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Effects of long-term cultivation on phosphorus (P) in five low-input, subtropical Australian soils

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ABSTRACT

Despite the importance of P for cropping, there remains uncertainty regarding the effects of long-term cropping on P behaviour in soils. Using five soils (Billa Billa, Cecilvale, Riverview, Thallon, and Waco) from subtropical Australia cropped for ≤70 y with low rates of P-fertilizer inputs, changes in soil P (organic, inorganic, and total) were assessed and related to P removal in wheat grain. For four of the five soils, concentrations of organic P decreased significantly with increasing period of cropping, decreasing between 20 and 36%. In contrast, concentrations of inorganic P generally remained relatively constant. Despite the decrease in organic P, the C/P ratio remained relatively constant in all five soils (average of 99), indicating that organic P is protected within the soil organic matter in a manner similar to the organic C. Furthermore, although increasing period of cropping decreased soil organic P concentrations, grain P concentrations decreased significantly only for Billa Billa and Thallon. Finally, although the rate of P removal in grain was low (1.6 to 9.3 kg ha^{-1} y^{-1}), the rate of removal exceeded inputs from P-containing fertilizers. Thus, there is a need to consider the long-term P-fertilization to ensure adequate P nutrition of the crops. This study provides important information regarding changes in P within long-term cropping systems and will assist in their sustainable management.

1. Introduction

An estimated two-thirds of soils worldwide contain insufficient P for optimal plant growth (Batjes, 1997; Cakmak, 2002). Furthermore, in Australia (and many other tropical and subtropical regions), issues of P deficiency are even more pronounced due to the high degree of weathering in ancient soils (Walker and Syers, 1976). As a result of the inherently low concentrations of P, the addition of P as fertilizers is essential to maintain and increase agricultural production. Currently, an estimated 261 million tons of phosphate rock are used annually for crop production (U.S. Geological Survey, 2017). Furthermore, it is estimated that demand for P will increase by 50–100% by the year 2050 due to increasing demand for food production and shifts in diet compositions (Steen, 1998; EFMA, 2000). Of the 14 nutrients that are essential for plants, global reserves of P are the smallest (Gilbert, 2009) with the majority of these in a single country, Morocco. As a result, the use of the remaining P reserves must be efficient, with supply of P fertilizers influenced both by scarcity and political instability.

To achieve this increased efficiency, a better understanding of how agricultural cropping practices influence the behaviour of soil P is needed, particularly in low-input systems. Low-input agricultural systems are defined here as those with low external inputs, particularly fertilizers. For example, yields in many cropping systems of Australia are often limited by a water deficit, with external inputs (including fertilizer) also low as a result. Despite the importance of P and its fertilization for global food production, there remains a lack of a detailed understanding about how P changes in soils over time as a result of cropping practices in long-term agricultural systems (Kopittke et al., 2017). This lack of understanding hinders ongoing research efforts to improve the efficiency of P usage and to increase crop productivity in P-limited soils. Of particular interest to the present study, despite the inherently low P concentrations of many soils, several studies have shown that long-term cultivation and product removal have resulted in further substantial reductions in soil P concentrations (Hedley et al., 1982; Tiessen et al., 1983; Beck and Sanchez, 1994; Dalal, 1997; Motavalli and Miles, 2002; Kopittke et al., 2017). Generally, these previous studies have found that long-term cropping results in appreciable decreases in organic P concentrations, whilst inorganic P often (but not always) remains relatively constant. For example, Bowman et al. (1990) found that after cropping for 60 y, organic P

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concentrations decreased by 47% whilst inorganic P concentrations decreased by only 11%. In the present study, we extend these previous findings by examining long-term changes in five low-input subtropical cropping systems of Australia.

Primary soil minerals, mainly apatites, are the original source of 95% or more of the P in soils, with this P released during mineral dissolution (Stevenson, 1999). As a result, few of these primary minerals are found in highly weathered soils. Rather, the majority of P in weathered soils is associated either with secondary soil minerals or with soil organic matter – these two pools accounting for 98–99% in weathered soils. The relative importance of these two pools (i.e. organic P and inorganic P associated with secondary minerals) varies depending upon soil properties and mineralogy, with between 20 and 80% present as organic P and 20–80% present as inorganic P in secondary minerals (Stevenson, 1999). The relative importance of changes in these organic and inorganic fractions upon long-term cultivation remains unclear, with few studies examining these changes in low-input systems, particularly in tropical and subtropical soils (Hedley et al., 1982; Tiessen et al., 1983; Dalal, 1997; Motavalli and Miles, 2002; Crews and Brookes, 2014). In an interesting study, MacDonald et al. (2012) utilized a meta-analysis and reported that abandonment of agricultural land generally resulted in increases in soil P concentrations.

The present study aimed to examine the effects of long-term (≤70 y) cultivation and product removal on concentrations of P in soil and wheat grain from five systems in sub-tropical Australia. These five soils received either no P fertilizer or it was applied at low rates. Examining the surface 0–10 cm of the soil profile, changes in total P, organic P, inorganic P, and plant-available P (estimated using bicarbonate-extractable P) were assessed. These changes in organic P were also related to those of organic C. Finally, consideration was given to the concentration of P in wheat grain and the magnitude with which it is exported from the agricultural systems. This information is important in understanding the impacts of long-term cropping systems on soil nutrient reserves and will assist in the sustainable management of these soils.

