

See discussions, stats, and author profiles for this publication at:
<https://www.researchgate.net/publication/309204145>

Phosphorus fertilization and management in soils of Sub-Saharan Africa

Chapter · January 2016

CITATIONS

0

READS

202

4 authors, including:



Idupulapati M. Rao

International Center for Tr...

268 PUBLICATIONS 5,873

CITATIONS

SEE PROFILE



Rolf Sommer

International Center for Tr...

81 PUBLICATIONS 1,063

CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:



Meta-analysis of crop response to fertilizer as a basis to design site-specific fertilizer recommendation [View project](#)



soil microbiology [View project](#)

8 Phosphorus Fertilization and Management in Soils of Sub-Saharan Africa

*Andrew J. Margenot, Bal R. Singh,
Idupulapati M. Rao, and Rolf Sommer*

CONTENTS

8.1	Introduction	152
8.2	Phosphorus Chemistry and Cycling in Soils	155
8.2.1	Factors Controlling P Availability in Soils.....	156
8.2.2	Organic P.....	157
8.2.3	Soil Conditions Relevant to P Management in SSA.....	157
8.2.4	Knowledge Constraints on Soils Affect P Management	159
8.3	SSA versus Global P Fertilizer Use and Trends	161
8.4	Types of P Inputs	162
8.4.1	Inorganic P Sources	162
8.4.1.1	Phosphate Rock: The Basis of Concentrated P Inputs.....	163
8.4.1.2	PR Chemistry and Quality.....	163
8.4.1.3	PR Deposits in SSA	165
8.4.2	Strategies to Improve P Solubility of PR.....	165
8.4.2.1	Biological Approaches	165
8.4.2.2	Physical and Chemical Treatments	167
8.4.3	Soil Properties: Interactions and Trade-Offs for Inorganic P Inputs.....	168
8.4.4	Organic P Resources.....	170
8.4.4.1	Mechanisms by Which Organic Inputs Improve P Availability	170
8.4.4.2	Manure	171
8.4.4.3	Plant-Based OM: Residues and Green Manures.....	172
8.4.4.4	Overlooked P Sources: Waste Streams and Ash.....	174
8.4.4.5	Crop Rotations: Legume Interactions with P Inputs.....	175
8.4.5	Combining Inorganic and Organic Amendments.....	176
8.4.6	Indirect P Management by Liming to Ameliorate Fixation	176
8.4.6.1	Liming Decreases Sorption of Native and Added P in Soils	176
8.4.6.2	Considerations on the Use of Lime in Acid, P-Deficient Soils.....	177
8.4.6.3	Liming for P Management in SSA.....	178

8.5	Assessment of P Availability in Soil	179
8.5.1	Soil Phosphorus Tests	180
8.5.2	Sink-Based Methods	180
8.5.3	P Sorption Measurements	181
8.5.4	Sequential Extraction: Hedley Fractionation	181
8.6	Improving P Efficiency of Crops for Low P Soils	182
8.6.1	P Acquisition Efficiency	183
8.6.2	P Use Efficiency	185
8.6.3	Precision Agriculture	186
8.7	Modeling Crop Response to P	186
8.8	Conclusions and Research Perspectives	189
	Acknowledgments	190
	References	190

8.1 INTRODUCTION

Phosphorus (P) is an essential plant nutrient that is required for all major developmental processes and reproduction in plants (Marschner 1995). P is involved in plant energy relations and in the structure of nucleic acids. In soils, P is available to plants in the form of hydrated orthophosphate in the soil solution. Purple or bronze leaves are common P deficiency symptoms (Figure 8.1). In plants, reductions in leaf expansion (Rao and Terry 1989) and also number of leaves (Lynch, Läuchli, and Epstein 1991) are the most obvious symptoms of P deficiency. Compared with shoot growth, root growth is less inhibited under P deficiency, leading to a typical decrease in shoot/root ratio (Fredeen, Rao, and Terry 1989). P is also a major constituent of fertilizers required to improve and sustain crop yields. Low P soils support 70% of all terrestrial biomass and also account for over half of the total agricultural land (Lynch 2011). Soils containing insufficient amounts of plant-available P not only produce economically unacceptable yields but also decrease the efficiency of other inputs, particularly nitrogen (N). Thus, there is an urgent need to seek strategies by which P fertilizers can be used more effectively in those farming systems where P is currently deficient and where their use is economically feasible.

In sub-Saharan Africa (SSA), soil P availability is declining because of soil degradation. The low availability of soil P is a major constraint to agroecosystem productivity in SSA due to interrelated material (e.g., soil properties, crop germplasm), knowledge (e.g., input management), and socioeconomic (e.g., market access, input costs, best practices) factors. Material investments are necessary to overcome low P reserves resulting from weathering processes, strong cultivation intensity, and/or limited P additions. These material investments must be complemented by knowledge investments, the lack of which constrain and undermine resource use efficiency and farmers' capacity and willingness to make future investments. Such knowledge investments include management practices like application rates and methods, which in turn are supported by soil surveys and field trials to determine soil- and crop-specific P management. Both material and knowledge investments in P management face unique but interrelated challenges in SSA.



(a)



(b)

FIGURE 8.1 (See color insert.) (a) Phosphorus-deficient 20-day maize exhibiting characteristic purple veining and stunting consistent with low available soil P (1.9 mg kg^{-1} soil, Olsen test). (Courtesy of International Plant Nutrition Institute, Peachtree Corners, Georgia, <http://media.ipni.net/>.) (b) Phosphorus omission trial demonstrating severe stunting in the check (no P added; left) as compared to a 33 kg P ha^{-1} treatment (right). (Courtesy of Dr. Thomas Morris.)

Low inherent nutrient reserves, especially for P in highly weathered soils that are prevalent in SSA, combine with soil degradation to contribute to food insecurity. For example, in East Africa, the majority of agricultural soils are estimated to experience P limitations, e.g., >50% in Tanzania (Okalebo et al. 2007) and 80% in Kenya (Jama and Van Straaten 2006). P deficiency limits the efficiency of other resources

like N and water, which may often limit agricultural productivity in resource-poor regions of SSA. However, the projected increase in N inputs with stagnant P inputs is expected to increasingly unbalance the input N:P ratio in SSA agroecosystems, with negative effects on future crop yields (van der Velde et al. 2014).

In addition to replenishment of nutrients as a sound management practice, net addition of P is necessary—sometimes termed *investments in soil P capital* (Buresh, Smithson, and Hellums 1997; Sanchez et al. 1997; Sanchez 2002). Increasing cultivation intensity and nutrient export of long-cultivated and/or weathered soils with already low P availability is largely not being compensated by P inputs. For each ton of maize dry matter harvested, 2–4 kg of P is removed (Simpson, Okalebo, and Lubulwa 1996). The result is mining of soil P, which in SSA is estimated at 3 kg ha⁻¹ year⁻¹ (Stoorvogel, Smaling, and Janssen 1993; Mwangi 1996). While mining of soil P is generally lower than that of other nutrients like N, there is no opportunity for fixing P from an atmospheric pool. Indeed, the declines in crop productivity with continued cropping in regions like East Africa are largely attributable to negative P balances (Mnkeni, Semoka, and Buganga 1991; Bekunda, Bationo, and Ssali 1997). The strategic management of P including, external inputs, is needed to improve and sustain yields in SSA.

