Chapter 17 Management Impacts on Biological Phosphorus Cycling in Cropped Soils

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17.1 Introduction

Global population is forecast to increase to 7.6 billion by the year 2020 and to about 9 billion in 2050 (UNPP 2008). The FAO (2009) estimates that food production will have to increase by 70% by 2050 to meet the needs of the increasing world population. About 80% of the increase in agricultural production will have to come from increased productivity (FAO 2009). This will be related to a strongly growing demand for fertilizers (see Tiessen et al. 2011). In view of the projection that phosphorus (P) deposits, which can be mined at a relatively low cost to be processed for fertilizers, will be exhausted in about one century (Cordell et al. 2009), P management in cropping systems will have an important impact on future food security.

Harvested products are removed from cropped fields for human or animal consumption. With these products, P is removed and has to be restituted through fertilizer P inputs to maintain soil fertility, except in soils with a high P fertility where soil P can serve as the sole P source for a limited time. Another specific trait of cropped soils is the cyclic presence of crops, with related changes in soil cover and rooting, and the continuous disturbance through interventions by farmers. These interventions include soil tillage, sowing or planting, water management such as irrigation or drainage, fertilizer application, plant protection measures, and harvesting. The farmers select the crops and varieties, thus managing crop diversity because soils can be repeatedly cropped by the same crop (monocropping), by a sequence of crops (crop rotation), or by mixed stands (e.g., intercropping). Soil tillage affects soil P dynamics through modification of the spatial distribution of P between soil layers and soil aggregates, and through the incorporation of crop

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residues and fertilizers. It also affects soil microbial activity through changes in environmental conditions such as infiltration, aeration, and access to organic substrates. Organic P sources (animal manure, plant residues) will undergo microbiological transformations to a higher degree than mineral P fertilizers and may affect organic P contents in the soil. Crops affect biological P cycling in several ways, ranging from root-induced processes to the impact of above- and belowground residues on soil microbial activity and P availability.

This chapter summarizes current knowledge on the impact of management and crop-specific factors on biological P cycling in cropped soils of temperate and tropical regions. Cropped soils can belong to a mixed crop–livestock farm or an arable farm; the term "cropping system" as used in this chapter does not preclude linkage to livestock production. Emphasis is put on microbial functions in soil P dynamics, which are presented in Sect. 17.2. We then address the effect of soil tillage on microbial functions and on the forms and distribution of P in soils. In Sect. 17.4 we analyze the impact of long term application of organic versus mineral fertilizer inputs on microbial functions, and the role of biological processes in the use of P by crops. Finally, in Sect. 17.5 we analyze the importance of crop rotations, with emphasis on the impact of legumes on processes of P dynamics when introduced into tropical cropping systems with low-P soils. Overall, we scrutinize whether increased soil microbial activity results in a more efficient use of soil and fertilizer P.

17.2 Microbial Functions in Cropped Soils

Microorganisms mediate several key processes in the P cycle (Fig. 17.1), which affect P availability to plants (Oberson and Joner 2005). Mycorrhizal fungi colonize the roots of most crops, among them major food crops such as wheat, maize, rice, potatoes, and cassava (Jansa et al. 2006). Their role in P absorption and transport to plant roots is described in Jansa et al. (2011). Microorganisms can solubilize or desorb poorly available inorganic P by releasing organic acids and inducing changes in pH (see Jones and Oburger 2011). By their ability to synthesize extracellular phosphatases to hydrolyze organic P, microorganisms take a key role in the mineralization of organic P (Jones and Oburger 2011; Nannipieri et al. 2011). If these processes occur in the rhizosphere or mycorrhizosphere of crops, then plants may benefit from increased P availability (George et al. 2011; Jansa et al. 2011). The constantly ongoing processes of soil organic matter decomposition and turnover of microbial biomass represent a less specific but highly important process in soil P dynamics (Oberson and Joner 2005).

Organic inputs such as manures and plant residues are a major source of organic carbon (C) to the soil microorganisms. The availability of organic substrates, either specific substrates like glucose or cellulose (Bünemann et al. 2004a), or complex sources such as animal manure (Wichern et al. 2004) and plant residues (Bünemann et al. 2004a, c), induces microbial growth. Plants also



Fig. 17.1 Microbial functions in soil P dynamics of cropped soils. The microbial biomass includes microorganisms living in the rhizosphere of crops. *Italics* nonmicrobial processes, *bold italics* farmers' interventions

promote microbial populations and subsequent turnover by exuding organic C and nitrogen (N) from the roots (Wichern et al. 2007). Even under low-P conditions the microbial biomass can grow rapidly and take up substantial P amounts when readily degradable C is available (Bünemann et al. 2004a). Such an increase in microbial P is usually connected with a rapid decrease of soil solution P concentration (Oehl et al. 2001), suggesting that microorganisms may compete with plants for available P (Olander and Vitousek 2004). If P-containing organic inputs such as plant residues are added to the soil, then microorganisms immobilize P from soil and residues, and the respective contribution of the two sources can be derived using P radioisotope techniques (McLaughlin et al. 1988). For instance, residue P and soil P contributed similar parts to the increase in microbial P following the addition of the legume residues in Bünemann et al. (2004c). The recovery in the microbial biomass of P added with the legume residues was about 15% according to Bünemann et al. (2004c) and 22-28% according to McLaughlin et al. (1988). In comparison, only about 5% of mineral fertilizer P was incorporated into the soil microbial biomass (Bünemann et al. 2004c; McLaughlin et al. 1988). This is because even in soils with low plant-available P content, soil microorganisms are limited by C and N rather than by P availability (Bünemann et al. 2004b; Ehlers et al. 2010). Most P (64-68%) added with the legume residues and the mineral P was recovered in the NaOH-extractable inorganic P fraction of the soil 10 days after amendment (Bünemann et al. 2004c).

During microbial growth, microorganisms take up P from less-available P pools (Bünemann et al. 2004a, c). For instance, within 2 days of the addition of glucose plus N to soils low in available P (i.e., 2–7 mg anion exchange resin-extractable P kg⁻¹ soil), microorganisms took up from 18 to more than 40 mg P kg⁻¹ soil (Bünemann et al. 2004a). However, it remains unknown whether this P was acquired from inorganic or organic soil P pools.

