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Improved sampling methods document decline in soil organic carbon stocks and concentrations of permanganate oxidizable carbon after transition from swidden to oil palm cultivation

Thilde Bech Bruun[a,*], Kelvin Egay[b,1], Ole Mertz[c,2], Jakob Magid[a,3]

[a] Department of Plant and Environmental Sciences, University of Copenhagen, 1871 Frederiksberg, Denmark
[b] Faculty of Social Sciences, Universiti Malaysia Sarawak, 94300 Kota Samarahan, Sarawak, Malaysia
[c] Department of Geosciences and Natural Resource Management, Øster Voldgade 10, 1350 København K, Denmark

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ABSTRACT

Oil palm plantations are spreading rapidly throughout Southeast Asia and in some countries, they are promoted as carbon sinks compared to the swidden cultivation systems that they often replace. However, little is known about the impacts of this land use change on soil organic carbon (SOC) stocks or soil quality. This study uses resampling of archived soil samples to investigate the sensitivity of permanganate oxidizable carbon (Pox-C) concentration to a change in land use from swidden cultivation to small-scale oil palm plantation on an Ultisol in Sarawak, Malaysia. Furthermore, the results of two different methods of calculating SOC stocks are compared – namely the fixed depth approach and the equivalent soil mass approach, which is sensitive to changes in soil bulk density. Results show that using a method that is sensitive to changes in bulk density is important as the soil bulk density increases upon establishment of oil palm. Thus, topsoil carbon stocks significantly decreased 3–8 years after oil palm establishment as measured by the equivalent soil mass approach, but only marginally and insignificantly decreased according to the fixed depth approach. After 15 years of oil palm, carbon stocks were 40% lower according to the fixed depth approach but 50% lower when using the equivalent soil mass approach. Importantly, the resampling of geo-referenced soil gives more consistent data, and lends credibility to the observation of large reductions in SOC stocks. The concentration of Pox-C in the 0–10 cm layer declines exponentially as oil palm plantations age and can serve as an indicator of change in the soil ecosystem brought about by the investigated land use transition. Pox-C is not more sensitive to this change than standard SOC analyses, but it may serve as an inexpensive, fast and field-suitable means of estimating the SOC status of different land use systems.

1. Introduction

The last few decades have seen a rapid expansion of oil palm cultivation throughout Southeast Asia, particularly in Malaysian and Indonesian Borneo (Cramb, 2007). In the sloping uplands, oil palm plantations have mainly replaced swidden cultivation, which was once the dominant land use system in these areas. Most Asian governments have condemned swidden cultivation, as they associate the system with low productivity, deforestation, soil degradation and CO_2 emissions, despite this perception being increasingly challenged by scientists (Fox, 2000; Padoch et al., 2007; Mertz et al., 2009; Ziegler et al., 2011). In contrast, governments all over Southeast Asia, and particularly in Sarawak, are promoting oil palm plantations. The Sarawak government target of bringing one million hectares under oil palm plantation was reached in 2010 (Cramb, 2011) and targets to reach two million hectares by 2020 have since been set (Davidson, 2012).

The transition in land use from swidden cultivation to oil palm plantations has considerable impacts on both social and natural environments, yet most research to date has focused on the socio-economic consequences (Ngidang, 2002; Hansen, 2005; Hansen and Mertz, 2006; McCarthy and Cramb, 2009), while evidence of the highly debated environmental effects of widespread oil palm cultivation remains sparse (Bruun et al., 2009; Ziegler et al., 2012). Results of the few published studies of the effects of oil palm on soil quality show somewhat conflicting results. Substantial losses of soil organic matter after conversion to oil palm have been documented by some authors (Aweto, 1995; Sommer et al., 2000), and one study reported irreversible changes to topsoil quality following

* Corresponding author. Tel.: +45 35333412.
E-mail address: thbb@life.ku.dk (T.B. Bruun).
[1] +60 82581962.
[2] +45 35322529.
[3] +45 353-33491.

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the establishment of an oil palm plantation in Malaysia (Hamdan et al., 2000). While these studies point towards serious problems with the long-term sustainability of oil palm cultivation, Tanaka et al. (2009), using a space-for-time substitution approach, found that despite initial losses of soil organic carbon (SOC) and deterioration of physical soil properties following establishment of oil palm plantations in Sarawak, soil quality recovered over time.

As geo-referenced soil archives are rarely available in a tropical context, most studies of the effects of land use changes on soil properties and SOC stocks apply the space-for-time substitution method, in which soil samples are collected from areas under the land use type that is being converted and from adjacent areas under the succeeding land use type. This approach assumes that the soil properties of the two land use types were once the same, and that differences in soil properties can therefore be ascribed to land use. This premise has recently been countered by suggestions that farmers purposefully select soils with the highest quality and highest SOC contents for the most intensive agriculture or high-investment perennial crops, and use the poorer soils more extensively, for example with longer fallow periods or as forests (Mertz et al., 2008; Aumtong et al., 2009; Bruun et al., 2009). Results obtained using the space-for-time substitution sampling method may thus be confounded if the criteria for farmers' land use decisions are not carefully assessed and controlled for during site selection. In upland areas, the potential error is presumably increased by the fact that spatial heterogeneity (e.g. in terms of soil texture, clay mineralogy and topography) is high compared to lowlands (Bruun et al., 2006, 2010).