Nutrient balances alone cannot adequately describe P deficiencies, because a high proportion of soil P can be fixed in biologically unavailable forms (Smaling, Nandwa, and Janssen 1997). Such phosphate fixation capacities are another constraint and tend to co-occur in weathered soils with generally low P stocks. Acidity for such soils is also common, meaning that farmers often face P deficiencies in tandem with Al toxicity (Roy and McClellan 1986). High P saturation capacities of weathered soils compromise input-only approaches to P deficiencies.

The presence of regionally and locally available resources such as phosphate rock (PR), manure, and green manure crops provides lower cost and ultimately more realistic options for improving soil P availability. Recent geological surveys have identified P resources in East Africa, including PR and lime in southern Tanzania (Kalvig et al. 2012). These offer local inputs for regional use in a relatively unprocessed form that may remove the dependency on expensive processed and/or imported inputs. Yet P management in SSA has yet to address the master variable of soil fertility: pH. Given the strong pH control on P availability and fixation, and the common co-manifestation of Al toxicity in acid soils, we emphasize the potential of pH management as an indirect way of managing soil P in SSA. In contrast to other regions with similar soil constraints such as the Brazilian *cerrados* or the Colombian *llanos*, liming in SSA is relatively underutilized despite its proven track record to markedly increase the productivity of acid, weathered soils (Sánchez and Salinas 1981). Liming offers resource-strapped SSA farmers greater mileage on of limited P inputs and overall improvements in soil fertility from acidity amelioration (Margeton and Sommer 2014).

Strategic P management in SSA also requires investment in knowledge resources, such as mapping of soils and establishing P response trials to determine appropriate soil P test levels. These are the less commonly addressed challenges to P management specific to SSA. The unavailability and/or the affordability of analytical methods for (1) assessing the quality of low-cost, local alternatives to concentrated and

soluble but high-cost P inputs like triple super phosphate (TSP) and (2) diagnosing P deficiency and fixation potential limits research and outreach in regions such as East Africa (Nziguheba 2007). Field data increasingly support the notion that one-size-fits-all approaches are not useful and are potentially problematic for the management of nutrients like P in a region as diverse in soils and climates as SSA. For example, a recent study dismisses the idea of a best P management when considering the net financial returns to farmers, instead highlighting the interactions of P input type (PR vs. TSP), other nutrient inputs, and the high variability of the agronomic response and the financial returns to the same P management strategies (Lamers, Bruentrup, and Buerkert 2015a,b).

Finally, knowledge capital applies to soil management. The high variability of soil conditions in SSA suggests that investments in soil P capital will be most successful if management recommendations and practices are regionally tailored to agroecological zones (Bationo et al. 2006). Broad generalizations are not helpful for the site-specific management that is needed. The diversity of soil conditions, compounded by management, encompasses different kinds of constraints and opportunities for increasing available soil P.

The objective of this review is to assess the developments in P management in SSA, with specific reference to the soil, crop, and economic conditions unique to the subcontinent. To this end, we provide a brief summary of the basic principles of P chemistry and plant uptake and how these principles play out under the confluence of soil conditions, resource availability, and managements. Furthermore, we strive to identify promising and underexplored approaches to P management.

8.2 PHOSPHORUS CHEMISTRY AND CYCLING IN SOILS

Phosphorus is the tenth most abundant element on earth yet the second most limiting nutrient across biomes (Walker and Syers 1976; Canfield, Erik, and Bo 2005). It is essential to life because of the structural (DNA, RNA, phospholipids) and functional (ATP, NADPH) roles it performs in cells. Inherent chemical properties make P unique in its biogeochemical cycling, particularly in comparison to the other major nutrients for ecosystem productivity. In contrast to other elements such as carbon (C), N, and sulfur (S), the challenges to monitoring biogeochemical transformations of P result from its unique chemistry: P has no gas phase, only one stable isotope (^{31}P), and exists almost exclusively in one oxidation state (+5) (Blake, O'Neil, and Surkov 2005). Due to its largely linear biogeochemical cycle, P is highly limited in weathered soils, which constitute a significant (29%) portion of soils globally (Sanchez and Logan 1992; Vitousek et al. 2010). Generally, plant-available inorganic P is scarce relative to organic P (P_{org} , 20–90% of the total soil P), through which the existing P in terrestrial systems is cycled (Harrison 1987; Celi and Barberis 2005; Jones and Oburger 2011; Turner and Engelbrecht 2011).

In soils, contrasting but coupled abiotic and biotic processes regulate P cycling and availability, including sorption to minerals and mineralization of organic P (Oberson et al. 2011). The mineral weathering of phosphates occurs at low rates that are generally insufficient to meet crop demand, exacerbated by P export via harvesting and losses (chiefly erosive). The result is that agroecosystems face simultaneous

strong demands for P and limitations on its availability, a dynamic that is exacerbated in input-limited systems of SSA.

This section provides a brief overview of the soil conditions governing P availability. For further reading on P cycling and geochemistry, other reviews are available. As a starting point, the reader is referred to a review of P geochemistry during pedogenesis (Walker and Syers 1976) and a discussion of the drivers of P limitation in terrestrial systems (Vitousek et al. 2010). Other reviews are also recommended to understand the different aspects of organic P cycling (Turner, Frossard, and Baldwin 2005) and the role of biological drivers of P cycling for its management in agroecosystems (Oberson et al. 2011).

8.2.1 FACTORS CONTROLLING P AVAILABILITY IN SOILS

The chemistry of phosphate in soil involves interactions with mineral and organic soil components, which in turn govern its availability for crop uptake and mediate soil P dynamics in response to management practices like P inputs. The strong influence of edaphic properties, most notably interactions of pH and mineralogy, mean that soil P cycling and its availability to crops can strongly vary by soil type.

Soil P chemistry is dominated by pH-dependent binding processes and consequent precipitation of P (Sharpley 1995). Plants uptake phosphate (PO_4^{3-}) from the soil solution in the form of orthophosphate: HPO_4^{2-} or H_2PO_4^- depending on the soil solution pH (Tisdale, Nelson, and Beaton 1985). As an anion, phosphate can bind to positively charged binding sites on the surfaces of soil minerals and soil organic matter (SOM). Strong binding of phosphate by cations and consequent precipitation are strong controls on P availability: Fe^{2+} and Al^{3+} at low pH and Ca^{2+} at high pH (Figure 8.2).

Adsorption to mineral surfaces is influenced by pH, because soil solution proton concentration affects the surface charge of minerals and SOM and thus the number and strength of P-binding sites. For variable charge minerals, commonly present in weathered minerals (e.g., kaolinite), soil pH also strongly influences P sorption.

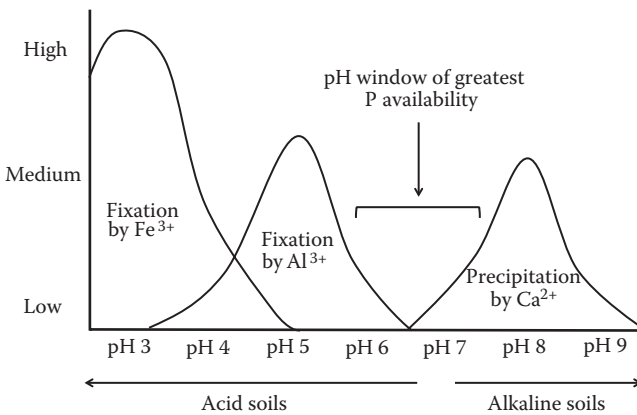


FIGURE 8.2 Influence of soil pH on soil phosphorus availability by binding of cations.

