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Can conservation agriculture improve phosphorus (P) availability in weathered soils? Effects of tillage and residue management on soil P status after 9 years in a Kenyan Oxisol

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ABSTRACT

The widespread promotion of conservation agriculture (CA) in regions with weathered soils prone to phosphorus (P) deficiency merits explicit consideration of its effect on P availability. A long-term CA field trial located on an acid, weathered soil in western Kenya was evaluated for effects of reduced tillage and residue retention on P availability. Reduced tillage and residues were hypothesized to increase soil aggregation, and as a result, reduce P sorption potential, increase labile and organic P (P_o), and stimulate phosphatase activities. After 9 years (18 cropping seasons), residue management had no effect on soil aggregate mean weight diameter (MWD), soil P fractions, or phosphatase potential activities. However, reduced tillage increased soil MWD and labile soil P stocks at 0–15 cm depth. Total P was greater at 0–15 cm depth under reduced tillage, but not for 0–30 cm depth, indicating stratification of P under reduced tillage. Increases in total P at 0–15 cm depth were correlated with maximum P sorption (P_{max} sorption), whereas labile P increased with MWD and P_o stocks. Reduced tillage also decreased pH and increased P_{max} sorption, but these properties were not correlated. Despite a positive association of MWD and P_o, weak or no changes were observed for P_o and phosphatase activities, nor were there management effects on soil C stocks. Low residue retention rates (2 t maize residue yr^{-1}) and relatively small improvements in soil structure due to reduced tillage were likely insufficient to yield changes in P_o. Fertilizer P inputs at recommended rates (60 kg P ha^{-1} per season) may have also muted treatment effects on organic P cycling, though phosphatase activities were positively correlated with inorganic P fractions. The reduced tillage component of CA offers some improvements in P availability in weathered soils of western Kenya. However, relatively low soil available P across treatments suggests that CA with P fertilization may not be an optimal P management strategy for weathered soils in this region.

1. Introduction

Conservation agriculture (CA) is a management concept with increasing global adoption due to its potential for soil conservation and increased crop productivity (Andersson and Giller, 2012; Hobbs et al., 2008; Powlson et al., 2016). Minimal soil disturbance (e.g., reduced tillage) and soil cover (e.g., residue retention) are key components of CA. Reduced tillage and residue retention have been reported to reduce soil erosion and runoff, increase soil moisture, and promote soil organic matter accrual (Brouder and Gomez-Macpherson, 2014; Palm et al., 2014), all of which can be conducive to improving crop yields. Widespread soil degradation and low yields in regions such as East Africa (Sanchez et al., 1997; Stoorvogel et al., 1993) have prompted investigation on the potential of CA practices to improve soil conditions that support long-term productivity in this region (Corbeels et al., 2015).

Despite its promotion and adoption in areas with phosphorus (P) deficient soils such as western Kenya, CA has not been explicitly considered for its potential to improve soil P availability. Phosphorus remains a major limitation to agricultural productivity in western Kenya (Nziguheba, 2007; Nziguheba et al., 2015). Recently, a meta-analysis of on-farm trials in this region (n = 126

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fields) identified greater limitation of maize yields by P (50%) than by N (43%) (Kihara and Njoroge, 2013). This partly reflects the low native P stocks, acidic pH (<6), and mineralogy of weathered soils in this region (Braun, 1997; Kanyanjua et al., 2002). In such soils, low pH and high concentrations of reactive iron and aluminum (hydr)oxides drive fixation of plant-available inorganic P (P_i) (Pypers et al., 2006). As a result, cycling of P through organic pools, including mineralization of organic P (P_o) to P_i by enzymes (i.e., phosphatases), is key for meeting crop P demand in weathered soils (Ayaga et al., 2006; Oberson et al., 2006, 2011).

Improving P availability may represent an additional advantage of CA in weathered soils because reduced tillage and residue retention could reduce P fixation, increase labile P, and increase P_o accumulation and its mineralization by phosphatases. Organic matter (OM) additions under residue retention can reduce P fixation by increasing organic anion competition for P binding sites (Nziguheba et al., 1998; Palm et al., 2014). Improvements to soil structure or aggregation (often expressed as mean weight diameter; MWD) in weathered soils can result from OM retention and reduced tillage (Shang and Tiessen, 1997, 1998; Wei et al., 2014a) and may be conducive to greater P availability. In such soils, improved aggregation can reduce P fixation by decreasing the relative soil surface area, and therefore potential sorption sites, to which soluble P_i is exposed (Linquist et al., 1997; Wang et al., 2001; Zhang et al., 2003). Slower diffusion and equilibration of P with sorption sites within larger aggregates can also contribute to lower P fixation in weathered soils with greater MWD (Linquist et al., 1997).

