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Research Paper

Soil phosphorus sorption capacity after three decades of intensive fertilization in Mato Grosso, Brazil

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ABSTRACT

Soil phosphorus (P) availability commonly limits the productivity of tropical croplands. While large fertilizer inputs can alleviate P limitation, this strategy is costly and relies on finite phosphate rock resources subject to price volatility. Nevertheless, high-P-input agriculture on P-poor and P-fixing soils is spreading rapidly in some regions of the tropics, particularly in Brazil, where farmers on average add twice as much P to soils as they harvest to ensure high yields. Here we ask whether P fertilizer inputs to tropical soils in excess of harvested P outputs will eventually build up a residual pool of soil P that crops can tap into if fertilizer inputs are decreased – a phenomenon observed in the U.S. and Western Europe, albeit on very different soils. We pose this question in Mato Grosso, Brazil, where we quantified soil P input-output budgets, total P, Bray-extractable P, P sorption capacity, P saturation, and other characteristics from a chronosequence of 31 plots that had been in soybean production for 0–31 years. Farmer interviews revealed ongoing annual additions of P fertilizer greater than P removals in crops, with an average farm P balance in the most recent year, including soybeans and a second harvest, of $+14$ kg P ha^{-1} y^{-1}. Soil total P and Bray-P_1 have increased, and P sorption capacity has decreased, with time in production. However, clayey soils rich in iron- and aluminum-oxides still have high P sorption capacity and low P saturation, even after three decades of intensive fertilization and residual P build-up. Our findings suggest that commodity crop producers farming on this soil type in Mato Grosso and other tropical regions may need to add annual inorganic P fertilizer inputs greater than the quantity of P recovered in harvests for up to a century or more before soil P budgets can be balanced without endangering yields. This result has implications for the sustainability of agricultural intensification in the tropics.

1. Introduction

Tropical regions are widely expected to play a growing role in global agricultural production (Alexandratos and Bruinsma, 2012). Croplands in the tropics are often characterized by highly weathered soils having low phosphorus (P) stocks and high capacity for P sorption (i.e., P fixation) (Roy et al., 2016). These soils are rich in iron and aluminum oxides that fix P added in fertilizers before it can be accessed by crops (Palm et al., 2007; Syers et al., 2008). This suggests that reaching a degree of P saturation where P inputs can be reduced to match P in crop harvests – without sacrificing yield – may take longer than in most temperate regions (Nziguheba et al., 1998; Wisawapipat et al., 2009; Riskin et al., 2013a; Rodrigues et al., 2016; Guedes et al., 2016). Yet how much longer remains an open question, and is the motivation of this study.

The expansion of high-input intensive agriculture in the Brazilian state of Mato Grosso highlights the importance of this question. Soybean production in Mato Grosso increased rapidly over the past few decades, and now accounts for approximately 8% of the world's total soybean production. Farmers in Mato Grosso predominantly grow soybeans (often double cropped with maize), and apply much more P in fertilizer than they harvest in crops (Fig. 1; Roy et al., 2016). The

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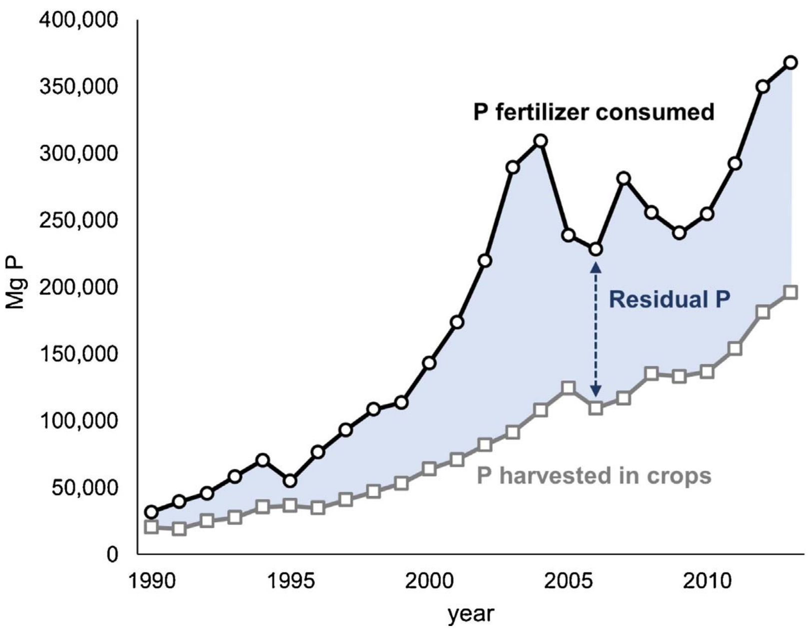

Fig. 1. Phosphorus balance for the Brazilian state of Mato Grosso (1990–2013), including P fertilizer consumed (circles) and P harvested in all crops (squares) each year. Residual P is equal to the P fertilizer consumed minus P harvested in crops. These data include and build upon those presented in Roy et al. (2016). Methods are described in Section 2.6.