Downloaded by [University of California, Davis (CDL)] at 09:24 03 November 2016

For example, the maximum adsorption of phosphate to kaolinite was observed at pH values of 4–5 and rapidly decreased above pH 6 (Chen, Butler, and Stumm 1973). Phosphate sorption to iron (hydr)oxide goethite is maximized at pH 5–6 and decreases to 60% of this value at pH 9 (Hawke, Carpenter, and Hunter 1989). Surface area effects are critical because they increase potential binding sites of plant-available inorganic P. For this reason, amorphous Fe and Al (hydr)oxides possessing greater surface area than crystalline forms have greater P retention potential. Likewise, SOM exhibits pH-dependent binding sites for phosphate and other anions, which would be expected to substantially influence P sorption at high SOM levels and low pH values. However, P sorption to SOM is thermodynamically weaker than its bonds with Al, Fe, and Ca.

8.2.2 ORGANIC P

In unmanaged and many managed systems, P in biomass and thus largely in organic forms is the chief input to soils. Organic P has a unique role in meeting crop P demand in tropical regions because of (1) the high potential turnover of organic P into plant-available inorganic P (mineralization) under warmer climates and (2) the lower fixation of organic P forms by mineral surfaces relative to inorganic P in weathered soils that are prevalent in such regions.

The mineralization of organic P can contribute up to 25 kg P ha⁻¹ year⁻¹ in mineral soils and as much as 160 kg P ha⁻¹ t year⁻¹ in organic soils (Sharpley 1995). Thus, enzymes performing mineralization of organic P, known as phosphatases, can significantly influence P availability (Vance, Uhde-Stone, and Allan 2003; Turner and Engelbrecht 2011). Phosphatases are able to mineralize P which is subsequently competed for by geochemical and biological sinks (Esberg et al. 2010). Weathered soils are generally P-limited and consequently display increased enzymatic pressure on P cycling (Stursova and Sinsabaugh 2008; Sinsabaugh, Hill, and Follstad Shah 2009; Sinsabaugh and Follstad Shah 2012; Waring, Weintraub, and Sinsabaugh 2014). Organic P tends to accumulate in soils largely as inositol P forms (Turner et al. 2002), the recalcitrance of which may reflect stabilization by mineral weathering products such as iron and aluminum oxides (Turner, Richardson, and Mullaney 2007; Turner and Blackwell 2013).

8.2.3 SOIL CONDITIONS RELEVANT TO P MANAGEMENT IN SSA

In general, P deficiency is one of the largest constraints to crop production in SSA agroecosystems owing to (1) low native soil P and (2) high P fixation capacity. This reflects pedogenic factors: a high degree of weathering and/or a low concentration of P in the parent material (van der Waals and Laker 2008; Sugihara et al. 2012). Ultisols and Oxisols therefore represent as much as 70% of P-deficient soils globally (Fairhurst et al. 1999). These two soil orders are estimated to constitute 20.5% of the total land area in Africa (Table 8.1). Soil acidity has a strong control on P availability with P availability maximized between pH 6 and 8 (Figure 8.2), yet less than 22% of African soils exhibit pH values in this range. Specifically, 14.7% of soils exhibit pH < 5.5, which favors P fixation by Al and Fe, and nearly half of all African soils are above

pH 8.5, which favors P fixation by Ca (Table 8.2). However, the majority of these less weathered (Entisols, Inceptisols) and alkaline soils tend to occur in North Africa. As a result, the majority of soils in SSA, in particular cultivated areas, are generally weathered and low in pH (Figure 8.3).

In addition to pH and mineralogy, soil texture and morphology can influence P availability. For example, low-permeability horizons in the profile can prevent the downward movement of P inputs (Allen et al. 2006). Although P is generally considered less mobile than N, P translocation can be significant even in fine-textured soils. For example, on a clay soil, up to 45% of P applied at 50 kg P ha⁻¹ year⁻¹ for 4 years

TABLE 8.1
Prevalence of Soil Orders in Africa, USDA Classification

Soil Order	Area (10 ³ km ²)	Percentage of Total
		Land Area
Andisols	49	0.2
Histosols	15	0.1
Spodosols	31	0.1
Oxisols	4389	14.3
Vertisols	990	3.2
Aridisols	8076	26.4
Ultisols	1906	6.2
Mollisols	70	0.2
Alfisols	3200	10.4
Inceptisols	2378	7.8
Entisols	7506	24.5
Nonsoil surface	2063	6.7

Source: Eswaran, H., R. Almaraz, E van den Berg, P. Reich. *Geoderma*, 1.77:1–18, 1997.

TABLE 8.2
Estimated Distribution of Soil pH across Africa

pH	Area (10 ³ km ²)	Percentage of Total
		Land Area
<3.5	31	0.1
3.5–4.2	1193	3.9
4.2–5.5	3278	10.7
5.5–6.5	4306	14
6.5–8.5	6997	22.8
>8.5	14,845	48.4

Source: Eswaran, H., R. Almaraz, E van den Berg, P. Reich. *Geoderma*, 1.77:1–18, 1997.

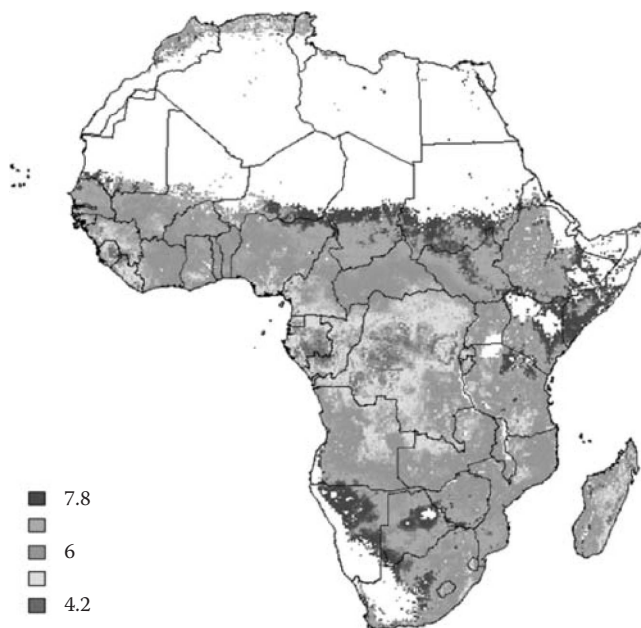


FIGURE 8.3 (See color insert.) Working map of predicted pH of surface soil (0–5 cm) developed by AfSIS. Note the prevalence of acidic (pH < 7) soils in SSA. (Courtesy of AfSIS, Wageningen, Netherlands, <http://soilgrids.org>.)

was not accounted for in 0–15 cm layer, and up to 69% for a sandy soil. The lower mineral oxide content in the sandy soil likely resulted in greater leaching (Sugihara et al. 2012). Such results suggest the need to literally dig deeper and consider soil depths beyond typical surface sampling depths to establish meaningful soil P budgets. Although the vertical distributions of total and labile P are generally surficial compared to other nutrients (Jobbágy and Jackson 2001), soils in the tropics, including weathered soil orders, can exhibit variable vertical P trends (Dieter, Elsenbeer, and Turner 2010).