P taken up by microorganisms will be incorporated into newly synthesized inorganic and organic compounds (Bünemann et al. 2011). Immobilized P is released because of depletion of readily available C (Oehl et al. 2001; Bünemann et al. 2004a) when cells are disrupted, e.g., in response to sudden changes in soil water content (Turner et al. 2003) or due to predation (Bonkowski 2004). The decrease in microbial P after exhaustion of glucose in the incubation studies of Oehl et al. (2001) and Bünemann et al. (2004a) resulted in an increase in plant-available P. Microbial immobilization and release cycles following plant residue addition differ from those induced by glucose addition in temporal dynamics and differ in the amount of P turned over, but likewise demonstrate the dynamic nature of microbial P (Bünemann et al. 2004a). In strongly P-sorbing soils, microbial P turnover may keep P in a potentially plant-available form (Bünemann et al. 2004b; Oberson et al. 2001).

The functions of microorganisms in the biogeochemical cycling of P are not specific to cropped soils, but they are affected to a high degree by farmers' interventions, and the microbial P pool size is usually lower in cropped soils than in grassland or forest soils, both in relative and absolute terms. A compilation by Oberson and Joner (2005) shows that topsoil layers of cropped soils contain 2-21 mg microbial P kg⁻¹ (median 5.5 mg P kg⁻¹), which corresponds to 0.4–2.5% of total soil P. In comparison, grassland soils contain 4–77 mg microbial P kg⁻¹ (median 18 mg P kg⁻¹), which is 0.5–7.5% of total P. From their compilation. Oberson and Joner (2005) deduced that soil type, texture, and soil organic matter content are the major factors producing this broad range in microbial P content, and that lower soil organic matter content is the main reason for the usually lower microbial P content in cropped soils than in grassland soils. The close relationship between soil organic matter content and microbial biomass has also been demonstrated using microbial C as a measure of microbial biomass (Houot and Chaussod 1995; Moore et al. 2000). Although soil type and texture cannot be modified by the farmer, management can affect soil organic matter content, its location, and its dynamics in cropped soils.

17.3 Tillage Impacts on Biological P Cycling

To reduce the risk of soil erosion and to decrease energy consumption and labor related to ploughing, systems of no-tillage and other conservation tillage systems have been established under a wide range of climates and farm types, and are being further developed (Huggins and Reganold 2008; Séguy et al. 2006). Soil tillage

affects the distribution of P along the soil profile and changes the environment of soil microorganisms. Clearest demonstrations of such effects arise from the comparison of soils under conventional tillage using a plough versus no-tillage systems, which are characterized by minimal disturbance to the soil at seeding (direct seeding) and usually by the management of crop residues at or near the soil surface.

17.3.1 Tillage Effects on P Distribution and P Dynamics

Under no-tillage, total and available P concentrations are higher in the topsoil than in the lower soil horizons (Jansa et al. 2003) because fertilizer P as well as P released from plant residues remain at the soil surface. Organic C content is also higher in the topsoil layer of no-tillage soils than in ploughed soils (Daroub et al. 2000; Jansa et al. 2003; Zibilske and Bradford 2003). This is paralleled by increased organic P in the topsoil layer of no-tillage soils (Bünemann et al. 2006a). The greater offer of organic matter for microbial growth results in higher soil microbial biomass and activity (Rabary et al. 2008). In turn, microbial P is higher in the topsoil of no-tillage soils than in ploughed soils (Balota et al. 2003; Daroub et al. 2000). In both studies, plant-available inorganic P also tended to increase, although not significantly. This agrees with the accumulation of total P in the topsoil, but also suggests that greater microbial P immobilization did not reduce available P content, presumably because of microbial P turnover. Zibilske and Bradford (2003) found higher plant-available P, increased phosphatase activity, higher soluble organic C, and greater soil respiration in soils under no-tillage than in ploughed soils, and concluded that greater organic P mineralization occurs under no-tillage. Organic P mineralization may explain why labile organic P fractions were not significantly increased under no-tillage (Daroub et al. 2000).

17.3.2 Interactions Between Tillage, Specific Organisms, and P Dynamics

Soil tillage affects specific organism groups such as earthworms (Ernst and Emmerling 2009) and mycorrhizal fungi (Jansa et al. 2003). Effects can be indirect through a modification of the environment, e.g., the amount and location of organic residues presenting the nutritional basis for some earthworm species. Direct effects are mechanical damage to earthworms or cutting of mycorrhizal hyphae at ploughing. Density, biomass, and community composition of earthworm populations are affected by the tillage system, with decreased tillage intensity having a positive effect on biodiversity (Ernst and Emmerling 2009) but not necessarily on earthworm density and biomass (Berner et al. 2008). Earthworms create structures with characteristics different to those of the surrounding soil (Chapuis-Lardy et al. 2011). Plant-available P concentrations are usually higher in earthworm casts (Chapuis-Lardy et al. 2009; Jiménez et al. 2003)

and in burrow walls (Tiunov et al. 2001). Location and composition of these structures varies depending on the species involved and can be affected by tillage. Likewise, Jansa et al. (2003) showed an effect of soil tillage on the community structure of mycorrhizal fungi in maize roots, and there is functional complementarity among species within the arbuscular mycorrhizal fungi community colonizing a single root system (Jansa et al. 2008). A series of studies carried out at Guelph (Canada) revealed larger early-season P uptake by maize due to a more effective arbuscular mycorrhizal symbiosis when the soil was not disturbed. The larger P uptake was mostly a result of the undisrupted mycelium present in an undisturbed soil, rather than of the increased colonization (Miller 2000). Thus, mycorrhizal symbioses might compensate for the poorer root growth during the early growth stages of maize grown under no-tillage than under conventional tillage (Chassot et al. 2001).

17.3.3 Tillage or No-Tillage: Trade-Offs in the Use of Crop Residues

Direct seeding combined with a permanent soil cover is currently being promoted for small-scale farmers in the tropics (Husson et al. 2006; Séguy et al. 2006). In such systems, the soil is never ploughed and the staple crops (maize, rice, soybean, or cassava) are grown either in a mulch of plant residues (e.g., cereal straw or legume residues) or intercropped with another plant (e.g., Brachiaria ruziziensis or Stylosanthes guianensis). The mulch or the cover crop play a key role in soil protection, organic matter input, nutrient recycling, and weed control. A successful implementation of direct seeding systems requires that plant residues are largely retained in the field. Without sufficient surface cover, soils will compact, infiltration will reduce, maximum temperatures will increase in the surface layer, and crop growth will be negatively affected (Giller et al. 2009). Under such conditions, crops often show signs of P deficiency because of impaired root growth, even though soils may contain sufficient P. Small-scale farmers in sub-Saharan Africa often use crop residues as livestock feed, as firewood for cooking, or traditionally burn them for weed and pest management. When applied to the soil, they are often broken down within a few weeks by termites (Giller et al. 2009). This hampers adoption of notillage systems with direct seeding systems into living or dead mulch. Before direct seeding systems can be recommended to resource-poor farmers in the tropics, tradeoffs between different uses of crop residues need to be evaluated.

