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Review paper

Crop residue contributions to phosphorus pools in agricultural soils: A review

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ABSTRACT

The phosphorus (P) content of crop residues and its availability to a subsequent crop can range from agronomically insignificant, to quantities in excess of crop P requirement. However, the contribution of crop residues to the P nutrition of subsequent crops has not been widely recognised, and simple predictive tools are lacking. By reviewing the published literature in which quantitative measurements of P transformations from plant residues applied to soil have been reported, we have evaluated the contribution of crop residue-derived P to the P nutrition of subsequent crops, assessed the key factors involved and summarised the knowledge as an empirical model. The contribution of crop residues to P availability is likely to be significant only under conditions where large amounts of crop residues of relatively high P concentration are applied to soil. Crop residues with low P concentration, such as cereal stubble (eg. due to re-translocation of a large proportion of stubble P into grain), will not make an agronomically significant contribution to soil P availability, but may reduce P availability due to assimilation in the microbial biomass. However, a productive green manure crop may release sufficient P to meet the requirements of a subsequent cash crop. The release of P from crop residues is significantly reduced in systems where the P-status of crops and soils is low, which reinforces the reliance on external P inputs for sustained crop productivity. The large variability in the potential contributions of plant residues to the P nutrition of subsequent crops suggests that there is a strong need to integrate model predictions of organically-cycled P with fertiliser management strategies.

1. Introduction

Optimising phosphorus (P) use efficiency will deliver agronomic, economic and environmental benefits as agricultural production systems adjust to meet future global food production targets (Heffer and Prud'homme, 2013). Such optimisation will rely on adequate knowledge of the dynamics of soil P pools to enable accurate predictions of the required external P inputs to achieve optimum growth of subsequent crops. While our understanding of soil inorganic phosphate (Pi) pools is relatively comprehensive, the value of P returned to the soil in crop residues has not been fully resolved. Agronomically significant amounts of P can be present in crop residues and the microbial biomass associated with their decomposition, and the potential contribution of this pool to the P nutrition of cropping systems is significant (*eg.* Chauhan et al., 1979; Dalal, 1979; White and Ayoub, 1983; Thibaud et al., 1988; Umrit and Friesen, 1994; Kwabiah et al., 2003a; Nachimuthu et al., 2009). The main factors influencing the amount of crop residue P, its rate of mineralisation and subsequent availability to crops have been identified (Stockdale and Brookes, 2006; Guppy and McLaughlin, 2009; Simpson et al., 2011); but their interactions remain poorly elucidated and largely unquantified. By reviewing the published literature in which quantitative measurements of P transformations from plant residues applied to soil have been reported, we will evaluate the contribution of crop residue-derived P to the P nutrition of subsequent crops, assess the key factors involved and summarise the knowledge as an empirical model.

The dynamics of organically-derived nitrogen (N) and carbon (C) in agricultural soils has been extensively described, and a wide range of predictive tools have been developed. These have proved a

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valuable asset for landholders, agronomists and policy makers by providing good estimates of the impacts of agronomic management options on the dynamics of both C (*eg.* Parton et al., 1988; Coleman and Jenkinson, 1999; Grace et al., 2006) and N (see Herridge et al., 2008) in agricultural soils. Considering our extensive knowledge of the N cycle in agricultural systems, and the benefits (economic, social and environmental) that have been obtained by our ability to predict and manipulate it, similar knowledge of the organic P cycle could also yield significant benefits. Yet, although the principal driving factors of organic P cycling have long been recognised and modelled (Cole et al., 1977), models have not proven to be universally applicable (Gijsman et al., 1996; Schnepf et al., 2011). Several models have demonstrated a capacity to incorporate P release from crop residues and manures into projected crop growth and yield, notably The Agricultural Production Systems Simulation (APSIM) (Keating et al., 2003), Century (Parton et al., 1988) and CERES-Wheat (Ritchie et al., 1988; Godwin et al., 1989; Singh et al., 1991; Daroub et al., 2003) modelling frameworks. However, these models require detailed climate and site information that may not be available, and are specialised tools that cannot be operated by the layperson. The contribution of crop residue P to the nutrition of subsequent crops has not been widely recognised, and there is currently no decision support system (DSS) that can predict it from a simple, readily-available set of variables.

Plant uptake of residue-derived P has predominantly been evaluated using isotope labelling and isotopic dilution methodologies. Residues labelled with ^{32}P or ^{33}P isotopes have been applied to soil, enabling the differentiation of residue-derived P, native soil P and mineral fertiliser P through the plant-soil system (eg McLaughlin and Alston, 1986). Such studies have typically been conducted over a short term (1–2 months), according to the half-life of the available P isotopes, with the amounts of residue-derived P recovered in plants generally being 5%–10% of the total P content of the residues (Blair and Boland, 1987; Nachimuthu et al., 2009), 20–30% (Umrit and Friesen, 1994) and as high as 40% (Dalal, 1979). Similarly, a large proportion of crop residue P is generally recovered from soil as inorganic P (Pi) in plant-available and sorbed pools (Chauhan et al., 1979; White and Ayoub, 1983; Kwabiah et al., 2003a) in proportions similar to those observed when P is applied as mineral P fertiliser (Friesen and Blair, 1988; Cong and Merckx, 2005).