8.2.4 KNOWLEDGE CONSTRAINTS ON SOILS AFFECT P MANAGEMENT

The residual effect of P inputs and the effect on soil P by other parameters sensitive to land use history require improved soil maps and soil testing. Better recommendations can be supported by high-resolution soil maps, in conjunction with trials that calibrate P application rates to match specific locations with local recommendations. Here, the importance of soil maps is discussed; soil testing for P is addressed in Section 8.5.

As for many parts of the world, soil maps for SSA are often too low resolution to be of use for land management (Sanchez et al. 2009). Soils maps are developed at different scales for different purposes. For example, in USDA soil taxonomy, order 5 is 1:5,000,000 and order 1 is 1:1000. A map at 1:1,000,000 is limited to showing

soil suborder groups, which can be useful for showing regional soil constraints to agriculture (Soil Survey Staff 2015). Order 1:190,000 is commonly used for county-wide projections in the United States for agricultural mapping. The small size and heterogeneity that defines SSA smallholdings (Vanlauwe et al. 2014) as well as their strong management-induced soil fertility gradients (Tittonell et al. 2013) suggests the need for high-resolution soil maps, with emphasis on soil properties useful to and/or influenced by management, such as cation exchange capacity (CEC), pH, and C content (Sanchez et al. 2009). Thus, at the scale of smallholder agriculture (<2 ha) in East Africa, conventional soil maps at order 1 are appropriate.

Nevertheless, legacy maps are often the only soil maps available for many regions of SSA. For example, soil mapping done in 1980 (Sombroek, Braun, and van der Pouw 1982) is used as a basis for soil characterizations in Kenya, despite the 1:1,000,000 scale used. As Sombroek, Braun, and van der Pouw (1982) pointed out, this soil map was exploratory and meant to provide general information on the land use potential. However, their maps continue to be the basis for many soil descriptions, e.g., the Acrisol–Ferralsol association in western Kenya. Such low-resolution maps and broad soil classification are not helpful for practical soil fertility management.

To this end, rapid advancements are being made on techniques and approaches to construct high-resolution soil maps for SSA. The African Soil Information Service (AFSIS) develops digital soil maps for 17.5 million km² across 42 nations on the continent. With a resolution of 1000–250 m, these soil maps offer improvement over legacy maps and provide information on currently unmapped regions. AFSIS and its collaborators employ remote sensing (satellite-based) measurements and legacy soil profiles ($n = 12,000$) for a total of 28,000 sampling points, in tandem with regression techniques (Vågen et al. 2010; Leenaars 2013). A related effort is the infrared-based prediction of soil properties to provide maps based on soil C, pH, or clay content (Figure 8.3) (Sanchez et al. 2009). Like remote sensing, these approaches are regression based. A trade-off of their rapidity is the limitation to maps of surface soils.

Though digital maps can provide accurate predictive maps of certain soil parameters useful for basic fertility baselines (e.g., clay content, CEC, pH) (Minasny et al. 2009; Terhoeven-Urselmans et al. 2010), the prediction of soil P is more difficult. Infrared spectroscopy is well suited to predicting soil properties relevant to P management (pH, mineralogy, P fixation capacity), but less so to P pools, in particular labile P (Bogrekci and Lee 2005; Hu 2013; Soriano-Disla et al. 2013). Interactions of P with soil components means that its availability can be decoupled from C, in contrast to N (Turner, Frossard, and Baldwin 2005) and is often fundamentally different from other nutrient cations like potassium (K), creating a challenge for its spatial prediction relative to other nutrients. For example, across 385 smallholdings in Niger involved in yam cultivation and encompassing a diversity of management practices, the spatial modeling of N and K could successfully provide site-specific recommendations for these nutrients (Jemo et al. 2014). In contrast, soil P was poorly spatially modelled, and as a result, the management recommendations for P were limited to regional scale, in contrast to N and K.

8.3 SSA VERSUS GLOBAL P FERTILIZER USE AND TRENDS

The application of concentrated fertilizers to soils in Africa has been very low in comparison to other regions of the world (Figure 8.4). Fertilizer use, in the continent, especially P and K, has been stagnant in the last three decades but has markedly increased in other regions of the developing world, such as East and South Asia and Latin America. For example, by the turn of the century, fertilizer use in Africa was 8 kg ha⁻¹, compared with 96 kg ha⁻¹ in East and Southeast Asia and 101 kg ha⁻¹ in South Asia (Morris 2007). The consumption of P fertilizers in all SSA countries except Ethiopia has generally decreased or stagnated in the past decade and, in some countries such as in Uganda and Mozambique, remains very low (Table 8.3).

The limited use of fertilizers is determined by a variety of reasons. These include high purchasing costs, especially after market reforms removed subsidies in African nations, inefficient marketing systems, and restricted markets for outputs that constrain investment opportunities (Bekunda, Sanginga, and Woomer 2010; Sommer et al. 2013). Additional constraints on the profitability of fertilizer use include low access to agricultural technologies like seeds and irrigation. Transportation costs can also be a significant obstacle to fertilizer accessibility. As a result, in nations like Nigeria, the reduction of transportation costs is estimated to have a greater effect on fertilizer profitability than fertilizer subsidies (Liverpool-Tasie et al. 2015).

The trend of low fertilizer use in SSA has been partially reversed with the introduction of targeted subsidies by African governments such as Malawi and Kenya (Sommer et al. 2013). As a result, the prospects of the increased use of mineral fertilizers in such nations are promising. In 2013, it was estimated that African governments allotted nearly US\$ 1 billion annually to fertilizer subsidies (Jayne and Rashid 2013). If the average application rates of inorganic fertilizer in SSA rose to 50 kg ha⁻¹, from 10 kg ha⁻¹ currently, there would be a substantial impact on agricultural yields (Larson and Frisvold 1996). However, recent work highlights the significant role of the illicit use of funds in smart subsidy programs in overestimating fertilizer use in case study nations of Kenya, Malawi, and Zimbabwe (Jayne et al. 2013). Additionally, conventional benefit-cost analyses tend to overestimate

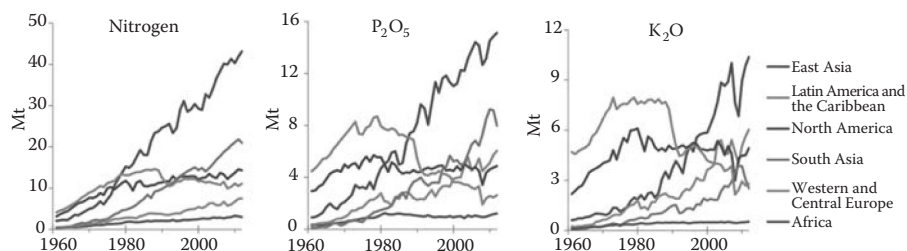


FIGURE 8.4 (See color insert.) Total annual nitrogen, phosphate (P₂O₅ equivalent), and potassium (K₂O equivalent) fertilizer consumption (Mt) from 1961–2015 for various regions of the world. (Courtesy of International Fertilizer Industry Association, Paris, France, <http://ifadata.fertilizer.org/ucSearch.aspx>, 2015.)