17.4 Fertilizer Inputs: The Form of Nutrient Sources Matters

The repeated input of organic amendments such as animal manure, composts, or plant residues usually results in higher soil organic matter content and in larger soil microbial biomass and activity compared to soils receiving mineral fertilizers (Bünemann et al. 2006b; Fliessbach et al. 2007; Liebig and Doran 1999; Wells et al. 2000). The resulting feedback on P cycling has been studied under field situations in different climate zones and on different soil types. Here we present a case study using animal manure.

17.4.1 Animal Manure Promotes Microbial P Cycling: A Case Study on Organic Versus Conventional Farming in Switzerland

The recycling of animal manure is of increasing importance globally (Tiessen et al. 2011). Organic farming largely depends on organic P sources (Oberson and Frossard 2005). Manure P is composed of inorganic and organic forms (Toor et al. 2006). After application to the soil, these compounds undergo abiotic and biotic reactions, which determine the availability of manure P to crops.

In 1978, a long-term experiment was started in Switzerland to study the effects of organic and conventional farming systems on crop performance and soil fertility (Mäder et al. 2002). The trial includes two organic systems (biodynamic and bioorganic), which are both fertilized exclusively with animal manure and receive no synthetic pesticides, in contrast to the conventional systems. The two organic systems differ in the treatment of manure during storage on the respective farms, with composting of farmyard manure and aeration of slurry in the biodynamic system, whereas slightly decomposed manure and slurry are applied in the bioorganic system. Specific to the biodynamic system are the biodynamic preparations described in Mäder et al. (2002), which are used as composting additives or for plant protection. In the two conventional systems, either mixed mineral and organic inputs or exclusively water-soluble mineral fertilizers are applied. The systems differ also in applied P amounts. In both organic systems, amounts are based on manure production by 1.4 livestock units per hectare, whereas in the conventional systems amounts correspond to the Swiss fertilization guidelines, resulting in the average P inputs indicated in Table 17.1. The field experiment includes a control without nutrient inputs. All systems follow the same crop rotation sequence, which lasts for 7 years. Likewise, all systems are under conventional tillage. Because of different plant protection and nutrient input strategies, the farming systems differ in productivity (Mäder et al. 2002). Potato yields in the organic systems were around 60% of those in the conventional plots whereas cereal yields were around 80% and grass-clover yields nearly the same as under conventional management.

Systems that regularly receive animal manure, i.e., both organic systems and one of the conventional systems, maintained a higher soil organic C level than the nonfertilized control or the conventional system with exclusively mineral fertilizers (Leifeld et al. 2009). It was shown that soil microbial biomass and activity is highest in soils of the biodynamic system, followed by the bio-organic and the conventional system receiving manure inputs (Fliessbach et al. 2007; Mäder et al. 2002). On the

	Cropping system						
	Control	Biodynamic	Bio- organic	Conventional mixed	Conventional mineral		
Type of fertilizer	None	Organic	Organic	Organic + mineral	Mineral		
Fertilizer P input (kg ⁻¹ ha ⁻¹ per year) ^a	0	24	27	43	28 ^b (41)		
P balance $(kg^{-1} ha^{-1} per year)^a$	-21	-8	-6	+4	$-5^{b}(+6)$		
Water-soluble P $(mg^{-1} kg^{-1})^{c}$	0.05^{*}	0.4^{+}	0.6^{\ddagger}	1.9 [¶]	$1.0^{\$}$		
Microbial P $(mg kg^{-1})^{c}$	4.7^{*}	11.8^{\dagger}	13.0^{\dagger}	12.1 [†]	6.6^{*}		
Organic P (mg kg^{-1}) ^c	339 ns	379 ns	364 ns	352 ns	349 ns		
Total P (mg kg ^{-1}) ^c	563^{*}	$640^{+,1}$	629^{+}	683 [§]	658 ^{‡,§}		
Acid phosphatase activity (mg paranitrophenol $kg^{-1} h^{-1}$) ^d	nd	182*	172†	nd	148 [‡]		
P mineralization (mg kg ⁻¹ per day) ^e	nd	2.5^{\dagger}	1.7*	nd	1.5*		
Exchangeable P (mg kg ⁻¹ per day) ^f	nd	27.6*	24.8*	nd	31.8 [†]		
Mineralizable P/exchangable P (%) ^g	nd	9.1 [†]	$7.0^{*,\dagger}$	nd	4.9*		
$^{33}PO_4$ incorporation (%) ^h	nd	6.1 [†]	3.8*	nd	2.5^{*}		
Manure P recovery in ryegrass ⁱ	35 [‡]	$28^{*,\dagger}$	$30^{+,1}$	24*	$29^{*,\dagger,\ddagger}$		
Mineral P recovery in ryegrass ⁱ	39 ns	39 ns	43 ns	37 ns	40 ns		
Residual P recovery in ryegrass ^j	na	9^{*}	12^{\dagger}	15 [§]	13 [‡]		

 Table 17.1 P status and indicators of biological P cycling in soils of a field experiment in

 Switzerland under organic and conventional cropping

Values within a line followed by different symbols (*, *, *, *, *) are significantly different (Duncan's multiple range test)

ns not significant, nd not determined, na not applicable

^aAverage annual fertilizer P input (mineral and/or organic) and P balance (difference between P inputs by fertilizers and outputs by harvested products) for 21 years of field experimentation (Oberson et al. 2010)

^bDuring the first crop rotation period lasting 7 years, the conventional mineral system was used as an unfertilized control. The value in brackets therefore shows the average for the second and third crop rotation periods when it was fertilized as conventional mineral system

^cData from Oberson et al. (2010)

^dData from Oehl et al. (2004)

^eBasal organic P mineralization rate per day assessed using isotopic dilution techniques; data from Oehl et al. (2004)

^fQuantity of inorganic P exchangeable within 1 day determined by isotopic exchange kinetics; data from Oehl et al. (2004)

^gRatio between quantities of daily mineralized organic P and isotopically exchangeable P

^hPercentage of applied ${}^{33}PO_4$ taken up by microorganisms 5 days after soil labeling; data from Oehl et al. (2001)

ⁱPercentage of manure P and mineral P, respectively, taken up by four harvests of ryegrass (Oberson et al. 2010)

^jPercentage of residual P taken up by four harvests of ryegrass (Oberson et al. 2010)

other hand, during the course of the field experiment, the total and available P contents decreased more in both organic systems than in the conventional systems because of their P budget deficit (Oehl et al. 2002) (Table 17.1). Thus, in the organic

systems, yields were partly attained at the expense of soil P reserves. In the control, soil P reserves were the only source for crop P uptake.

