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Deforestation for oil palm alters the fundamental balance of the soil N cycle

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ABSTRACT

Expansion of commercial agriculture in equatorial regions has significant implications for regional nitrogen (N) budgets. Here we investigate changes in N availability and turnover in Southeast Asia following the replacement of tropical forest with oil palm plantations along a chronosequence of oil palm maturity (3-months to 15-year-old stands) and secondary to primary forest succession in Sabah, Malaysian Borneo. Ten sites were sampled during March and April 2012 and rates of gross ammonium (NH_4^+) and nitrate (NO_3^-) production (mineralisation and nitrification) and consumption ($n = 8$), potential denitrification and "anaerobic ammonium oxidation" ("anammox") ($n = 12$) were determined using ^{15}N isotope additions to soil cores and slurries respectively. Gross mineralisation rates (0.05–3.08 g N m^{-2} d^{-1}) remained unchanged in oil palm relative to forests. However, a significant reduction in gross nitrification (0.04–2.31 g N m^{-2} d^{-1}) and an increase in NH_4^+ immobilisation disrupt the pathway to nitrogen gas (N_2) production substantially reducing (by > 90%) rates of denitrification and "anammox" in recently planted oil palm relative to primary forest. Potential nitrous oxide (N_2O) emissions were greater than potential N_2 production and remained unchanged across the chronosequence indicating a potentially increased ratio of N_2O:N_2 emission when soils were first disturbed. These results are an important precursor to studies that could yield improved estimates of regional N turnover and loss in Southeast Asia which will have global implications for N biogeochemical cycling.

1. Introduction

Inputs of reactive N to the terrestrial biosphere have more than doubled over the past century (Gruber and Galloway, 2008; Hietz et al., 2011) and globally, N-fixing crops, chemical fertilisers and fossil fuel combustion have overtaken biological N fixation and lightning as the principal reactive N inputs (Gruber and Galloway, 2008). This has implications that include enhanced greenhouse gas emissions (Park et al., 2012), surface-water eutrophication (Bouwman et al., 2002), soil acidification and changes in biodiversity (Pheonix et al., 2006; Bobbink et al., 2010; Lu et al., 2010). Most global analyses of the N cycle and associated environmental problems draw heavily upon inferences from studies in temperate regions where the majority of research has been undertaken to-date (Pheonix et al., 2006; Bobbink et al., 2010). However, the combination of population increase and extensive land-use change in tropical regions since 1950 is changing the N cycle significantly. Particularly significant in this respect are increases in deforestation, fertiliser use, and combustion of fossil fuels with attendant increases in the input and mobility of reactive N that are affecting regional N deposition in the tropics (Hietz et al., 2011; Sullivan et al., 2014). Of major concern are increased N_2O and NO emissions, produced largely through microbial nitrification and denitrification. However, estimates of soil N turnover and loss through denitrification and N_2 production remain poorly constrained (Groffman, 2012), particularly in tropical regions of Southeast Asia. Understanding the changes in soil N processes associated with the conversion of tropical forest to agriculture is therefore critical in seeking to improve models of tropical N cycling in a region of global importance to N biogeochemical cycling.

Recent rates of deforestation in Southeast Asia have been higher than in any other tropical region (Achard et al., 2002; Miettinen et al., 2011). The expansion of oil palm (*Elaeis guineensis*) plantations over ~17 million ha of the lowland tropics is an important

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driver of this deforestation resulting in detrimental changes in above-ground biodiversity (Fitzherbert et al., 2008), and greater air pollution from increased N and carbon emissions (Hewitt et al., 2009; Carlson et al., 2013). Rates of microbial N cycling are also likely to be altered by the physical and chemical changes to soil that accompany oil palm development.

Initially, N is lost through forest clearance, burning and land preparation and N mobility increases post-disturbance as soils with little vegetation cover experience leaching and erosion (Malmer, 1996; Yashiro et al., 2008; Nykvist and Sim, 2009). In situations where they are able to recover naturally, forests appear able to reduce N-deficits through increased N-retention and reduced nitrification and denitrification (Robertson and Tiedje, 1988; Keller and Reiners, 1994; Templer et al., 2005; Davidson et al., 2007). However, as forest succession proceeds, N status and cycling rates increase, and with them, the potential for N loss through N gas production (Davidson et al., 2007). If forests are converted to agricultural use, N imbalances resulting from *inter alia*, harvesting of crops or additions of inorganic fertilisers, complicate attempts to predict N loss and retention pathways (Silver et al., 2005; Verchot et al., 2006; Corre et al., 2006; Burton et al., 2007).

