



Phosphorus cycling within soil aggregate fractions of a highly weathered tropical soil: A conceptual model



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ABSTRACT

Effective use of soil phosphorus (P) for crop production requires an understanding of how P pools are stabilized and cycled within soil aggregates, rather than assuming that P dynamics, particularly organic P, closely follow those of C. The main goal of this study was to compare C and N cycling with P dynamics in soil aggregate fractions under two distinct crop species, maize (*Zea mays*) and pigeon pea (*Cajanus cajan*) in a highly-weathered Lixisol. We found that while C and N follow an open cycle, whereby C and N are mineralized from microaggregates during macroaggregate turnover and partially exit the soil system as gas and leachate, P has a relatively closed cycle, where most of the mineralized and solubilized P from microaggregates is lost from the plant-available pool via sorption to the unaggregated silt and clay-sized particles (< 53 μm). While the above postulated P cycling mechanisms were the same for maize and pigeon pea, P loss from microaggregates and subsequent enrichment of the silt and clay particles was significantly higher in soils under maize compared to pigeon pea (320 and 331 mg P kg⁻¹ lost from occluded microaggregates and gained by free silt and clay particles, respectively, compared to 129 and 97 mg P kg⁻¹ under pigeon pea). This is attributed to the significantly increased soil aggregation under pigeon pea, which led to greater accumulation of P, particularly organic P, in the free microaggregates (77 mg P kg⁻¹ compared to 29 mg P kg⁻¹) and slower rates of macroaggregate turnover. We conclude that increasing soil aggregation can substantially reduce organic P losses from aggregate occluded fractions and its subsequent sorption as inorganic P to silt and clay particles. Thus, P cycling can be improved in tropical cropping systems on highly-weathered soils by introducing crop species that enhance the occlusion of organic P into aggregates.

1. Introduction

Phosphorus (P) is an essential crop macronutrient and soils contain between 200 and 800 mg P kg⁻¹ soil (Tiessen, 2008), but less than 0.1% of this total P is in a form available for plant uptake (Fardeau, 1996; Raghothama, 2005). In tropical soils, dominated by 1:1 clay minerals, this can be even less due to sorption of available P to aluminum (Al) and iron (Fe) oxides, and often limits crop production in low input agricultural systems (Tiessen, 2008). While this issue is generally overcome by the use of P fertilizers, these can often be difficult to access in some countries, and may have significant negative ecological implications in other countries (Raghothama, 2005).

To reduce dependency on P fertilizers, innovative cropping systems that can more efficiently use soil P are under development. These strategies include intercropping cereal crops with legume species

capable of mining sparingly soluble soil P reserves through root exudates such as phosphatases and organic acids (Li et al., 2007; Hinsinger et al., 2011). Although the mechanisms involved remain largely unstudied, there is convincing evidence that at least one tropical legume species, pigeon pea (*Cajanus cajan*) can mobilize P (Ae et al., 1990), and can be incorporated into African agricultural settings across broad areas of southern Africa (Snapp et al., 2010). There have also been calls for future initiatives that might include breeding and selecting for crop root structures designed to increase P foraging or managing interactions between crops and arbuscular mycorrhizal fungi and other microbial inoculants which have been shown to increase P acquisition by the plant (Richardson et al., 2011). This effort is particularly needed in developing countries, where the population growth and demand for increased food production is highest, and the economic stability and accessibility to fertilizers is lowest (Childers et al., 2011). However, one

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of the first steps to effectively utilize soil P for crop production is to understand how P pools are stabilized and cycled within soil aggregates, as this is a key driver of nutrient storage and availability to plants (Six et al., 2004).

While the study of C and N cycling within soil aggregates has a long history of advancement, and much information has been gathered regarding the effect of different crop management systems on N storage, soil organic matter (SOM) transformations and stabilization, and greenhouse gas emissions (Six and Paustian, 2014), the effect of soil aggregation on P dynamics has been the subject of few studies. Carbon and N dynamics are intimately linked with P availability, through processes that include N fixation, C sequestration, and adenosine triphosphate (ATP) for energy transfer reactions (Tiessen, 2008). Thus, this knowledge gap has limited our understanding of key processes at the soil structural level. Although studies of aggregate fractionation are increasingly incorporating P measurements (Wang et al., 2001; Fonte et al., 2014; Nesper et al., 2015), no major trends have yet emerged to either link or make a distinction between C, N and P cycling at the aggregate level, which could aid in our understanding of the mechanisms controlling P cycling in the soil-plant system.

The main goal of this study was to investigate the links between C and N cycling with P dynamics by comparing aggregation as well as C, N and P pools in free and occluded soil aggregate fractions between soils of two distinct crop species, maize (*Zea mays*) and pigeon pea (*Cajanus cajan*). We then present potential impacts these differences could have on P availability in highly-weathered tropical soils, specifically highlighting a possible mechanism through which pigeon pea is associated with improved P-use efficiency and reduced P sorption to soil minerals. Integrating the results of this study as well as previous studies of C and N cycling we then developed a novel perspective of P stabilization and turnover within soil aggregates, and discuss how this may influence P accumulation and availability over time.