TABLE 8.3
Phosphorus (P₂O₅ Equivalent) Fertilizer Consumption (10³ t year⁻¹)
in Selected SSA Countries

Country	Year				
	2002	2004	2006	2008	2010
Tanzania	5.28	9.73	11.55	9.26	8.06
Zambia	13.47	11.41	8.55	8.89	8.43
Zimbabwe	48.09	20.41	45.30	35.18	48.08
Ethiopia	69.98	45.60	64.48	122.25	162.06
Uganda	2.13	3.30	2.17	5.49	2.81
Mozambique	2.00	3.47	2.84	10.36	2.59

Source: Food and Agriculture Organization of the United Nations—Statistics Division, Rome, Italy, <http://faostat.fao.org/>.

the benefit of such subsidy programs by not taking into account the effects on local fertilizer markets (Jayne et al. 2013).

8.4 TYPES OF P INPUTS

8.4.1 INORGANIC P SOURCES

Inorganic P inputs consist of PR mined from geological deposits or products derived from PR. The acidulation of PR provides a more concentrated and soluble P input, such as TSP. Total and highest-quality PR deposits are globally concentrated in North Africa (Morocco), although there are local deposits of lower but appreciable quality and quantity throughout SSA. PR is a lower-cost alternative to more soluble inputs like TSP, which are more expensive. Unawareness of the proper use of high- and low-cost inputs can discourage their use. The dissolution of PR translates to slower crop response to lower-cost P inputs, typically at least 3 years at application rates affordable to smallholders, which can be long enough to discourage their continued use (Bationo, Mughogho, and Mokwunye 1986). Other problems with the use of PR may include bulkiness, low market availability, and high content of heavy metals (Vanlauwe and Giller 2006).

The strong residual effect of P inputs, especially PR, highlights both the longer-term importance of P management and concurrent soil testing to understand soil P fertility changes. The strong residual effect of P is the basis for the concept of *investments in soil P capital*, as changes in pH and P stocks improve P fertility as a function of time. The profitability of repeated inorganic and organic additions of P has been shown to gradually increase over the years (4+) (Lamers, Bruentrup, and Buerkert 2015b).

The majority of studies on P inputs in SSA are short term (<4 years) and thus do not sufficiently address medium- to long-term effects of certain P management strategies. This can potentially create bias in P fertilization recommendations.

Given the propensity of P to accumulate in soils, this has important implications for effective and economical P use. For example, in western Kenya, the national extension services (Kenya Agricultural and Livestock Research Organisation, KALRO, formerly abbreviated as KARI) promotes an application rate of 40 kg P ha⁻¹ year⁻¹ based on 20 kg P ha⁻¹ per maize crop, which is in close agreement of the estimated optimal returns at 38 kg P ha⁻¹ year⁻¹ (Kihara and Njoroge 2013). These rates are likely to satisfy crop requirements within several years, necessitating lower maintenance rates (Woomer 2007). Preliminary results from a long-term trial by the International Center for Tropical Agriculture (CIAT) on an Oxisol in western Kenya showed that P additions in the form of PR and TSP at these rates for 11 years increased the labile P levels by 2.5-fold greater than maize minimums (Margenot et al. 2014).

8.4.1.1 Phosphate Rock: The Basis of Concentrated P Inputs

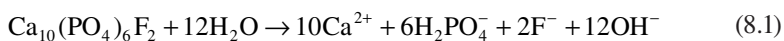
PR refers to a broad class of phosphate-rich minerals that typically contain calcium and fluoride, and exhibit high diversity in mineralogy, geographical distribution, and value for agricultural management of P fertility (Notholt 1994). The majority of global PR deposits are sedimentary (80–85%), followed by igneous (17%), which are more suitable for P fertilizers than the remaining metamorphic deposits (Sabihah et al. 2009; Notholt 1994). PR can be directly applied to soils or used as the feedstock for concentrated and soluble P fertilizers, by treatment with sulfuric acid or phosphoric acid to produce SSP and TSP. Over 80% of mined PR is used for the manufacture of water-soluble P fertilizers (Pur'Homme 2010). The net effect of PR on soil P and crop performance depends on the interaction of PR quality (e.g., P content, solubility) and soil conditions (e.g., pH, mineralogy, and soil Ca and P concentrations).

8.4.1.2 PR Chemistry and Quality

The quality of PR is important for its use as a direct amendment and is the result of its chemical composition and surface area. The chemical composition dictates the potential P input (concentration) and the availability over time (solubility) (Chien, Hammond, and Leon 1987). Sedimentary PRs generally consist of apatite with isomorphous substitution for phosphate by carbonate and fluoride (i.e., carbonate apatites, fluoroapatites). Important for their direct application as P fertilizers, sedimentary PRs express high net surface area due to microcrystallinity and internal surface area, which facilitates greater solubilization in soils relative to coarsely crystalline igneous and metamorphic deposits, despite higher P content of igneous PR (Khasawneh and Doll 1979). Sedimentary calcium apatites are economically viable as fertilizers; in addition to providing P, they also are a significant source of Ca, which in soils of high exchangeable acidity serves as a liming agent.

PR is effectively water insoluble (Bolan and Hedley 1989, 1990), and its solubilization in soils is made possible by soil conditions like pH and sinks for dissolution products, chiefly Ca and P. The congruent dissolution equation of PR idealized as fluoroapatite (Equation 8.1) highlights the importance of soil pH and Ca and P sinks as the three drivers of this process (Chien 1977a; Robinson and Syers 1990; Rajan, Watkinson, and Sinclair 1996). The percentage of Ca saturation, the P sorption

capacity, and the Ca-exchange capacity can be used to predict the extent of the PR dissolution in soils (Mackay et al. 1986).



A sufficiently high Ca content can inhibit PR dissolution despite a low pH, because CaCO_3 in the apatite lattice preferentially dissolves relative to $\text{Ca}_3(\text{PO}_4)_2$ (Robinson and Syers 1990). Evidence suggests the Ca sink is the most significant control on PR dissolution (Robinson and Syers 1990). At ideal conditions of low pH (4.5) and strong Ca and P sinks, the dissolution of PR can be nearly complete (95%) within 44 days (Robinson and Syers 1990). In a review of SSA field experiments comparing PR and soluble P fertilizers like TSP, Szilas et al. (2007) identifies pH and soil P availability as the best predictors of yield response to PR but noted that less acidic soils can still benefit from PR application if there is a strong P sink (i.e., low soil P).

Given the low base saturation and high exchangeable acidity of acid, weathered soils, it is not unexpected that studies show that these soils strongly benefit from PR application. Acid, weathered soils display the greatest PR dissolution, which consequently increases crop available soil P (Kanabo and Gilkes 1988). In fact, the high Ca content of PR makes it a high-quality Ca amendment (Khasawneh and Doll 1979), which is critical for weathered soils with inherent low Ca status further exacerbated by cultivation (Sale and Mokwunye 1993; Vitousek et al. 2010). Ca deficiency is only now being recognized as a limiting factor in many SSA soils. In regions like western Kenya, Ca deficiency may match P as a constraint on yields (Kihara and Njoroge 2013).

PR thus offers a two-for-one benefit from the P management perspective: in addition to providing P, it can ameliorate soil acidity, which typically accompanies and enforces P deficiencies (see Section 8.4.6). The extent of the increase in crop available soil P with PR reflects the decrease in P fixation via a liming effect and net P addition. The liming effect of PR results from proton consumption and addition of base cation of Ca^{2+} , and particularly for sedimentary PR, CO_3^- . PRs can have calcium carbonate equivalency (CCE) values of >50% (Sikora 2002). For example, the northern Tanzania Minjingu PR (MPR) can have up to 68% CCE, making it a low-grade liming agent (Nekesa et al. 2005). The liming effects of PR also reflect its particle size (Tisdale, Nelson, and Beaton 1985), known as the fineness factor (FF) (Peters 1996).