Where P pools and mineralisation were measured over a period of decades, rotation management has been shown to have a significant effect on the dynamics and partitioning of soil P. In the context of a pasture/cereal cropping rotation, Bünemann et al. (2006) measured accumulation of P in the organic fraction during a wheat/pasture rotation at ~2 kg ha^{-1} year^{-1} (a trend previously reported by McLaughlin et al., 1988), but no accumulation under continuous cropping. Soil organic matter has been shown to increase under legume pasture phases, with subsequent release of nutrients through mineralisation of the organic matter during cropping phases (*cf.* Simpson et al., 2011). Although the accumulation of soil N is usually the focus of pasture phases, there is also the potential for pasture or green manure phases to augment soil P availability in the subsequent cropping phase (Horst et al., 2001). Interestingly, pulse crops including chickpea, white lupin, and faba bean have been shown to enhance the P nutrition of subsequent cereal crops even when legume residues have been removed from the soil (Nuruzzaman et al., 2005; Rose et al., 2010), and some legume genotypes improve the P nutrition of subsequent cereals more than others (Rose et al., 2010b). However, the mechanism(s) responsible for this are not clear, the impact of the time lapse between legume harvest and subsequent cereal sowing on potential P benefits is unresolved, and there are currently insufficient data to incorporate such mechanisms into predictive models for P turnover.

Although the processes determining the cycling of P in soils are indisputably complex, several key factors have consistently been demonstrated to govern the mineralisation and availability of crop residue-derived P. These main factors can be broadly grouped as the quality of the crop residues, the activity of the soil microbial biomass, and the subsequent sorption reactions of mineralised P in soil (summarised in Fig. 1 as a conceptual model). We characterise the process of P release from crop residues based on four key P pools; namely the inorganic and organic P components of crop residues, P assimilated in the microbial biomass and Pi associated with the soil. The key processes of P transfer between these pools are represented by five vectors: the rate of release of the inorganic and organic P fractions from residues (k_{Pi} and k_{Po}) and the microbial biomass pool (k_{Pm}), the assimilation of Pi by the microbial biomass as it proliferates after the addition of crop residues (M_{Pm}), and the uptake of native soil Pi by the stimulated microbial biomass (M_{Pi}) when Pi released from crop residues is less than M_{Pm}.

We present herein a quantitative summary of the available literature resources, with respect to the rate and magnitude of P transfer from crop residues to the plant available soil pools, and the major environmental and management factors involved. We discuss how the pools and vectors represented in Fig. 1 describe the major processes governing the transfer of crop residue P to plant available soil P, and quantify them. This knowledge is then integrated as a simple empirical model of the response of soil P availability to various crop residue scenarios. We draw as broadly as practicable on the published literature, to represent averaged values that can be expected across a diversity of conditions, thereby summarising key areas of scientific consensus, and processes that are as yet poorly elucidated. As the sum of existing knowledge and in the interest of robustness and simplicity, the release of P from crop residues is described according to the major processes illustrated in Fig. 1; they have been quantified widely. The numerous

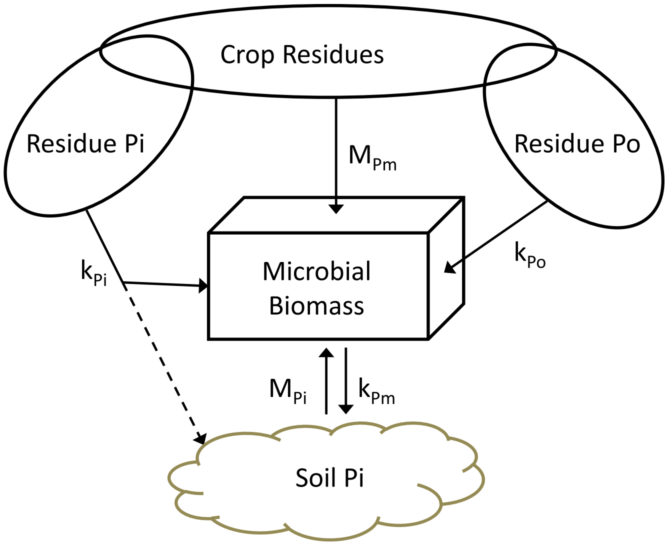

Fig. 1. A schematic representation of the conceptual pools and vectors as described and quantified. 'Residue Pi' represents water-soluble phosphate and 'Residue Po' represents the organically bound component of P in 'Crop Residues'. 'Soil Pi' represents all Pi that is associated with the mineral component of soil that is potentially exchangeable with the soil solution. 'k_{Pi}' and 'k_{Po}' represent the decay constants for the rate of release of 'Residue Pi' and 'Residue Po', respectively. 'M_{Pm}' represents the amount of Pi assimilated by the 'Microbial Biomass' as it proliferates in response to the availability of C substrate from 'Crop Residues', whereas 'M_{Pi}' represents the uptake of 'Soil Pi' by the stimulated 'Microbial Biomass' where P released from crop residues is less than 'M_{Pm}'. 'k_{Pm}' represents the decay constant for the rate of release of Pi from the 'Microbial Biomass' as it decays in response to diminishing availability of C substrate from 'Crop Residues'.