2. Materials and methods

2.1. Soil collection and description

Soils were collected from five locations in southern Queensland (Australia), with the locations being called Billa Billa, Cecilvale, Riverview, Thallon, and Waco. Mean annual rainfall ranges from 480 mm for Thallon to 670 mm for Cecilvale. A detailed history of all five sites is provided by Dalal and Mayer (1986a), but is briefly summarized here. Of the winter crops grown at these five sites, 90% were wheat (*Triticum aestivum* see later), with 90% of summer crops being sorghum (*Sorghum bicolor*). The average number of winter crops and summer crops each year was 0.8 (winter) and 0.1 (summer) at Billa Billa, 0.6 and 0.2 at Cecilvale, 0.5 and 0.2 at Riverview, 0.6 and 0.1 at Thallon, and 0.6 and 0.3 at Waco. At all five sites, applications of P-containing fertilizers were low, ranging from 0 to 7.7 kg ha^{-1} y^{-1} (Supplementary Table S1). The P-fertilizers were typically applied as monoammonium phosphate. Soils were generally cultivated using a chisel plough, sweep plough and scarifier, or occasionally a disc plough. The average number of cultivation operations per year was 4.8 for Billa Billa, 4.9 for Cecilvale, 2.9 for Riverview, 3.0 for Thallon, and 5.0 for Waco.

For each location, samples were collected from various nearby fields that differed in the length of time since being first cultivated. Thus, these samples represented soils that had been cropped for ≤70 y, with samples collected from a total of 64 individual cropped sites across the five locations (being 14 sites for Billa Billa, 12 for Cecilvale, 11 for Riverview, 14 for Thallon, and 13 for Waco). Samples were also collected from nearby undisturbed (virgin) sites with native vegetation, with up to seven sites used for the undisturbed samples at each of the five locations. (Multiple sites were used for the undisturbed samples to ensure that all samples collected from cultivated sites had an adjacent undisturbed site for comparison). Unless otherwise stated, all data presented hereafter for the undisturbed sites (0 y cultivation) is the average across the ≤7 sites at each location. In total, 94 individual sites were sampled, being 64 cropped sites and 30 undisturbed sites.

At each individual site, samples were collected across a 0.1 ha area using a 5 × 8 m grid at a depth of 0 to 0.1 m. A total of 25 samples were collected from each of the 94 sites (i.e. 2350 samples in total), with five of these samples then mixed to form a single composite sample (yielding a total of five composite samples for each of the 94 sites). Upon collection, the soil samples were placed in plastic bags and stored at 4 °C until further processing. Thereafter, the soil samples were dried at 25 °C in an oven, ground to pass a 2 mm sieve, and stored in sealed plastic containers at room temperature until analysis. Samples of wheat straw and grain were collected where possible.

The soils have been described in detail previously (Dalal and Mayer, 1986a; Kopittke et al., 2016), with some properties presented here (Supplementary Table S1). All soils were Vertisols (Vertisols in the World Reference Base classification system) other than Riverview which was an Alfisol (Lixisol in the World Reference Base classification system). The parent material at Billa Billa is calcareous sediments, at Cecilvale it is clay alluvium derived from basalt and sandstone, at Riverview it is weathered ferruginized sediments, at Thallon it is Quaternary argillaceous alluvium, and at Waco it is clay alluvium derived from basalt. For undisturbed soils, pH values were near-neutral or alkaline, organic C contents were modest (0.78–1.7%), with clay content highest for Waco (72%) and lowest for Riverview (18%).

2.2. Soil and plant analyses

Estimates of available P concentrations were made using sodium bicarbonate (Colwell, 1963; Rayment and Lyons, 2011). Organic P was determined as described by Saunders and Williams (1955), total P concentrations were determined using X-ray fluorescence (Rayment and Lyons, 2011), and inorganic P was determined as the difference between total and organic P. The organic C concentration was determined using the Walkley-Black method. After drying at 65 °C for 48 h, plant tissues were digested in concentrated HNO_3 before analysis. The concentrations of P in the soil extracts and the plant digests were assessed colorimetrically using the ascorbic acid method (Murphy and Riley, 1962).

2.3. Statistical analyses

Data were analysed using SYSTAT 13.1 (Cranes Software, India), with changes in P concentrations assessed using the first-order kinetic model, similar to that for N (Stanford and Smith, 1972),

$$P_t = P_e + (P_0 – P_e)\exp(-kt) \quad (1)$$

where P_t is the concentration of P after t years, P_e is the concentration of P at equilibrium following a long period of cultivation, P_0 is the P concentration prior to disturbance (virgin site), and k is the rate of P loss per year. For Eq. (1), the half-life ($t_{½}$) can be calculated as: ln2/k. Where 95% confidence intervals encompassed zero, changes in P were instead examined using linear regressions

$$P_t = P_0 – at \quad (2)$$

where a is the average annual decrease in P. Throughout this study, no coefficient is reported (and regressions are not plotted) where the 95% confidence interval encompassed zero.