Changes in the concentration of total SOC are often used to evaluate the long-term effects of land use changes on soil quality. However, this parameter is unlikely to be particularly sensitive to changes in land use as it changes relatively slowly, and its generally high background levels make changes difficult to detect (Blair et al., 1995). Numerous attempts have therefore been made to identify sub-pools of SOC that can serve as more sensitive indicators of land-use induced changes in soil quality and total SOC stock. Fractions of SOC that have been widely used as early indicators of management-induced changes in soil quality and total SOC stock include: microbial biomass (MBC) (Powlson et al., 1987; Carter et al., 1999), particulate organic matter (POM) (Cambardella and Elliot, 1992; Wander and Bidart, 2000; Bruun et al., 2013), light fractions (Magid et al., 1997, 2010), and light fractions in combination with aggregates (Six et al., 1999, 2000). The sensitivity of these fractions to changes in land use and management is well proven, as is their positive relation to soil function (Wander, 2004; Grandy and Robertson, 2007). However, determination of MBC and POM is time-consuming and requires complex laboratory manipulation, and methodological variation can make comparisons of POM and MBC difficult across studies (Culman et al., 2012). The concentration of permanganate oxidizable carbon (Pox-C) in the topsoil has been suggested as a relatively easily measurable indicator of land use induced changes in soil quality and SOC stocks, and the method has shown promising results with temperate soils. Several studies have found Pox-C concentration to be a more sensitive indicator of the effects of tillage treatments than total SOC content, and strong correlations between Pox-C and several commonly used soil quality indicators (i.e., MBC, POM, basal respiration and soluble carbohydrate C) have also been documented (Weil et al., 2003; Melero et al., 2009a,b; Culman et al., 2012). Studies of Pox-C in tropical soils, conducted by Moody et al. (1997) and Bell et al. (1998), documented a positive relationship between Pox-C and physical (aggregate stability) and chemical (ECEC) soil parameters in Australian Oxisols, and Aumtong et al. (2009) found concentrations of Pox-C in Thai Ultisols to be related to land use type. Nevertheless, the vast majority of studies that apply the Pox-C method have been carried out in temperate regions; hence experience of using the method in tropical soils remains limited, as does evidence from perennial cropping systems and land use systems that do not involve tillage.

The objectives of this study are therefore: (I) to investigate the potential of the Pox-C method to capture the effects of the transition from swidden cultivation to small-scale oil palm plantations on a typical soil type of the humid tropics (Ultisol) and (II) to assess the effects of oil palm plantations on SOC stocks using both the fixed-depth approach and the equivalent soil mass approach. To overcome the critical assumptions associated with the space-for-time substitution method, the study uses a resampling approach in which an archive of geo-referenced soil samples from swidden fields collected in 2002 are used as a baseline, and sites where a land use change to oil palm has occurred are revisited and resampled in 2011.

2. Materials and methods

2.1. Study area

The study was carried out in the state of Sarawak on Malaysian Borneo. The study area was confined to the agricultural areas of the two Iban longhouse communities, Rumah Muyang (UTM zone 49 N; 415722 E; 807165 N) and Rumah Ulat (UTM zone 49 N; 417636 E; 804849 N), located in the Niah sub-district of Miri division (Fig. 1). The area has a humid tropical climate with an average annual temperature of 27 °C and an average annual precipitation of around 2710 mm (meteorological data from Miri Airport from the period 1971–2000). The natural vegetation of the study area is Mixed Dipterocarp Lowland Rainforest, and the landscape is characterized by undulating hills with elevations around 100 m above sea level. The soils of the study area are developed on argillaceous sedimentary rocks and are highly weathered and acidic (Bruun et al., 2006). The characteristics of the investigated soils resemble the Tropudults of the USDA Soil Taxonomy. The traditional land use of the area is swidden cultivation of upland rice using fallow periods of between 5 and 40 years, as well as pepper and rubber. The environmental and socioeconomic aspects of this land use system were intensively investigated from 2001 to 2003 (Bruun et al., 2006; Hansen and Mertz, 2006; Nielsen et al., 2006; de Neergaard et al., 2008; Mertz et al., 2008). A 2011 study documents that since 2002 the area has undergone substantial conversion of traditional land use systems to small-scale oil palm

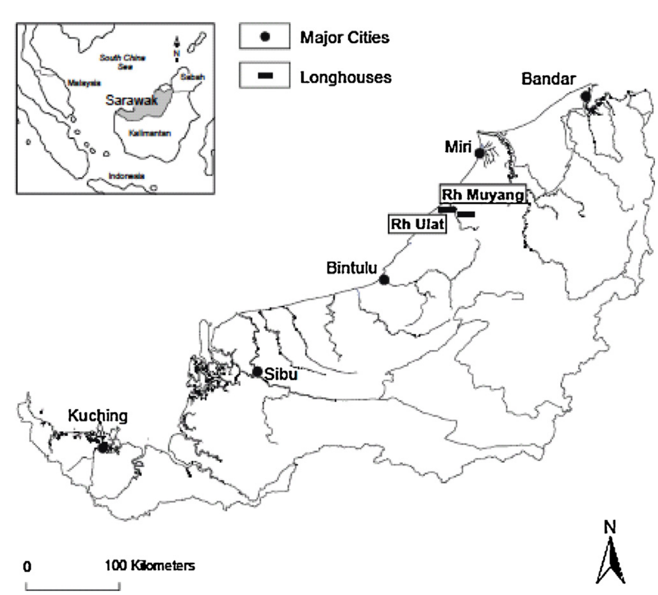

Fig. 1. Map of Sarawak with location of the longhouses studied.