As new PR deposits are explored in SSA, their analysis should be standardized to ensure the comparability of studies. Laboratory measurements are helpful to accurately determine the PR liming potential based on specific PR and soil properties. In general, the phosphate content is a more sensitive proxy for predicting the liming potential of PR than directly quantifying the carbonate content because of its greater relative molar quantity.

On the other hand, the liming potential of PR makes it less ideal for circum-neutral or alkaline soils to address P deficiencies and potentially decreases its efficacy in initially acid soils with repeated application over time as the liming effect increases pH. The decreases in exchangeable acidity tend to be greater than the pH

increases because of the high Ca loading from PR. Since exchangeable Al^{3+} markedly decreases at $pH > 5.5$ in weathered soils, and because short-term (1–3 years) pH increases following PR applications at agronomic rates are typically +0.5 pH units (Pearson 1975), decreases in Al^{3+} from PR can be appreciable in soils with $pH \sim 5.5$ (Chien and Friesen 2000).

These chemical principles have been corroborated by field experiments in SSA. A compilation of crop yield response to MPR versus soluble P fertilizers like TSP finds (1) a lag in P availability for PR due to dissolution, which entails (2) 74% relative yield with MPR compared to soluble P fertilizers in the first year, but (3) an increase in MPR relative yield to 94% in year 2, and 104% in year 3 and thereon (Szilas, Semoka, and Borggaard 2007). The overyield effect of PR relative to soluble P fertilizers after multiple seasons is attributable to the addition of Ca^{2+} and the decrease in exchangeable acidity from PR.

8.4.1.3 PR Deposits in SSA

SSA constitutes 22% of earth's land area but contains only 2% of known PR deposits (Sheldon and Davidson 1987). These deposits are of variable reactivity and size (Roy and McClellan 1986), and there are likely additional undiscovered PR deposits due to the inadequate exploration of deep soils in the subcontinent (Sheldon and Davidson 1987). Due to their extent and the quality of deposits, East Africa has two highly used PR deposits: Minjingu (Tanzania) and Busumbu (Uganda). Additional deposits include Tilemsi (Mali), Matam (Senegal), Dorowa (Zimbabwe), and Sukulu (Uganda) (Van Kauwenbergh 1991). An excellent overview of PR resources in SSA is provided by van Straaten (2002).

Of all PR sources in SSA, only those from Tilemsi (Mali), Matam (Senegal), and Minjingu (Tanzania) are known to have a solubility in 2% citric acid exceeding the 10% threshold for agronomically significant dissolution (Vanlauwe and Giller 2006). MPR is the most commonly studied PR in SSA and is a relatively large (10 million tons) and high-quality (5.6% neutral ammonium citrate solubility) deposit (Van Kauwenbergh 1991; van Straaten 2002; Jama and Kiwia 2009). The increasing abundance of agronomic trials examining the effectiveness of various PRs makes the compilation of these data a useful resource because field trial data are needed to complement lab analyses of chemical composition.

8.4.2 STRATEGIES TO IMPROVE P SOLUBILITY OF PR

The low solubility of PR means that its ability to meet crop P demand can be limited, particularly at low application rates and/or in initial seasons. Various chemical, physical, and biological approaches can be used to improve solubility.

8.4.2.1 Biological Approaches

Composting with PR is one of the pillars of integrated soil fertility management (Sanginga and Woomer 2009), but the empirical data from SSA reviewed by Vanlauwe and Giller (2006) suggest no benefit to P availability in the short term. The increases in available P from co-composting PR reflect P mineralized from the organic matter (OM) rather than increased dissolution of PR. Using ^{32}P -labeled

synthetic (i.e., francolite) and mined PR (labeled by neutron bombing) allowed P from PR to be distinguished from P mineralized from manure. Isotope labels demonstrated no significant increase in PR dissolution during composting (Mahimairaja, Bolan, and Hedley 1994). This could be for two reasons: First, acidification during composting and even nitrification from added ammonium is of insufficient magnitude to significantly increase PR dissolution (Mahimairaja, Bolan, and Hedley 1994; Mowo 2000). Compost products express near-neutral pH not favorable for increasing PR dissolution (Vanlauwe and Giller 2006). Second, organic materials used in composting, in particular manure, have high Ca concentrations which thermodynamically disfavor PR dissolution (Equation 8.1) (Robinson and Syers 1991). From a P availability standpoint, PR application is most effective when directly added to soils, especially those with lower pH values. Despite this, the inclusion of PR in composting is still proposed as a means to enhance the PR improvement of soil P at the extension level, such as in Mali and Burkina Faso (Vanlauwe and Giller 2006). Although there are logistic advantages to combining inputs in a single application, these practices do not improve PR as a P input and may be a misuse of PR if the target soil exhibits low pH, as this favors for dissolution of PR applied directly.

Additional biological approaches to improving PR solubility involve phosphate-solubilizing microorganisms (PSM) and arbuscular mycorrhizal fungi (AMF) to scavenge P (Maheshwari 2011). Fomenting mycorrhizal associations can improve P uptake of low native soil P and added PR alike. In acid, weathered soils, AMF alone can also improve the P uptake from soluble P inputs such as $\text{Ca}(\text{H}_2\text{PO}_4)_2$ (Cozzolino, Di Meo, and Piccolo 2013), which is consistent with evidence that AMF improve P acquisition regardless of the source in weathered soils (Alloush, Zeto, and Clark 2000). AMF associations are most beneficial at low soil P levels and under conditions of low soil disturbance such as reduced tillage (Grant et al. 2005). Inoculation with PSB and PSM can improve the availability of added PR added (Miyasaka and Habte 2001). Generally, inoculation with PSM improves the availability of PR, although weaker effects on plant growth occur on more strongly P-fixing soils (Osorio and Habte 2015). AMF can desorb P from mineral surfaces by secreting organic chelators such as oxalic acid, although the efficacy of this strategy depends on the mineral type (Osorio and Habte 2013a). The low desorption of P by AMF from allophane suggests that such mechanisms are least effective in volcanic soils, followed by weathered soils with iron oxides and kaolinite, and most effective in less weathered soils dominated by 2:1 phyllosilicate minerals such as montmorillonite.

However, AMF contributions to plant P uptake are typically observed at high P application rates (Bâ and Guissou 1996; Alloush, Zeto, and Clark 2000; Satter et al. 2006), which may not be feasible for smallholders. For example, inoculation of *Leucaena leucocephala* with AMF (*Glomus fistulosum*) significantly increased its P uptake at PR application rates equal to or greater than 300 mg P kg^{-1} soil in an acid, weathered soil (Typic Haploustox, pH 4.9) (Osorio and Habte 2013a). Assuming a bulk density of 1.10 g cm^{-3} and an incorporation depth of 0.25 m, this translates to a minimum application rate of 825 kg P ha^{-1} .

Coupling PSM with arbuscular mycorrhizae can improve the plant response to PR, highlighting the importance of soil–microbe interactions for PR dissolution. Many PSM are rhizosphere-associated and can increase the plant P supply by

secreting organic acids to solubilize plant-unavailable P pools, including fixed P (Fe- and Al-oxide bound) and Ca-P in parent materials or PR. An excellent overview of biological strategies to improve the P availability in weathered tropical soils is provided by Oberson et al. (2006).