Several biological processes were shown to be involved in the use of soil P reserves. Monitoring of changes in total P stocks in different soil layers gave evidence that with increasing depletion of available P in the topsoil, crops increasingly took up P from deeper soil layers (Oehl et al. 2002). This process was manifested in all systems having a P deficit. In contrast, microbial functions that promote access to P and availability of soil P were more important under organic than conventional cropping. The percentage of root length colonized by mycorrhizal fungi was 30–60% higher in crops growing in soils from the organic rather than the conventional systems (Mäder et al. 2000). The activity of acid phosphatase, which can be of plant or microbial origin, was also increased under organic cropping (Oehl et al. 2004). A radioisotope P dilution experiment revealed a higher basal mineralization of soil organic P in soils from both organic systems than in the soil under the conventional system without manure (Oehl et al. 2004). Also, soils of the organic systems had a larger microbial P pool with a faster turnover (Oehl et al. 2001) (Table 17.1).

Greater microbial activity in the soils of the organic systems, however, did not significantly affect the P uptake by ryegrass from fresh fertilizers (Oberson et al. 2010). In a pot experiment using radioactive P labeling techniques, we studied the uptake of P applied with animal manure or water-soluble mineral P. In each soil, manure addition increased microbial P content, with similar amounts of P immobilized. Recovery of manure P in ryegrass was lower than that of water-soluble mineral P. It ranged from 24 to 35% for manure, and from 37 to 43% for mineral P (Table 17.1). Differences in microbial activity among soils had little importance in the use of these fertilizers. However, recovery of manure P at higher soil P availability. Because of their lower available P content, organically cropped soils therefore have the potential for higher efficiency of manure use.

In the same experiment, labeling of available P allowed the assessment of the uptake from residual P (composed of plant-available soil P depleted in the control soil but not in the fertilized soils, and of residual fertilizer P remaining in the fertilized soils). Residual P uptake was lowest for the biodynamic soils (Table 17.1), probably because their lower residual P contents were composed of stable P forms (Keller et al. 2009; Oberson et al. 2010). The treatment of manure during storage affects the availability of P (Dao and Schwartz 2011). Presumably, composting of manure prior to application in the biodynamic plots resulted in more stable inorganic and organic P forms.

In conclusion, manure addition stimulates microbial activity, which translates into greater basal soil P mineralization and higher microbial P turnover. Decreases in available P in the topsoil may increase the use of soil P by P uptake from deeper soil layers, particularly in situations where past fertilizer P inputs surplus to crop uptake also increased available P in deeper soil layers. Plant roots as well as mycorrhizae could be involved in this process. On the other hand, we have no evidence that higher microbial activity rendered the poorly soluble soil P fractions available for crop uptake (Oberson et al. 1993; Keller et al. 2009). Also, Dann et al.

(1996) reported that uptake from rock phosphate was equally low in soils under organic and conventional cropping.

17.4.2 Availability and Quality of Animal Manure and Recycling Fertilizers

P limitation in organic farming systems may increasingly limit crop production, particularly on large-scale arable farms with little organic P resources and with neutral to alkaline soils where rock phosphate (the only nonorganic P source permitted in organic farming) is virtually plant-unavailable (Cornish 2009). The use of animal manure is far from specific to organic farming systems but is common in conventional mixed crop-livestock farms. Also, many stockless, conventional arable farms use organic inputs such as organic waste composts or sewage sludge. A compilation on comparative effects of inorganic and organic fertilizers (farmyard manure, sewage sludge, composts) shows that organic fertilizers usually increase the microbial biomass and enzyme activities, whereas the effects of mineral fertilizers are more variable (Bünemann et al. 2006b). They induce no change or enhance biological activity via increases in system productivity and crop residue return or, in some cases, have negative impacts on soil organisms, e.g., through soil acidification (Bünemann et al. 2006b). Thus, the use of organic inputs increases biological P cycling. In industrialized countries, new trends of manure management in large livestock production farms arise, such as gasification or incineration of animal manure (Kuligowski and Poulsen 2009). These treatments remove organic matter and leave a P-rich ash. The products permit the recycling of P, but direct beneficial effects on soil organic matter content and microbial activity are lost.

Small-scale farmers in sub-Saharan Africa, like most subsistence farmers everywhere, use manure, but only in limited quantities. Manure is a rather scarce resource and is of very variable quality (Rufino et al. 2006), whereas mineral fertilizer (particularly P fertilizer) is often expensive. Integrated soil fertility management options for smallholders should consider manure quality and availability as well as access to mineral fertilizer and competing uses for crop residues (Tittonell et al. 2008). Purely organic farming systems are often not viable under conditions where soil P stocks have been depleted and manure is scarce. Therefore, combining mineral and organic resources at practicable and economic rates is recommended (see Sect. 17.6) (Bassala et al. 2008; Vanlauwe et al. 2010).

Interactions between manure and mineral fertilizer application are not clear-cut. Effects of both resources can be additive (Akponikpe et al. 2008) or may interact positively (Abunyewa et al. 2007; Onduru et al. 2008; Opala et al. 2007). However, at the same P dose, water-soluble P fertilizer application often results in a superior response relative to manure addition (Materechera and Morutse 2009). Much depends on the quality of the manure as well as on the inherent soil fertility and the crop. Manure application has positive impacts on the soil organic C content and microbial activity and is essential for the rehabilitation of degraded soils (Zingore

et al. 2008), but if the manure is of inferior quality, soil restoration can only be achieved by combining manure and mineral fertilizer application (Tittonell et al. 2008). Given the limited P resources and the differential resource endowments of farmers, appropriate strategies are required for improving manure storage, quantity, and quality, and for efficient use of both organic and inorganic resources (Rufino et al. 2007).

17.5 Crop Rotation: Higher P-Use Efficiency Through the Integration of Legumes?

Dinitrogen fixation by the symbiotic associations between legumes and rhizobia is a major source of N input into agricultural soils (Herridge et al. 2008). Important arable crops like soybean can largely rely on symbiotically fixed N (Alves et al. 2003). Legumes are an essential part of crop rotations in organic farming systems, but also in many conventional farming systems such as in southern and western Australia or in Switzerland. Nonfixing crops planted after legumes can benefit from the improved N availability (Peoples et al. 2009). Rotational effects of legumes on P availability have also been observed (Bünemann et al. 2004b; Pypers et al. 2007; Muchane et al. 2010).

