2} yr^{-1} (Roulet, 2000) while those in tropical regions can exceed 80 g C m^{-2} yr^{-1} (Page et al., 2004). However, tropical peatlands are highly impacted by the diminished water inputs resulting from drainage and drought.

Indonesian peatlands, estimated to cover an area of 206,950 km^2, comprise 50% of the global tropical peatland area, and store approximately 57.367 Gt of carbon (Page et al., 2011). An extensive area of this region has been drained and converted to agricultural fields continuously. Hooijer et al. (2010) reported that approximately 47% of the peatland area present in Southeast Asia in 1985 had been drained for plantations and agriculture by 2006.

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In addition to local land use changes, global climate change also affects the water regimes in Indonesia. For example, warm ENSO (El Niño Southern Oscillation) events reduce the precipitation levels in South Asia during the monsoon season (Kumar et al., 1999).

With soil drainage, anaerobic surface peat becomes aerobic, resulting in increased decomposition rates. Microbial activity and aerobic respiration increase as soils become oxygenated and the abundance of inhibitory compounds such as humic substances decreases as phenol oxidase activity increases under aerobic condition (Wetzel, 1992; Freeman et al., 1996; Freeman et al., 2004). As a result, peat can be easily oxidized, releasing a larger amount of dissolved organic carbon (Freeman et al., 2001; Clair et al., 2002) and CO_2 (Freeman et al., 1992; Kasimir-Klemedtsson et al., 1997; Hergoualc'h and Verchot, 2011). In addition, when peat soil is exposed to the atmosphere, it can show greater fluctuations in temperature and higher temperature values because convection in air is greater than in water (Lieffers, 1988; Freeman et al., 1996). As a result, decomposition rate of aged, recalcitrant organic carbon with complex structures that has high activation energy can increase substantially even with a very small increase in temperature (Fierer et al., 2005; Craine et al., 2010). Studies predict that such changes in temperature will intensify carbon loss from these ecosystems (Ise et al., 2008; Dillon et al., 2010).

Such dramatic changes in the soil environment can influence the structure, abundance, and activity of microorganisms, which play a critical role in decomposition of organic matter and greenhouse gas emissions in soil. Changes in water availability can cause considerable shifts in microbial community structure, as these organisms are very sensitive to water and oxygen availability (Drenovsky et al., 2004; Jaatinen et al., 2007, 2008). A drawdown of water in wetland ecosystems enhances extracellular enzyme activities (Freeman et al., 1996), increases microbial biomass (Mäkiranta et al., 2009), and alters trace gas emissions resulting from microbial activities (Regina et al., 1996; Aerts and Ludwig, 1997; Kettunen et al., 1999; Strack et al., 2004; Mäkiranta et al., 2009). Hydrological changes can also release a large amount of phosphorus (Song et al., 2007) and nitrous oxide (Freeman et al., 1992; Regina et al., 1996) by changing microbial activity and composition, indicating that not only carbon cycle but also phosphorus and nitrogen cycles can be modified. In the long-term, a lowered water table can lead to shifts in the composition of vegetation (Laine et al., 1995), which will alter microbial activity and function (Fisk et al., 2003), thus accelerating the changes in the microenvironment.

Because of the significant effects of drainage and drought on a large proportion of accumulated organic carbon in Indonesia, it is critical to predict the response of decomposition rates to these changes in hydrology. To examine this question, 3 study sites were chosen according to their historical water regime: (a) a site with a continuous low water table located approximately 30 m from a drainage ditch; (b) a site with an intermediate, fluctuating water table (edge site); and (c) a site with a constantly high water table, located near the center of a pristine peatland. To examine how peat soils with contrasting antecedent water regimes respond to a drought event, samples from these 3 sites were incubated in dry conditions for 28 days to simulate a severe drought. By analyzing decomposition dynamics (extracellular enzyme activities, and microbial community structure and abundance) and decomposition products including water-soluble carbon and CO_2 and CH_4 during the course of this drought incubation, we aimed to provide an insight into the impact of long-term and short-term hydrological dynamics on decomposition patterns of tropical peat soils.

2. Methods

2.1. Site description

Our study site was located in central Kalimantan, Indonesia (1°53′25″S, 113°32′09″E; altitude, 57 m). Three sites were selected according to their water regime: (1) ditched site (adjacent to a drainage ditch: 1°53′25.74″S, 113°32′09.64″E; altitude, 57 m) with at least a 6-year drainage history. Although no historical records were available for the exact time of ditch construction, the ditch was identified in the satellite image collected in 2004. In addition, there was renovation of the drainage ditch while establishing plantation nearby two years before the sampling, which might have aggravated water level lowering; (2) edge site at the margin of a pristine area with an intermediate water regime (edge: 1°53′26.36″S, 113°31′19.13″E; altitude, 55 m); and (3) undisturbed site located near the center of a pristine peatland (center: 1°52′35.94″S, 113°31′31.24″E; altitude, 57 m). *Combretocarpus rotundatus* (Miq.) Danser and *Cratoxylum glaucum* Korth were dominant vegetation species at the ditch and the edge sites while *Palaquium leiocarpus* Boerl and *Syzygium creaghii* (Ridl.) Merr. & Perry were dominant vegetation at the center site. During the rainy season when the soils were sampled, a low water table (40 cm below the soil surface) was maintained at the ditched site to ensure continuous drainage. The water table at the edge site was about 20 cm below the surface. The center site was fully saturated with an undisturbed, high water table, approximately the same as the soil surface. Water table depth was approximately 20 cm and 15 cm lower during the dry season at low water level (the ditch and the edge sites) and at high water level sites (the center site), respectively. According to the Von Post Scale for classification of peat (Ekono, 1981), surface soils (0–5 cm) from the ditch and edge sites were designated H9 (almost completely decomposed with indistinct plant structure), and soils from the center were designated H4 (weakly decomposed with distinct plant structure). Further information on the sampling sites can be acquired in Shiodera et al. (2012) and Shimada et al. (2001). Triplicates or quadruplicates of peat soil of each site were collected from the surface peat (0–5 cm) under *ca.* 1 cm of litterfall, and transferred to the lab to be stored at 5 °C until analysis. The mean value for bulk density of the sites was 0.143 g $cm^{-3}$and that of organic carbon content was 92.7% (Shimada et al., 2001).

Soils from the ditch and edge sites were regarded as peat from low water regimes, and those from the center site were regarded as peat from a high water regime.

Ten grams of each soil sample was analyzed to characterize *in situ* conditions, and the remaining 10 g of each soil sample was transferred to an individual 600-ml plastic chamber and incubated in the dark for 28 days at 26 °C, which is the average annual temperature of the study region. No water was added during the incubation to simulate a complete drought.

2.2. Soil chemistry analyses

Approximately 3 g of each soil sample was dried at 103 °C for 24 h to measure water content. The dried soil was then converted to ash at 600 °C for 24 h to measure organic carbon content. Water and organic carbon content were described on a percentage basis. Peat soil was suspended in distilled water (soil to water ratio = 1:2) and centrifuged at 900 × *g* for 20 min, after which the pH value was measured with an Orion 3-star (Thermo, USA). To measure dissolved organic carbon (DOC), 5 ml of distilled water was added to 0.5 g of peat soil and filtered through 0.45-μm filter paper (Whatman). A TOC-V CPH (Shimadzu) was used to analyze the DOC concentration, using potassium hydrogen phthalate for a standard