surplus remains in the soil, and this P inefficiency has important economic implications, as fertilizers account for 30% of per hectare total soybean production costs in the state (Meade et al., 2016). These costs are different than for commodity producers in the world's temperate breadbaskets – soybean farming in Mato Grosso requires 1.5–2 times the amount of phosphate fertilizer compared to farms achieving similar yields in the U.S. Midwest (Riskin et al., 2013a; Roy et al., 2016; USDA NASS, 2017). This so-called soil P 'tax' (Roy et al., 2016), potential threats of fertilizer price fluctuations (Huang, 2009; Elser et al., 2014; Mew, 2016), and the limits of the global phosphate rock supply (Edixhoven et al., 2014) call into question the long-term sustainability of farming on high-P-fixing soils.

Evidence from temperate regions suggests that elevated P fertilizer additions can build up a residual bank of P in soils that remains accessible to plants, enabling reductions in P input without negative consequences for productivity (Sattari et al., 2012; Rowe et al., 2016). It has been hypothesized that plant-availability of this residual P is supported by a decline in short-term buffering caused by a decrease in charge resulting from diffusive penetration of phosphate ions, as well as a decline in longer-term sorption effects when the pathways by which P penetrates the soil matrix become saturated (Barrow and Debnath, 2014). Few studies have examined whether exploitation of residual soil P can also occur in emerging tropical agricultural powerhouses, such as Brazil. Field experiments on farms in Brazil's Cerrado biome, which includes much of Mato Grosso (Fig. 2), have shown that while decades of high inorganic fertilizer inputs to croplands can nearly double total soil P, most of that P remains bound in plant-unavailable forms associated with Fe/Al oxyhydroxides (Rodrigues et al., 2016). Similar farm-level findings have been reported for shorter time durations in the Amazon region of Mato Grosso (Riskin et al., 2013b). How representative these studies of a small number of farms are of the broader agricultural landscape in Mato Grosso remains unclear, as variability in soil texture and bulk chemistry can have important implications for P sorption (Sanchez et al., 2003). Thus, we do not know to what extent, if at all, past P applications can alter soil P sorption capacity across Mato Grosso's croplands.

To address these questions, we visited 16 Mato Grosso farms and collected more than 100 soil samples from plots in intensive soybean cultivation for 0 (still hosting native vegetation adjacent to farms) to 31 years. Our study objectives were to: (1) conduct farmer surveys and interviews to develop soil P input-output budgets for each farm, (2) characterize surface soils, including total P, Bray-extractable P, remaining P sorption capacity, and P saturation, and (3) estimate rates of change in soil P properties over time in production while accounting for variability in soil characteristics. We hypothesized that soil total P and Bray-extractable P would both increase with time in production, but also that most accumulating residual P would be in forms not extracted by the Bray-P_1 solution. Based on previous farmer interviews that showed high fertilizer inputs even after decades in production (Roy et al., 2016), we expected that P sorption capacity would decrease only marginally and remain high, and that P saturation would remain low, in soils now cultivated for 2–3 decades, signaling a persistent P sink in Mato Grosso soils that restricts exploitation of residual P.

2. Methods

2.1. Study sites

We visited farms for soil sampling during July 2015 along a 300-km corridor spanning the Cerrado and Amazon regions in the Brazilian state of Mato Grosso (Fig. 2). The southern-most farms included in this study are located near the city of Lucas do Rio Verde, while the northern-most farm is located near the town of Nova Santa Helena. Average rainfall in the region ranges from 1500 to 2000 mm y^{-1}, with a pronounced dry season between May and September and an average annual temperature of 21–26 °C (Vourlitis et al., 2002). We selected farms from a larger pool described in Roy et al. (2016) and identified property boundaries by speaking with farmers on site and using spatial data from the Cadastro Ambiental Rural (CAR) database managed by the Brazilian government. Most of these farms grow soybeans (primary harvest) and maize (second harvest) in succession within a single year, a technique commonly referred to as double-cropping (Fig. 2; Spera et al., 2014). On 9 out of 15 farms where we sampled cropland soils, farmers reported cultivating rice for 1–2 years following forest clearing, with ~22 kg P ha^{-1} y^{-1} applied as fertilizer, before converting fields to soybean production. On 3 farms, soybean production was preceded by unfertilized pasture. The land use preceding soy for the remaining farms included forest (2) and coffee (1). The sixteenth farm was characterized by a more complicated land use history (cultivation, followed by ranching, followed by a return to cultivation). Therefore, we omitted cropland soil samples for this farm, but we did include forest soil samples from the property.

Fourteen of 16 farms were on land classified as LVAd19 (Latossolos Vermelho-Amarelos Distróficos + Latossolos Vermelhos Distróficos