Here, we focus on the integration of legumes into the crop rotation of smallholder farms in developing countries in the tropics for the following reasons: Population growth in the poor rural areas of developing countries has resulted in land use intensification. Fallow phases formerly used to restore soil fertility have increasingly been reduced and continuous cropping of the major crop (such as maize) has become widespread (Bünemann et al. 2004b; Douxchamps et al. 2010). Often farmers can afford only small amounts of mineral fertilizer or none at all. Soil nutrients are being depleted, and soil erosion due to poor soil cover further increases nutrient losses and soil degradation (Tan et al. 2005). N input through symbiotic fixation is recognized as a key component in the development of sustainable cropping systems (Boddey et al. 2006; Ojiem et al. 2007). P deficiency, however, is seen as the major factor limiting legume growth and symbiotic fixation (Hogh-Jensen et al. 2002; Mafongoya et al. 2004) and is widespread in highly weathered tropical soils. Under these conditions, legumes need specific strategies to satisfy their P requirements.

17.5.1 Legume Strategies for Acquiring P

Plant strategies for acquiring P in P-deficient soils can be grouped as follows:

- 1. Morphological root traits to improve spatial access to soil P
- 2. Increased spatial access to soil P through association with mycorrhizal fungi (Jansa et al. 2011)

- 3. Solubilization of recalcitrant inorganic P and mineralization of organic P in the rhizosphere (George et al. 2011)
- 4. Efficient mechanisms for uptake of solubilized P into the root (George et al. 2011)

Such strategies are not specific to legumes and have also been reported, e.g., for members of the families of Brassicaceae or Asteraceae (Hedley et al. 1982; Smestad et al. 2002).

Deep-rooting legumes such as Sesbania sesban (L) Merr can access nutrients in deep soil layers, e.g., N from a depth of 1 m (Gathumbi et al. 2003). This mechanism may also be significant for P uptake, particularly in highly weathered tropical soils where the topsoil is often P depleted and where gradients in total and available P along the soil profile are less pronounced than in P-enriched soils in industrialized countries (Bünemann et al. 2004b; Friesen et al. 1997). Arbuscular mycorrhizal fungi play an important role in the P uptake and growth of many legumes (Smith and Read 2008) although under low soil P conditions, the yields of crops depending solely on the arbuscular mycorrhizal fungi without any P inputs are lower than upon application of moderate P fertilizer level (Muchane et al. 2010). Arbuscular mycorrhizal fungi appear to access mainly orthophosphate in the soil solution, unlike the fungi forming other types of mycorrhizal symbioses (Jansa et al. 2011). Thus, there is no evidence that they can access significant amounts of recalcitrant inorganic or organic P. Under low-P conditions, P fertilizer application may improve colonization of roots by mycorrhizal fungi (Muchane et al. 2010; Jansa et al. 2011, and references therein), suggesting that arbuscular mycorrhizal fungi can increase fertilizer P-use efficiency by foraging for P within a greater soil volume than the roots, and by building up a strong gradient in P concentration between soil and the mycorrhizosphere. By doing this, plants can utilize P that could otherwise not be taken up by the roots or root hairs. As a particularity of legumes, the tripartite symbiosis between legumes, rhizobia, and mycorrhizal fungi reacts to the P status (Vanlauwe et al. 2000a), thus feeding back on N and P cycling.

Some legume species, including *Lupinus albus*, are nonmycorrhizal but form cluster or proteoid roots in P-deficient soils (Shane and Lambers 2005). Cluster roots are very densely branched roots that excrete large amounts of organic anions (mostly citrate and malate), protons, and acid phosphatases to mobilize phosphate in the rhizosphere (Neumann and Martinoia 2002). Organic anions are, however, not only exuded from cluster roots, but are detected in the rhizosphere of many legumes growing under low P availability. For instance, faba bean (*Vicia faba L.*) acidifies the rhizosphere via release of organic acids and protons (Li et al. 2007). The roots of some P-efficient genotypes of cowpea (*Vigna unguiculata* Walp) and soybean (*Glycine max. L.*) react towards P stress with the exudation of organic acid anions, whereas another P-efficient soybean genotype responds with a higher activity of root surface phosphatase (Jemo et al. 2006). Not all genotypes express these strategies, showing that there is scope for selecting and breeding P-efficient genotypes (Lynch 2007).

It is noteworthy that P-solubilizing microorganisms living in the rhizosphere can also mobilize organic P through the liberation of extracellular enzymes and/or inorganic P through the release of complexing or mineral-dissolving compounds (Jones and Oburger 2011). Jones and Oburger (2011) point out the great potential of coinoculating legumes with dinitrogen-fixing *Rhizobium* sp. and P-solubilizing microorganisms, but also stress the prevailing lack in mechanistic understanding, which currently renders success of inoculation in the field quite erratic.

Because of P acquisition strategies, legumes have access to nonlabile soil P, as demonstrated for cowpea compared to maize (Pypers et al. 2006). They also result in a better use of poorly available P inputs, such as rock phosphate (Vanlauwe et al. 2000b) or phytate (Li et al. 2003). Presumably, neighboring nonlegumes can also benefit from the legume's P acquisition strategies. Results from pot experiments using separated root systems suggest that legumes facilitate P uptake of a neighboring cereal crop from recalcitrant sources. Wheat took up more P from phytate when its roots were intermingled with cowpea roots than when it was growing alone (Li et al. 2003). However, wheat also took up more calcium, magnesium, and microelements (Li et al. 2004). This suggests that enhanced P uptake may result from a better supply of other elements. Thus, radioisotope P techniques should be used to clearly identify the P source used by the crop (Frossard et al. 2011).

17.5.2 Crop Rotations: Can Succeeding Crops Benefit from Legume P Acquisition Strategies?

Many field studies carried out on soils low in available P have shown higher yields for cereals growing after a legume crop than when monocropped (Bagayoko et al. 2000; Bünemann et al. 2004b; Horst et al. 2001; Jemo et al. 2006; Kamh et al. 2002; Pypers et al. 2007). Crops might have attained higher yields because of improved P nutrition through P contained in legume residues or because of better soil P availability because of changed soil properties. Higher crop yields are also attained through enhanced supply of other elements (particularly N), or through weed, disease, or pest suppression. Under field conditions, it is difficult to separate these effects.