Using PR can alter the populations of native soil PSM, with potential consequences for the PR efficacy over long-term management. The application of P at $40 \text{ kg}^{-1} \text{ ha}^{-1} \text{ year}^{-1}$ as MPR increased fungal diversity and the PSM population by up to +90%, whereas TSP application significantly reduced overall bacterial diversity and the PSM populations of PSB by up to -69%, with comparable yield increases (Waigwa, Othieno, and Okalebo 2003).

8.4.2.2 Physical and Chemical Treatments

Grinding to increase surface area and partial acidulation to improve the solubility can improve the efficacy of PR in the short term (initial season), albeit at the cost of a lower residual effect (Chien et al. 1990). In general, finer texture entails greater surface area and thus dissolution rates for a given PR. The benefits of partial acidulation on solubilizing PR depend on its particular composition (Chien et al. 1990). For example, the acidulation (50% with H_2SO_4) of Tahoui PR (Niger) did not improve its solubility because of its Al and Fe contents, in contrast to Parc PR (Niger), which exhibited comparable efficacy as SSP (91%) in terms of millet yield in the first and second seasons following application. Acidulation may not be necessary for PR with high reactivity. The partial acidulation of MPR did not improve clover biomass on a Vertisol in Ethiopia (pH 5.5), but it did for low-reactivity Chilembwe PR (CPR; Zambia) (Haqee, Lupwayi, and Ssali 1999). This was attributed to twofold greater soluble P content of MPR and high surface area typical of sedimentary deposits, in contrast to the igneous-origin CPR of lower P solubility and surface area (see Section 8.4.1.2).

Reduction-oxidation (redox) dynamics during wet-dry cycles can be exploited as a mechanism to manage P, particularly in lowland rice. For example, the reductive dissolution of Fe^{3+} under anaerobic conditions of soil submergence led to the release of Fe-bound P (Amery and Smolders 2012). The magnitude of the effect of redox cycles on freeing sorbed P, and on potential P loss, is influenced by not only the iron oxide content, but also the soil texture and the duration of these wet-dry cycles. Under the anaerobic conditions that occur in flooded soils, OM decomposition can further drive Fe reduction. Applying this concept, OM additions to flooded, weathered soils markedly increased the available P relative to flooding alone (Amery and Smolders 2012). Coarser-textured soils are more prone to leaching of desorbed P but, on the other hand, are less likely to be waterlogged as compared to fine-textured soils (Scalenghe et al. 2014). The reduction of Fe^{3+} via frequent wet-dry cycles used in the system of rice intensification (SRI) has been used to explain its high success on acid, mineral oxide-rich soils such as in Madagascar (Dobermann 2004), which could include effects on P availability. Furthermore, the diffusion of phosphate in submerged soils toward the crop roots is increased by a decrease in the diffusion impedance factor (Jungk and Claassen 1997), as well as potentially mineralizable organic P.

As a result, PR can be used in submerged acid soils as in lowland rice agroecosystems in West Africa (Nakamura et al. 2013). Field trials have found that PR is able to

improve rice yield, consistent with previous studies of the solubility of PR under submerged acid (pH 4.8) soils (Chien 1977b). As in nonsubmerged soils, the interplay of the PR dissolution rate and the sorption of newly available P account for a net change in available P. Consequently, highly P-fixing soils cultivated under submerged conditions may not experience increases in available P despite the dissolution of PR (Yampracha et al. 2006). Co-additions of OM may aid in the dissolution of PR in submerged soils via the chelation of soluble cations by organic acids. For example, the co-addition of legume biomass (mucana, cowpea) with Ogun PR (Nigeria) in acid soils (pH 5.2–6.6) significantly improved water-soluble P (Olajumoke Adesanwo, Adetunji, and Diatta 2012), although as discussed in Section 8.4.2.1, this may reflect P mineralization from residues.

Combining PR with soil-acidifying inputs (e.g., ammonium and urea) can improve the dissolution of PR via proton-producing processes such as nitrification (Akande et al. 2004; Vanlauwe et al. 2006). PR can also be mixed with zeolites, aluminosilicate minerals that serve as a sink for Ca^{2+} to drive its dissolution. The coapplication of PR with zeolite can produce comparable soil available P increases and maize biomass with 25% less PR application (Aainaa et al. 2014).

8.4.3 SOIL PROPERTIES: INTERACTIONS AND TRADE-OFFS FOR INORGANIC P INPUTS

Understanding the residual effects of P inputs is important for P management, because the effects of such inputs carry over into the second, third, and even fourth cropping seasons (Delve et al. 2009). The residual effect of P reflects strong interactions with soil properties such as P fixation capacity and texture (see Section 8.2.1). The high solubility of super phosphates may be a disadvantage in soils of coarser texture in which P leaching can limit the residual effect (Ojo, Akinrinde, and Akoroda 2010) and may partly explain why yields increase over time with PR relative to super phosphates. Slower dissolution of PR means that available soil P and crop response can lag behind for PR for 2–3 years following application compared to more soluble inputs (Msolla, Semoka, and Borggaard 2005). The modeling of residual P explained the crop response to continued P inputs over 14 years, which more strongly influenced maize yield than N application by years 3–4 (Janssen 2011).

The residual effect of PR offers a way for resource-poor smallholders to manage limited cash and/or unstable market prices, since it can extend P availability across years when P inputs are not possible. An application of 60 kg P ha⁻¹ as MPR led to an initial increase in pH, available P, and yield that declined to preapplication levels by the fourth growing season (Ndung'u et al. 2006). Soils with low P and associated soil conditions disfavoring its availability such as high exchangeable acidity may therefore need prolonged P investments before less frequent and/or lower maintenance applications can be used.

The high concentrations and solubility of P in these input types means that on P-deficient soils, application rates as low as 4.4 kg P ha⁻¹ can be profitable to farmers (Njui and Musandu 1999). At higher P application rates, N can become co-limiting and decrease PUE (see Section 8.6.2). For example, Njui and Musandu (1999) found that applications beyond 26.2 P kg ha⁻¹ on an P-deficient soil in western Kenya

(pH 4.5, Mehlich 1.7 mg P kg⁻¹) required 40 kg N ha⁻¹ to produce a P response. In a recent assessment of maize response to P fertilizers in western Kenya across 25 studies and 126 fields, Kihara and Njoroge (2013) identified 50 kg ha⁻¹ year⁻¹ as the upper limit for yield response, and 38 kg ha⁻¹ year⁻¹ as an optimal rate. Approximately 50% lower yields were observed for unfertilized soils relative to P-fertilized treatments.

Interactions of P inputs and soil properties engender management trade-offs across time and space. Spatially, P inputs can be applied via placement or broadcasting. The placement of P, also known as microdosing, bottle cap method, or Coca-Cola technique (Tabo et al. 2007; Twomlow et al. 2011), is a better option when less P fertilizer is available. Manual placement on a per-plant basis produced higher yields at rates of <50 kg P ha⁻¹ as TSP (van der Eijk, Janssen, and Oenema 2006). However, since plant location typically changes with each season, the coincidence of subsequent plantings on previous placements is not guaranteed, meaning that residual P effects are typically lower for placement versus broadcast. For this reason, the placement of lower P applications across growing seasons can be more effective than a single large placement in the first season.

