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Land use and fertilisation affect priming in tropical andosols

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ABSTRACT

Input of available carbon and/or mineral fertilisation can accelerate mineralisation of soil organic matter i.e. priming effect. However, studies to priming effects in andic soils are absent despite their unique physicochemical and biological properties. Nutrients and ^{14}C labelled glucose were added to Andosols of Mt. Kilimanjaro from six ecosystems: (1) savannah (2) maize fields (3) lower montane forest (4) coffee plantation (5) grasslands and (6) *Chagga* homegardens. Carbon-dioxide production was measured for 60 days. Maximal and minimal mineralisation rates immediately after glucose additions were observed in lower montane forest with N + P (9.1% ± 0.83 d^{-1}) and in savannah with N (0.9% ± 0.17 d^{-1}), respectively. Land use significantly influenced glucose induced priming effect measured as additional CO_2 compared to unfertilised soil. Variations of the priming effect in land use without fertilisation are attributed to differences in microbial biomass content. Depending on land use, nutrient addition increased or decreased glucose induced priming effect. Maximal and minimal priming effect were observed in grassland soils (0.171 mg C-CO_2 g^{-1} soil) with P and in soils under maize fields (0.009 mg C-CO_2 g^{-1}) fertilized with N, respectively. Microorganisms in *Chagga* homegarden soils incorporated the highest glucose percentage (6.47% ± 1.16), which was 3 times higher compared to grassland soils (2.18% ± 0.39). 50-60% of the ^{14}C input was retained in bulk soil. Land use and fertilisation (N and P) affected priming in Andosols. Andosols occurring at Mt. Kilimanjaro, especially those under the *Chagga* homegardens shows great potential for soil C sequestration.

1. Introduction

Soil organic matter (SOM) constitutes the largest proportion of organic C on earth's surface and plays a critical role in controlling greenhouse gases emissions, C sequestration and soil fertility [26]. Maintaining an adequate level of SOM should be the guiding principle to ensure ecosystem functionality and sustainable soil fertility. This is especially true and significant in environments where highly weathered and nutrient poor soils are often managed with few external inputs. Plant residues inputs provide the primary raw materials for SOM formation. However, release of organic substances by living plants in soil e.g. root exudates and litter can accelerate the mineralisation of native SOM by inducing fast C turnover in the vicinity of the roots [41]. This phenomenon is known as “priming effect” (PE), [23].

Priming effects are strong short-term changes in the turnover of SOM caused by relatively moderate treatments of the soil e.g. fertilisation and addition of fresh organic C [7]. Addition of easily available substances to soil provides C and energy sources to soil microorganisms [33]. Previous studies conducted in African countries (e.g. in Niger and Côte d’Ivoire) have reported 12-16% and 32% increase in native organic C mineralisation after organic C additions in forest and savannah soils respectively [13]. Under natural conditions [9], demonstrated that plant roots can increase mineralisation of native SOM by 383% above the respiration in control soil without plants. This suggests that energy-rich rhizodeposits can substantially increase SOM decomposition rate (Xiao et al., 2015; [14,27]. Accelerated SOM mineralisation can be attributed to stimulation of microbial activities in response to altered amounts of available C (Perveen et al., 2014; [4].

Soil microbial biomass (SMB) is an important component for SOM formation and regulates the cycling of organics and nutrients. Nutrient ratios in the refractory SOM are similar to those of soil microorganisms. This means that a large proportion of the SOM pool originates from microbial detritus, rather than directly from recalcitrant plant material [26]. The need to study PE in tropical soils is justified by the

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unsatisfactory knowledge of C and N transformations related to priming [36]. This is particularly true for African soils characterised low soil fertility, notably limitations in N and P, which has been recognised as a major biochemical constraint limiting their productivity. Tropical soils in Africa are known to be poor in nutrients and mainly rely on the recycling of nutrients from SOM to maintain their fertility. This has led to an increase in anthropogenic nutrient inputs in tropical ecosystems.

Consequently, there are fundamental questions about the role of nutrients on native SOM biodegradation. Mineralisation of SOM varies widely due to differences in availability of N and P to support microbial communities and processes. Depending on soil type, effects of nutrient additions on the microbial mineralisation of SOM are highly variable [11]. For example, fertilisation with N, P and N + P in P-poor lowland tropical forest soils in Costa Rica increased CO_2 production 56, 37 and 49% respectively [10]. Moreover, very few studies have been conducted to investigate PE across diverse land use systems with different land use history in Africa. For these reasons, we used the advantages of the elevation and climate gradient of Mt. Kilimanjaro to investigate PE in six natural and anthropogenically modified ecosystems well represented across East Africa.

Microbial processes remain a key regulator of nutrient cycles and respond to nutrient additions in tropical soils. However, studies to the impact of nutrient additions on accelerated SOM mineralisation i.e. PE and microbial biomass in tropical Andosols are absent. The main objective of this study was to analyse the effects of N and P additions on the short-term changes in SOM turnover triggered by addition of low molecular weight C input. We simulated the input of easily available C by adding ^{14}C labelled glucose in soil as a primer. This study focused on two hypotheses: (1) glucose and fertilisation induced PE in P-limited Andosols at Mt. Kilimanjaro region depend on land use and elevation; and (2) the magnitude of PE will be influenced by changes in microbial biomass.