17.5.2.1 Legume Residues as a P Source

In most cropping systems, legume residues are produced in situ. They are rarely a net P input because cut and carry systems have never been widely practiced. After decomposition of the legume residues, P taken up by the legume can become available to the succeeding crop. Residue decomposition is mediated by the activity

their quality, particularly on total P, total N, lignin, and soluble polyphenol concentrations (Kwabiah et al. 2003; Vanlauwe et al. 2008). P concentrations in legume residues can vary widely, as a function of species, plant age, and plant part. The organic resource database created by the Tropical Soil Biology and Fertility Program (TSBF) contains information on the quality of plant residues (macronutrients, lignin, and polyphenol contents) (Palm et al. 2001). The median P concentration in 550 legume leaves was 1.7 g kg⁻¹, with 50% of analyzed samples in the range 0.4-3.25 g kg⁻¹. In spite of legumes often having special P acquisition strategies, P concentrations in their leaves was not higher than those of other plant families (Palm et al. 2001).

Plant residue addition induces microbial immobilization and mineralization, which occur simultaneously and involve turnover of residue and soil P (see Sect. 17.2). If mineralization exceeds immobilization, then a net P release results. In several laboratory studies, total P concentration was the best predictor for residue P release, followed by the C:P and N:P ratios of the plant material (Kwabiah et al. 2003; Mukuralinda et al. 2009). Materials with total P concentrations higher than 2.0–2.7 g kg⁻¹, C:P below 156:1 to 252:1, and N:P higher than 7:1 to 14:1 were found to result in a net P release, i.e., an increase in available P in the soil at different times during the 56 days of incubation (Kwabiah et al. 2003). Other materials result in transient net P immobilization. Along the soil food web, C:P ratios decrease because CO₂ is produced, which will finally result in P release. Bünemann et al. (2004a) and Ehlers et al. (2010) have shown that organic substrate decomposition is only retarded by low P availability, but not prevented. Thus, microorganisms cover their need by the uptake of soil P, which involves microbial uptake from less-available soil P pools (Bünemann et al. 2004a, c). Still, experimental evidence that crops benefit from microbial P release is lacking. The higher microbial P pool in cropping systems with more organic inputs is probably rather like a turning wheel that keeps a higher proportion of soil P in a potentially available form (Stewart and Sharpley 1987). This function is important, particularly in highly P sorbing soils (Oberson et al. 2001, 2006).

The application of legume residues increased P uptake by maize (Nziguheba et al. 2000), and the P uptake by cereals growing after a legume was higher than when monocropped (Bünemann et al. 2004b; Horst et al. 2001; Jemo et al. 2006; Pypers et al. 2007), as stated above. Bünemann et al. (2004b) reported that P uptake by maize grown in the maize-legume rotation was about 150% of the P uptake when grown in monoculture, at the same fertilizer P application rate. However, under field conditions, without labeling of P contained in the legume residues or of available soil P, the two sources cannot be separated. In a pot experiment, radioisotope P-labeled residues from faba bean (Vicia faba) and field peas (Pisum sativum) contributed up to 10 and 5% of the total P uptake by corn, respectively, while water-soluble mineral P contributed 20–50% (Nachimuthu et al. 2009). However, in this experiment total plant uptake was low for all treatments, resulting in a fertilizer P recovery of only 3% for mineral P and less than 0.5% for legume residues.

The seminal work of McLaughlin and Alston (1986) on wheat grown in pots showed a significantly lower contribution of P applied with ³³P-labeled legume (Medicago trunculata cv. Paraggio) residues than with ³²P-labeled monocalcium phosphate. About 6–9% of P taken up by wheat was derived from the legume residues, while up to 40% was derived from the mineral P source. The addition of residues depressed wheat biomass production, which McLaughlin and Alston (1986) assigned to microbial P immobilization. Because many legumes contain secondary metabolites with allelopathic activity (Caamal-Maldonado et al. 2001), legume residues may depress plant growth, particularly in pot experiments where the soil volume is limited. Although the pot experiments using radioisotope-labeled inputs indicate that the recovery of residue P in the crop is about six times lower than that of mineral P, recoveries from legume N and mineral N differ somewhat less. Field studies using the application of ¹⁵N-labeled legume residues to maize under tropical conditions indicate that 9-15% of residue N is recovered in the crop (Douxchamps 2010; Vanlauwe et al. 1998), while mineral N recovery in the crop is around 35% (Douxchamps 2010) (see also compilation in Crews and Peoples 2005). Combined N and P tracer studies will improve our understanding of the fate of legume residue-derived N and P in the soil-plant system, but remain limited to studies of a few months duration because of the short half-life of P radioisotopes (Frossard et al. 2011). There is need for long-term field studies on the rotational effects of legumes on N- and P-use efficiency in cropping systems, including the effect on nutrient stocks and forms in the soil.

17.5.2.2 Improved Soil P Availability Because of Modified Soil Conditions

The integration of legumes in the rotation affects the size, activity, and community composition of the soil microbial biomass. Levels of microbial C and P were higher under maize-crotalaria rotation than under maize monocropping (Table 17.2) (Bünemann et al. 2004b). In spite of higher P immobilization in the microbial biomass, maize following crotalaria took up more P than monocropped maize, although it is unclear whether this was driven by increased P supply or by increased demand for P from more vigorous maize because of, e.g., increased N supply. Higher microbial biomass was connected with higher total amounts of phospholipid fatty acids and an increase in the relative abundance of indicators for fungi and Gram-negative bacteria (Bünemann et al. 2004a). Although the species diversity of arbuscular mycorrhizal fungal spores in the soil was not affected by the maizecrotalaria rotation in this field trial, the composition (relative species abundance) of spore communities was significantly altered by crop rotation, with two of the arbuscular mycorrhizal fungi species (Acaulospora scrobiculata and Scutellospora *verrucosa*) spores being more abundant in the rotated as compared to continuous maize plots (Mathimaran et al. 2007). The integration of legumes in a rotation increased mycorrhizal infection of maize (Horst et al. 2001) and other cereals such as pearl millet and sorghum (Bagayoko et al. 2000). Crop rotations versus monocropping also caused a significant shift in the rhizosphere bacterial community