Only one study to our knowledge has compared rates of gross N cycling in oil palm plantations with adjacent forests. In Sumatra, Allen et al. (2015) found that converting forests to oil palm plantations decreased gross mineralisation rates in clay Acrisols but not in loam Acrisols. Lower net N transformation rates have also been observed in plantations relative to forest soils (Ishizuka et al., 2005; Templer et al., 2005). Net rates are the consequence of both production and consumption processes and, as a result, may be a poor measure of gross N transformation. Therefore, gross rates are a better indicator of total N turnover, particularly in soils where N consumption is high. Moreover, higher N_2O emissions, and potential denitrification, have been observed from oil palm soils relative to native forests (Melling et al., 2007; Yashiro et al., 2007; Hewitt et al., 2009; Kimura et al., 2012). However, this increase in N-gas emission is inconsistent with the decline in N cycling which is often observed following forest conversion to agriculture in tropical soils (Neill et al., 1999; Silver et al., 2005; Templer et al., 2005; Verchot et al., 2006). Our study addresses this inconsistency in oil palm plantations for the first time, by investigating how land-use change impacts soil N cycling in Sabah, Malaysian Borneo. The aim of the paper is to test whether conversion from forest to oil palm alters the rate and balance of N cycling processes. Ultimately, however, changes in microbial processing affect N availability and emissions of N_2O, thus our results provide insight into the N status and sustainability of oil palm agriculture.

In this paper we investigate rates of gross mineralisation, gross nitrification and the potential for N loss through N_2 and N_2O production using a space-for-time substitution across a chronosequence of forest degradation and plantation maturity. Specifically, we examine trends in N cycling across this chronosequence to test the hypothesis that land-use change from forest to plantation agriculture decreases rates of soil N turnover. In undertaking this study we anticipated that as plantations mature, N cycling will follow a trajectory of recovery through plantation maturity comparable to that observed in studies of secondary forest succession (Davidson et al., 2007; Amazonas et al., 2011) with increasing N accumulation, turnover and loss with time since disturbance.

2. Materials and methods

2.1. Site description and sampling methods

This study was conducted in the Kinabatangan lowlands of Sabah State in Malaysian Borneo (Fig. 1). The climate is humid tropical with a mean annual (2008–2013) temperature of 27.4 °C and rainfall typically of 2500–3500 mm. The wettest months of the year (December to February) are commonly referred to as the "wet season" but monthly rainfall rarely falls below 100 mm. The Kinabatangan administrative district covers 17,800 km^2 and lowland areas (6630 km^2) have experienced rapid land-use change during the last 50 years. The predominant vegetation was formerly dipterocarp forest, although primary forest cover declined by 60–90% during the timber boom between 1975 and 1992 (Vincent and Rozali, 2005). During the same period, secondary forest and oil palm plantations increased commensurately, and oil palm plantations now occupy 2994 km^2 (~45%) of the lowland region where our study sites are located (Latip et al., 2015).

Soil samples were collected at the end of the wet season in March and April 2012 where monthly rainfall was ~280 mm, compared to an annual total of 3134 mm. Ten sites, each of 3–5 ha, were sampled within a 1300 km^2 area representing a chronosequence of forest to oil palm plantation transition. In each plot, 12 subplots of 3 m^2 were selected, within which five cores were randomly extracted for determination of edaphic properties. Minimum distance between subplots was 30 m. Cores were extracted using a 4 cm diameter pipe to 10 cm depth and were homogenised after removal of roots.

Plantations in our study area were established on land that had been degraded by forest clearance and biomass burning. Our chronosequence reflects this by showing the transition from primary, through disturbed forest and oil palm development. We sampled one primary forest (PF) and one early-successional forest (ES) clear cut 16 years prior to sampling (Fig. 1). Two secondary forests at intermediate successional stages (MS1 and MS2) were also sampled (see Supplementary Information for detailed site descriptions). The oil palm plantations comprised stands aged 3 months (3M) and 3, 5, 6, 8, and 15 years (3Y–15Y). Typically, oil palm has an economic life of 25–30 years after which palms are felled and replanted. Our 3M and 8Y sites were second generation plantations, whilst the remainder were first generation. For the 3M plantation, this transition was significant as 15 months prior to sampling, the old palms were uprooted, chipped and turned back into the soil with substantial physical disturbance. Management and planting practices varied between smallholdings (3Y and 15Y) and commercial plantations (3M, 5Y, 6Y and 8Y): 3Y was a recently converted smallholding whereas the palms in 5Y had been planted on mechanically-raised mounds to counter seedling mortalities associated with the high water table. Fertiliser application varied between smallholdings and commercial plantations: the former received sporadic applications of inorganic N (principally urea, $(NH_4^+)_2SO_4$ or NH_4NO_3) while the latter received bi-annual treatment. Typical fertiliser additions to mature oil palms in this region range from 280 to 570 kg N-based fertiliser ha^{-1} $year^{-1}$, with smallholdings falling at the lower end of this range and commercial estates in the higher range. Fertiliser additions also vary with plantation maturity. For example, the newly planted palms in 3M received 70 kg of $(NH_4)_2SO_4$ ha^{-1} $year^{-1}$ whilst adjacent, mature palms within the same plantation received 570 kg of $(NH_4)_2SO_4$ ha^{-1} $year^{-1}$ during 2012–2013. We minimised differences in fertilisation regime by sampling at the end of the wet season when fertiliser-N had not been applied to any of the soils at least three, and up to six, months prior to sampling.

In adopting a chronosequence approach to investigate changes to soil N cycling, we assumed that soil properties were similar prior to conversion. In validating this assumption, we employed several lines of investigation prior to our study. Firstly, we identified suitable study sites that were of similar elevation and slope and on comparable soil associations from regional soil maps. Whilst all sites were at low elevation (<100 m a.s.l.) and slope, they differed in