2. Materials and methods

2.1. Study area

Mt. Kilimanjaro is the highest mountain in Africa (5892 m) [1] and is situated 300 km south of the equator in Tanzania on the border to Kenya between 2°45′ and 3°25′ S and 37°00′ and 37°43′ E [17]. Diverse climatic differences at Mt. Kilimanjaro create a high diversity of ecosystems [21] and vegetation zonation [16,44]. Vegetation in Mt. Kilimanjaro is described in detail by [16]. Andosols are the most dominant soils [44]. Rainfall pattern is seasonal and varies greatly with altitude. The main rainy season lasts from March to May and the short rains from November to December [1]. Southern slopes at 700 m above sea level (a.s.l.) receive an annual rainfall of 800–900 mm and slopes at 1500 m a.s.l. Receive 1500-2000 mm. The forest belt lies between 2000 and 2300 m a.s.l [17]. Mean annual temperature varies between 10 and 21 °C [31].

2.2. Soil sampling design, preparation and description of study sites

Soils from six land use systems at Mt. Kilimanjaro, i.e. savannah, lower montane forest, grassland, *Chagga* homegarden, maize fields and coffee plantations (Table 1) were sampled at the upper 0-20 cm layer using a soil auger (2 cm diameter x 60 cm depth). These ecosystems are located at different elevation (Fig. 1) and represent the most common land use systems in East Africa [29,31,38]. Sampled depth corresponds to Ah or Ap horizons. Two experimental plots of 50 m × 50 m approximately 30 km apart representing each ecosystem were sampled. The two sites chosen per land use system were fair representations of the land use type in the region. Soil samples were taken in four corners and at the centre of each plot, giving a total of five positions per sampling. To obtain composite samples per position, four soil augers were taken per sampling position. This led to a total of five samples per plot and 10 samples (n) per land use system. We used a simple randomization method to select six out of the 10 samples to use in this study.

Human population pressure at Mt. Kilimanjaro has strongly influenced ecosystems as a result of increased demand of agricultural land, timber, energy sources, tourism activities [31]. Additionally, due to increasingly drier climate, rainfall has decreased by about 30% in recent years. Consequently, under higher human impact, fires have played an increasingly destructive role at Mt. Kilimanjaro region during the last 100 years, particularly over the last three decades [16]. Due to high demand for agricultural land and livestock feed lower montane forest has been converted to coffee and grasslands while savannah ecosystems have been converted to maize plantations. Maize fields and coffee plantations are characterised by mechanisation, organic and inorganic fertilisation and heavy use of pesticides for improved yields and pest control. The traditional *Chagga* homegardens developed through anthropogenic influence on lower montane forest have been described as a sustainable land use system model in the region and has evolved over five centuries. However, the system has remained unchanged over the last decades [38].

Visible plant debris and roots were removed using tweezers and the soil sieved through a 2.0 mm mesh screen. Soil samples were stored and maintained field moist at 4-6 °C during transportation and prior to their use in the incubation experiment and analysis in Göttingen, Germany. Prior to the start of the incubation, soil samples were pre-incubated for 10 days. This is a standard procedure to allow microbial activity to resume.

2.3. Treatments

There were five treatments: i) control soil, ii) soil + glucose, iii) soil + glucose + N, iv) soil + glucose + P and v) soil + glucose + N + P. N in the form of KNO_3 (1.29 mg ml $^{-1}$) and P as KH_2PO_4 (0.5 mg ml $^{-1}$) were added at the end of the pre-incubation period (10 days). ^{14}C labelled glucose (5 mg per sample) was added 10 days after the addition of the nutrient solutions. Nutrients and glucose were added uniformly in 1 ml aqueous solution to 20 g of soil. Each treatment had six replicates. Soil was maintained at 50% water holding capacity (WHC) using distilled water throughout the experiment.

2.4. Incubation and ^{14}C glucose labelling

Uniformly labelled ^{14}C glucose (activity of 2.00 kBq) was added to the soil as aqueous solution. 1.5 ml of 1.0 M sodium hydroxide (NaOH) in small vials were placed in the incubation vessels to trap CO_2 respired during the incubation period. The vessels were then closed air-tight and incubated in a darkened chamber for 60 days at an average temperature of 20 °C. Vials with NaOH solution containing the absorbed CO_2 were periodically removed and replaced by new vials with 1.5 ml aliquot of 1.0 M NaOH. Traps were changed 1, 3, 7, 11, 14, 20, 26, 32, 42, 50 and 60 days after labelled glucose addition. Four reference vessels containing only the vials with NaOH (without soil) accounted for the very small amount of CO_2 trapped from the air enclosed inside the vessels.

2.5. Chemical analyses

Microbial biomass was determined at 0, 30 and 60 days using the chloroform fumigation-extraction method [39]. Briefly, 4 g of fumigated and unfumigated field moist soil samples were extracted with 0.05 M K_2SO_4 at 1:4 ratio. 10-fold diluted K_2SO_4 solution allows the use of 'multi N/C 2100' (Analytik Jena, Jena) without dilution for C and N determination. C content in K_2SO_4 extracts from unfumigated soil samples was accepted as DOC [3]. Since not all the microbial C and N was extracted by K_2SO_4, k factors of 0.45, 0.54 [20] were used to convert microbial C and N extracted into MBC and MBN respectively.

CO_2 trapped in 1.0 M NaOH solution was precipitated with 0.5 M