	Crop rotation									
	Continuous maize		Maize-crota	laria fallow	Maize-natural fallow					
	-P	+P	-P	+P	-P	+P				
Fertilizer P input (kg P ha ⁻¹ per year) ^a	0	50	0	50	0	50				
P output (kg ha ⁻¹ per year) ^b	4.0-4.5	8.4–13.8	5.3–9.7	15.6–18.5	3.7–5.3	7.6–9.5				
Annual P balance (kg ha ⁻¹ per year) ^c	-4.2 ± 0.3	38.9 ± 3.8	-7.5 ± 3.1	32.9 ± 2.1	-4.5 ± 1.2	41.4 ± 1.4				
Available P $(mg kg^{-1})^d$	1.9 ± 0.1	7.9 ± 1.6	1.6 ± 0.1	8.3 ± 2.0	1.6 ± 0.4	11.0 ± 3.3				
Microbial P $(mg kg^{-1})^e$	2.8 ± 1.2	2.4 ± 0.9	6.7 ± 0.7	6.8 ± 0.8	5.2 ± 1.3	4.9 ± 1.0				
Organic P $(mg kg^{-1})^e$	310 ± 38	302 ± 29	328 ± 20	357 ± 17	327 ± 35	335 ± 28				
Total P $(mg kg^{-1})^e$	720 ± 26	838 ± 51	721 ± 38	829 ± 19	703 ± 26	837 ± 54				
Residue P recovery in microbial P (%) ^f	11.0 ± 1.4	nd	17.5 ± 2.1	nd	nd	nd				
Mineral P recovery in microbial P (%) ^f	5.1 ± 3.9	nd	3.3 ± 1.8	nd	nd	nd				

Table 17.2 P status and indicators of microbial P cycling in soils of a field experiment in western Kenya under different crop rotations (maize monocropping versus maize–fallow rotations) without (–P) and with (+P) mineral P fertilizer input

Values are average and standard deviations

nd not determined

^aApplied as triple superphosphate

^bP export in maize grains, maize stover, and fallow wood; average of 2 years; modified from Bünemann et al. (2004b)

^cAverage of 2 years [two cycles of short rainy (fallow or maize) and long rainy (maize) seasons]; modified from Bünemann et al. (2004b)

^dDetermined using anion exchange membranes; data from Bünemann et al. (2004b)

^eData from Bünemann et al. (2004b)

^fRecovery of 33-P labeled amendments (residues from *Crotalaria grahamiana* Wight & Arn.) and water-soluble mineral (P, respectively) in microbial P 10 days after amendment application; modified from Bünemann et al. (2004c)

(Alvey et al. 2003), and the increased phosphatase activity in the rhizosphere of cereals grown after legumes was related to microbial activity (Alvey et al. 2001). These results show that several microbial functions modifying P availability to crops are affected by the integration of legumes.

Soils in legume rotations have higher soil organic C content in the topsoil when legume residues are returned to the soil (Bünemann et al. 2004b). Many legumes exude protons into their rhizosphere when actively fixing N. Some tropical legumes,

however, do not acidify their rhizosphere as much as temperate legumes do because their N assimilation products are ureides (Bolan et al. 1991). The pH of bulk soil and in the rhizosphere of cereals was higher when cereals (millet or sorghum) were grown after a legume than when monocropped (Alvey et al. 2001). Changes in soil organic C content and pH can influence microbial activity and directly affect the availability of P and other nutrients. Probably also because of indirect effects on P availability, the recovery of mineral P fertilizer by maize was higher when applied in combination with organic residues than when applied alone (Nziguheba et al. 2002).

Finally, adapted germplasm of crops affects P losses. For instance, genotypic differences in root architecture of the common bean (*Phaseolus vulgaris* L.) led to a 20–50% variation in groundcover by shoots, which was associated with a 50–80% reduction in soil loss by erosion (Henry et al. 2010).

17.5.2.3 Effects Not Related to P

Physical conditions such as soil moisture and temperature are modified when legume residues are used as mulch and/or when soil cover is increased. Soil chemical conditions can also be changed. For example, Alvey et al. (2001) reported that the higher soil pH fed back to cause lower Al availability and enhanced Mg and Ca availability. Most importantly, the integration of legumes in the rotation improves the N supply to the succeeding crop (Bagayoko et al. 2000; Yusuf et al. 2009). Of high impact, however, are phytosanitary improvements such as weed control and suppression of parasitic nematodes (Cherr et al. 2006). These effects can be more important than changes in nutrient supply. For instance, in maize fields in western Kenya, a white lupin cover crop significantly inhibited infestation by Striga hermonthica (Weisskopf et al. 2009). Likewise, the infestation of cereals by plant parasitic nematodes has been reduced in rotations (Alvey et al. 2001; Bagayoko et al. 2000). Microbiological changes in soils under legume-cereal cropping systems may have positive effects on crop performance, but it is often difficult to distinguish causes from effects (Marschner et al. 2004). Still, if repeatedly grown, the legumes themselves can become affected by pests and diseases, and their biomass production and resulting benefits can decrease dramatically (Bünemann et al. 2004b).

17.5.3 Limitations of the Approach to Integrate Legumes in Crop Rotations

To benefit from the symbiotic N fixation potential of legumes, an external P fertilizer input is required on low-P soils (Okogun et al. 2005). On P-deficient sites, legume–cereal rotations (Bünemann et al. 2004b) or legume–maize intercropping systems (Mucheru-Muna et al. 2010) receiving P fertilizers are more productive than without fertilizer P input (Table 17.2). On strongly P sorbing soils, the

repeated addition of low doses of P fertilizers placed in the vicinity of the crop is recommended over single, high input doses (van der Eijk et al. 2006).

Legumes can accelerate soil P depletion if greater P export in the legume-cereal rotation is not balanced by fertilizer inputs (Table 17.2) (Bünemann et al. 2004b). The extent depends on the use of legumes and the productivity of the system. In the case of green manure cover crops, soil P taken up by the legume is recycled on the plot, but increased P output by the cereal (Table 17.2) needs to be compensated. In the case of grain or forage legumes, both the legume and the cereal remove P. Thus, P removal by the legume and the main crop (often a cereal) is usually higher in rotations than under monocropping and has to be compensated unless total soil P stocks are high and a limited reduction is justifiable. When legumes are used as animal forage, management of animal excreta becomes a key issue because, e.g., growing beef cattle and lactating cows convert approximately 15 and 25% of dietary P into carcass and milk P, respectively, and the rest goes into manure (Satter et al. 2005). Thus, under grazing a large proportion of legume P is recycled on the plots although spatial distribution of animal excreta is usually not homogenous. If animals are kept in paddocks or in a cattle shed, excreta can be collected, stored, and used as fertilizer. However, the infrastructure to do so is often poor in smallholder systems and measures to improve manure management should receive more attention (Rufino et al. 2006).