2. Materials and methods

2.1. Soil aggregate fractionation

The soils used in this experiment were collected from the top 10 cm of an unfertilized maize field in Linthipe, Malawi (14° 10' 0" South, 34° 10' 0" East). The soil is a Haplic Lixisol (51% sand, 32% silt, and 17% clay), which is generally characterized as a highly-weathered soil with a low cation exchange capacity, but high base saturation (World Reference Base, 2015). It is a weakly acidic soil with a pH of 5.9 and water-holding capacity of 0.54 g H₂O g⁻¹ soil. The pre-planting soil contained 25.8 g kg⁻¹ total C, 1.4 g kg⁻¹ total N, and 728 mg kg⁻¹ total P. The organic and inorganic NaOH-EDTA extractable P were 127 mg P kg⁻¹ and 158 mg P kg⁻¹, respectively. This soil was used in a maize-pigeon pea intercropping greenhouse trial described previously (Garland et al., 2016). Briefly, unfertilized maize and pigeon pea plants were grown from seed in 100 dm³ pots under controlled greenhouse conditions until the maize reached maturity, 138 days after germination. The treatments compared in this study were from the sole maize and sole pigeon pea treatments of Garland et al. (2016). These treatments were chosen in order to compare trends in C, N, and P cycling throughout soil aggregate fractions of the different plant species, where soils under pigeon pea were shown to be significantly more aggregated than under maize (Garland et al., 2017).

Following plant harvest, the field-moist soils were physically fractionated using a modified wet-sieving fractionation scheme (Garland et al., 2017) based on the method developed by Elliott (1986) and Six et al. (2000). Briefly, 90 g of field moist soil was fractionated into three different size fractions: macroaggregates (250–2000 μm), microaggregates (53–250 μm), and silt and clay fraction (< 53 μm) by sieving for 2 min at each decreasing sieve size after removal of large (> 2000 μm) iron concretions using a microaggregate isolator, which gently removed the large coarse particles without significantly

impacting the soil aggregate fractions (Garland et al., 2017). The sample remaining on top of each sieve size was placed into pre-weighed pans by rinsing with deionized water and then dried at 60 °C. After correcting for aggregate-sized sand particles within each aggregate fraction (Six et al., 1998; Garland et al., 2016, 2017), the total soil recovered in each fraction was then used to determine the percentage of each aggregate size class (referred to throughout as free aggregates).

The macroaggregates were then further fractionated using a microaggregate isolator into coarse particulate organic matter (cPOM) (250–2000 μm), occluded microaggregates (53–250 μm), and occluded silt and clay particles (< 53 μm) using the method developed by Six et al. (2000). Briefly, 5 g of macroaggregates and 40 glass beads (6 mm diameter) were placed in the microaggregates isolator fitted with a 250 μm sieve. Deionized water was slowly added to the soil through a 10 mm polyethylene tube connected to the top of the cylinder shaken reciprocally at 165 Hz. As the macroaggregates were broken, soil particles smaller than 250 μm were immediately transported to a 53 μm sieve via the flowing water through another polyethylene tube at the bottom. The fraction remaining on the 250 μm sieve was considered coarse particulate organic matter. The soils on the 53 μm sieve were then wet-sieved as described above, with all particles remaining on the 53 μm sieve after fractionation considered occluded microaggregates, and those that went through considered occluded silt and clay particles.

All free aggregates and fractions occluded within the macroaggregates (referred to throughout as occluded fractions) were dried at 60 °C and finely ground for further analysis. The free aggregates and occluded fractions were analyzed on a concentration basis (mg nutrient kg⁻¹ aggregate fraction), which was calculated on a non-sand corrected basis since previous results showed significant C, N, and P concentrations within this sand fraction (Garland et al., 2017). However, aggregation of the occluded fractions, as well as the percentage of microaggregates within macroaggregates, were compared on an aggregate-sized sand corrected basis, using the relative proportions of aggregate-sized sand in the microaggregate, as well as the proportion of cPOM (> 250 μm) in the macroaggregate, as described by Six et al. (2000).

2.2. Soil analyses

The total C, N, and P as well as the organic and inorganic NaOH-EDTA extractable P were measured on bulk soils as well as free aggregates and occluded fractions of each treatment. We chose to focus on the organic and inorganic NaOH-EDTA extractable soil P pools because, although they are not considered directly plant-available, their turnover in the soil-plant system over time significantly contributes to the replenishment of the plant-available pool (Cross and Schlesinger, 1995; Turner, 2008). Total C and N were measured by dry combustion (CHN628 Series Leco Elemental Determinator). Total P was measured by wet digestion using a digestion mixture of H₂O₂, H₂SO₄, Se, and Li₂O₄S at 360 °C for 2.5 h (Anderson and Ingram, 1993). A separate sample was then extracted with NaOH-EDTA according to Bowman and Moir (1993), where dried soil was extracted with a 0.25M NaOH-0.5M EDTA solution (1:10 soil:solution) by shaking overhead for 16 h. Following centrifugation for 10 min at 3000 rpm and filtering with 0.22 μm syringe filters, the inorganic P fraction (referred to here as oxide P) was measured on diluted subsamples (1:10) by colorimetric determination using malachite green (Ohno and Zibilske, 1991). The total P in this extract was measured following autoclave digestion with H₂SO₄ and ammonium persulfate, neutralization, and colorimetry. The difference between the total P and inorganic P of these NaOH-EDTA extracts is referred to as organic P.

The sum of the P extracted from the free aggregates on a mass basis had the following recovery averages and standard deviations compared to the P extracted from the bulk soil: 105 ± 3% for total C, 89 ± 8% for total N, 93 ± 7% for total P, 115 ± 11% for organic P, and 107 ± 11% for oxide P. Similarly, P extracted from the occluded

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