Enhanced P_o storage in macroaggregates in weathered soils (Fonte et al., 2014; Nesper et al., 2015) suggests that management effects on aggregation could influence soil P availability through additional means beyond P fixation, because P_o is a potential source of available P. Soil phosphatases drive mineralization of P_o to available P_i (Nannipieri et al., 2011), and may also be influenced by tillage and residue management. For example, acid phosphomonoesterase (ACP) potential activity increased under no-tillage in an Oxisol, and was strongly associated with MWD (Green et al., 2007), though the activities of alkaline phosphomonoesterase (ALP) and phosphodiesterase (PDE) were not examined. Additionally, phosphatase activities in weathered soils can be stimulated by OM additions (Cui et al., 2015; Senwo et al., 2007), and have been found to strongly correlate with greater macro- and microaggregation (Wei et al., 2014a,b). Linking phosphatase activities with additional measurements of soil P dynamics may provide a more comprehensive understanding of CA impacts on soil P availability.

Linkages between these three components of soil P supply—fixation, P fractions, and organic P cycling—in relation to CA management practices have yet to be evaluated. Accurate assessment of CA effects on soil properties requires long-term studies (Brouder and Gomez-Macpherson, 2014; Giller et al., 2009), and in particular for soil P_o response to tillage management, which can take up to one decade to stabilize in weathered soils (Beck and Sanchez, 1994). There is a need for such studies in regions of sub-Saharan Africa with strong promotion of CA by national and international agricultural agencies but few long-term studies on outcomes (Brouder and Gomez-Macpherson, 2014).

The objective of this study was to evaluate the impact of tillage and residue management after 9 years on soil P availability in an acid, weathered soil in western Kenya. Reduced tillage and residue retention were both expected to improve P availability by reducing soil P fixation and increasing plant-available P_i, and supporting P_o storage and its mineralization via greater phosphatase potential activities. Specifically, reduced tillage and residue retention were both hypothesized to: (1) increase stable soil aggregation (MWD) and decrease P fixation, (2) increase labile P_i and (3) increase P_o and stimulate phosphatase activities, relative to conventional tillage and residue removal.

2. Materials and methods

2.1. Site description

The field trial was established in Nyabeda, western Kenya, in March 2003, by the African Network for Soil Biology and Fertility (AfNet) and International Center for Tropical Agriculture (CIAT). The trial is located at 1320 m above sea level at 0° 7′46.96"N and 34°24′19.15"E, and experiences a mean annual temperature of 22.5 °C. Mean annual precipitation is 1800 mm, distributed bimodally over a long rain (March-August) and short rain (September-January). The trial is established on a Typic Rhodiudox (WRB Ferralsol) expressing clay texture (663 g clay kg^{-1}, 151 g silt kg^{-1} silt, 167 g sand kg^{-1}), and with low available (Bray) P (2.9 $\mu g\, g^{-1}$) and pH 5.5 (1:2 in water) at 0–30 cm depth in an uncultivated profile next to the trial (Jelinski, unpublished).

The trial was established as a randomized block design with tillage and residue as main factors, each with two levels: conventional tillage (+T) or reduced tillage (−T), and residue retention (+R) or residue removal (−R). Each treatment occupied an individual plot (7 m × 4.5 m) across each of the four replicate blocks. From the various crop-rotation and mineral fertilizer treatments, we selected treatments in which maize (*Zea mays* L.) was cropped during the period of long rains followed by soybean (*Glycine max* L.) during the short rains period. All plots were fertilized with 60 kg N ha^{-1} as urea, 60 kg K ha^{-1} as muriate of potash, and 60 kg P ha^{-1} as super triple phosphate (TSP) per growing season. Fertilizers were applied by mixing with soil in the planting hole, into which seeds were hand-planted. Prior to the experiment establishment, the site was under native grasses and shrubs, and was initially prepared by plowing to 0–15 cm depth (Muriithi-Muchane, 2013).

Tillage treatments mimicked practices used by smallholder farmers in this region, including use of the hand hoe (*jembe*) (Kihara et al., 2011). Under conventional tillage, the plots were prepared by hand hoeing to approximately 15 cm soil depth, and weeding was performed by hand hoe to 8 cm depth thrice per season. Under reduced tillage, the seedbed was prepared by hand hoeing to 3 cm, and hand pulling rather than hoeing was used to weed thrice per season. Beginning in the 2009 long rain period, herbicides (glyphosate and *2,4*-dichlorophenoxyacetic acid) were applied to reduced tillage treatment plots prior to planting, with subsequent weeding performed manually as described above. After harvest, maize residues were collected, dried, and stored during the dry season for approximately one month. Under residue retention, chopped maize residues were reapplied at a rate of 2 t ha^{-1} at commencement of the short rains, and were incorporated by conventional tillage or remained on the soil surface as mulch under reduced tillage just before soybean was planted. Maize residues were not reapplied for residue removal treatments. Soybean residues were left in the field irrespective of treatment, because soybeans drop leaves prior to maturity. Additional details on trial description and management are provided by Paul et al. (2013, 2015b).

Soil samples obtained by Paul et al. (2015b) were used for additional measurements on general soil properties (e.g., pH) and soil P. As described by Paul et al. (2015b), soils were sampled 4 weeks before maize planting (long rain period) in year 9 (2012), corresponding to 18 cropping seasons since treatment implementation. For the determination of MWD, undisturbed soil cores were sampled at 0–15 cm and 15–30 cm depths to obtain 500 g of representative sample. Bulk density values were derived from measurements by Paul et al. (2015b), which were obtained from