17.6 Integrated P Management for Sustainable P Use

Because of the P resource scarcity and the environmental and economic implications of P use (Tiessen et al. 2011), we need to optimize P-use efficiency in soil-plant systems, i.e., attain highest yields for a given P application rate. This requires that fertilizer P is either taken up by the crop and efficiently converted into biomass, or that it is kept in the soil in a potentially plant-available form for a subsequent crop. Based on the definitions of Vanlauwe et al. (2010) for Integrated Soil Fertility Management, and of Frossard et al. (2009) for Integrated Nutrient Management, we define Integrated P Management in cropping systems as follows: Integrated P Management aims at maximizing P-use efficiency in the cropping system while minimizing P losses to the environment and optimizing economic benefits. It considers all the biophysical components involved in P cycling as well as the relevant socioeconomic factors such as the production preferences of farmers, the food preferences of consumers, the markets, and trade policy. It includes the use of mineral and organic P sources, of improved germplasm, and of measures to control P losses to the environment, combined with the knowledge of how to adapt these practices to local conditions (Fig. 17.2).

The availability of soil and fertilizer P manifests the global divide in the distribution of this vital resource. The national P budgets of agriculture in industrialized countries often have a P surplus (Sharpley et al. 2005) whereas the P budgets of developing countries often have a deficit (Lesschen et al. 2007). In turn,



Fig. 17.2 Conceptual relationship between the P-use efficiency in smallholder cropping systems, where P limits crop production, and the implementation of various components of integrated P management. Soils that are responsive to P fertilizer (*solid line*) and those that are poor and less-responsive (*dotted line*) are distinguished. At constant fertilizer application rates, yield is linearly related to P-use efficiency (adapted from Vanlauwe et al. 2010)

soils of industrialized countries, particularly in areas with high livestock densities, are over-fertilized with P while soils in developing countries in the tropics are often P depleted. There is variation within countries, regions, and even within farms (Cobo et al. 2010). Different fields of a single farming household respond differently to fertilizer, which results in differential P-use efficiency (Vanlauwe et al. 2006). This variability needs to be accounted for by considering the local conditions, as suggested in the definition of integrated P management.

For cropping systems where soil nutrients are mined using the current practice, we can deduce the following recommendations:

- 1. Mineral fertilizer use needs to increase to improve crop production.
- 2. P use by crops needs to be maximized through the appropriate timing and placement of the fertilizer in the vicinity of the crop roots, and by the use of crop germplasm with a high P acquisition and/or a high P conversion efficiency (Fig. 17.2).
- 3. The introduction of legume fallows or green manures (which are system internal organic resources) can enhance P cycling and P use in the cropping system.
- 4. The proper reuse of animal manure and urban solid and liquid wastes is an important part of sustainable P use.
- 5. P losses by erosion and run-off have to be minimized. Minimal tillage and retention of groundcover, including legume cover crops, increases soil cover and reduces the risk of P losses.

In general, there are positive relationships between P-use efficiency, environmental friendliness, and profitability, but trade-offs may exist, e.g., as shown in Sect. 17.3.3 for the use of plant residues. The Integrated P management measures need to be adapted to the local conditions:

- 1. Input rates need to be tuned to the fertility level of the soil in each field and for each crop.
- 2. Degraded fields may not respond to P inputs because they are constrained by other factors, such as high soil acidity, moisture availability, or other nutrient deficiencies. Such soils typically require additional investments such as liming, erosion control measures, or organic amendments at high rates. Microbial inoculations may enhance P dynamics in degraded soils and thus support their restoration.
- 3. The management of organic P inputs needs to consider the availability and quality of animal manure and other organic resources, and competitive uses, e.g., the use of legume biomass as a green manure versus animal feed.
- 4. If reduced tillage is practiced, then sufficient biomass must be produced and retained to ensure adequate groundcover. The applicability of these technologies will therefore vary across agro-ecological zones, farming systems, and niches within the farm.

On soils where plant-available P concentration is sufficiently high for yields to be at the economic optimum, no additional P inputs are needed. In fields with very high concentrations of soil P, reflecting many years of over-fertilization or animal manure disposal, measures to reduce P losses are crucial. In farms and regions with surplus manure P, animal manure P should be applied to fields where P inputs are required and where the risk of P loss to the environment is low. However, because of the disintegration of agriculture into specialized farms, specialized regions, and even specialized countries, local nutrient cycles have been disrupted (Schröder 2005; Dao and Schwartz 2011). The P surpluses in industrialized countries are caused by feed and fertilizers imports, often from continents with predominantly low-P soils (Tiessen et al. 2011). Also, the global trend of urbanization results in sinks for P exported from arable fields, unless cities have an infrastructure for wastewater treatment that enables the proper reuse of sewage P. Sustainable P use requires recycling of P excreted by animals and humans back to the agricultural land in need of P.

17.7 Final Remarks and Research Needs

Farmer intervention affects biological processes in P cycling. Enhanced microbial P cycling is closely linked to the presence of organic matter and the use of organic inputs. Substantial amounts of P can be immobilized and released by microorganisms, with temporal dynamics depending on the characteristics of the inputs and on environmental conditions. We do not yet have sufficient knowledge about the

source of microbial P uptake. In particular, we do not know how to enhance access to recalcitrant inorganic and organic P. Also, there is a need to improve the understanding of the pathways that render microbial P available to crops. This knowledge is required to manage microbial immobilization and release of P so that there can be greater synchrony and synlocation with plant demand.

Tillage clearly affects P cycling, but the impacts of direct seeding systems on P dynamics and on the use efficiency of soil and fertilizer P need to be studied in more detail under different agro-ecological and socio-economic conditions, and with different scenarios of crop residue use.

We do not yet sufficiently understand how germplasm, which is efficient in P acquisition, can contribute to overall use efficiency of P inputs in rotation or intercropping systems. The N benefits of legume varieties with low N harvest indices and high N fixation capacity have been demonstrated and verified, but the contribution of P-efficient legume varieties with specific root architecture and P mobilization capacity to the recovery of P inputs is much less understood, especially if they influence microbial diversity and P pools.

Recently, great progress has been made in analyzing the biodiversity of microorganisms, but the significance of the microbial biodiversity in P dynamics is not understood. Often, large proportions of soil P are kept in recalcitrant forms, and also residual fertilizer and rock phosphate have limited availability for crops. There is a need to establish a better linkage between the microbial community composition and microbial P functions in cropping systems, and to understand under which conditions the combination of organic inputs with inoculants can improve P use.

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