Broadcasting is effective at high application rates, and depending on P input and soil type, there may or may not be advantages to applying P in a single higher application versus repeated lower applications across seasons. Using less-soluble inputs like PR makes concentrating application in a single season more optimal for crop response (Lamers, Bruentrup, and Buerkert 2015b). In contrast, highly soluble inputs like TSP generally show fewer differences between single high applications and repeated lower applications across seasons. Greater soil contact by broadcasting promotes PR dissolution, but high solubility of super phosphates can lead to P fixation. This may explain why single high doses of PR have been found to provide the greatest economic return relative to other P input types and application strategies (Chien et al. 1990; Lamers, Bruentrup, and Buerkert 2015b). Microdosing with PR may be less effective than with super phosphates, presenting a trade-off for PR between the amount applied and the application area. For example, broadcasting PR at 13 kg P ha⁻¹ showed comparable economic returns on millet in the Sahel relative to microdosing in mounded hills at 4 kg P ha⁻¹ (Lamers, Bruentrup, and Buerkert 2015b).

Input distribution across time is less significant at high application rates because sufficient crop available P will be solubilized from a larger PR dose. Over the course of 5 years, the application of a single 250 kg P ha⁻¹ in the first year or 50 kg P ha⁻¹ annually in the form of PR or TSP provided comparable maize yield and economic returns (Jama and Kiwia 2009). Because of its stronger residual effect, high PR application in the first year can be tapered to a low maintenance rate (25% of initial application) within 2–3 years, or alternatively, supplemented with super phosphates (Bonzi et al. 2011).

Practical consideration should also be given to the temporal distribution of P inputs. Lower and frequent P inputs are favored under conditions of competing demands on cash, labor, and time requirements, and avoid triggering strong weed competition observed under high applications (van der Eijk, Janssen, and Oenema 2006).

8.4.4 ORGANIC P RESOURCES

High quality OM amendments can provide comparable or superior improvements in soil P availability relative to inorganic P inputs. The benefits of organic inputs for soil available P include slow release of mineralizable organic P, increased microbial P cycling, and indirectly, improvement of non-P properties such as soil tilth and micronutrient additions. A general disadvantage of organic P inputs is low P content, both plant-available inorganic P and total P, and the unpredictability of organic P mineralization. Organic P inputs are therefore generally more complicated when considering short-term P management. Additionally, the availability of OM inputs in many regions of SSA is typically insufficient to meet crop P demands.

8.4.4.1 Mechanisms by Which Organic Inputs Improve P Availability

There are five potential mechanisms by which organic inputs can improve soil P availability (Guppy et al. 2005a,b; Iyamuremye and Dick 1996; Oberson et al. 2006, 2011): (1) inducing ligand exchange (i.e., organic sorbates competing with P for mineral binding sites); (2) buffering soil acidity; (3) providing a large sink for exchangeable P; (4) providing a potential P source via mineralization; and (5) stimulating biological cycling of P, chiefly via microbial drivers.

Guppy et al. (2005b) argue that at realistic application rates, OM inputs such as manure increase available soil P due to the addition of P in OM rather than organomineral interactions such as ligand exchange. For example, mesocosm studies typically use low-weight organic acids as model OM in concentrations of 3–5 orders of magnitude greater than in field experiments. Although OM may effectively compete with sorption sites, it can also increase the sorption of P to its chelated metal cations. Similarly, increases in available P during co-composting of PR with OM largely reflect the mineralization of organic P (Mahimairaja, Bolan, and Hedley 1994).

Nonetheless, there are improvements to P availability that can be achieved through the use of OM inputs like residues. The application of plant biomass from species like tithonia (*Tithonia diversifolia*) can produce increases in soil available P and maize yields comparable to inorganic P inputs (Jama et al. 2000; Nziguheba et al. 2000) while uniquely reducing P fixation (Nziguheba et al. 1998). Ameliorating P fixation with OM is thought to reflect decreases in binding sites and/or exchangeable acidity as a result of OM complexation of exchangeable Al^{3+} and consumption of H^+ via decomposition processes and OM buffering.

Biological cycling of P can play a significant role in provisioning plant-available P, in particular for weathered soils with high potential for fixation. Organic amendments can affect biological P cycling through microbial biomass P (MBP) and enzymes that hydrolyze organic P (phosphatases).

Microbial biomass can serve as a labile reservoir of plant-available P, which in P-fixing soils is an important mechanism for avoiding the geochemical capture of P by a microbial competition for soil solution P (Liu et al. 2008). Depending on management effects and microbial biomass size, inorganic P pulses to soils can be rapidly immobilized into microbial biomass (50% within 3 days) in cultivated soils (Oehl et al. 2001), with the turnover of MBP estimated to be 80% at 9 days in

forested Oxisols (Achat et al. 2010). The subsequent turnover of microbial biomass allows scavenged P to become transiently available to plants (Oberson and Joner 2005). On the other hand, a high turnover rate of MBP could also entail competition with plants for soil solution P (Achat et al. 2010). Furthermore, the dynamic nature of the soil microbial biomass and its sensitivity to management also make it difficult to predict. Lack of or excessive P fertilization can reduce the size of the microbial biomass, while organic amendments and inorganic–organic mixtures can increase the microbial biomass (Malik, Marschner, and Khan 2012). Evidence suggests that low-input systems can maximize the benefits of microbial P cycling by combinations of organic and inorganic P fertilizers rather than during separate application (Ayaga, Todd, and Brookes 2006). In this study, MBP positively correlated with maize grain yield in P-fixing soils, and there were greater relative increases in MBP on soils with greater P fixation. Similarly, increases in MBP followed additions of OM and inorganic P in strongly P-fixing but not weakly P-fixing soils (Koutika et al. 2013). Over 32 weeks, there was greater variability in MBP, from 22.5 $\mu\text{g P g}^{-1}$ soil in week 1 following the addition of manure (10 g kg^{-1}) and KH_2PO_4 (18.4 mg P kg^{-1}) to 4.8 $\mu\text{g P g}^{-1}$ soil in week 2, then increasing to 15 $\mu\text{g P g}^{-1}$ soil in week 16. Since microbial biomass and MBP increase with soil OM (Achat et al. 2010), OM additions can increase the MBP response to inorganic P inputs in P-fixing soils (Gichangi, Mnkeni, and Brookes 2010; Malik, Marschner, and Khan 2012).

Inputs of OM may additionally provide enhanced biological cycling of P via phosphatases in the soil, in particular extracellular phosphatases. An excellent overview of soil phosphatases and their role in biological P cycling to increase its crop availability is provided by Nannipieri et al. (2011). The changes in soil phosphatase activity may be a benefit of co-composting PR with OM, despite evidence that this method does not improve PR dissolution. The addition of compost produced from a mixture of coffee pulp, manure, gypsum, and PR to an Oxisol increased potential activities of soil enzymes with increased compost additions (10–80 g kg^{-1} soil) after 28 days, including both acid and alkaline phosphomonoesterases, in tandem with increased microbial respiration (Oliveira and Ferreira 2014).

8.4.4.2 Manure

Manure is a valuable resource for smallholders in SSA and can be used to meet P demands and improve soil conditions influencing P availability. However, the quantity and the quality of manures in SSA generally limit its ability to meet crop P needs. Low manure production and small herd size in much of SSA limit utility of P applications in the form of manure (Kibunja et al. 2012). The P content of manure can also vary across scales in SSA. For example, the total P content of manures varied from 2500 to 800 mg P kg^{-1} in East Africa and 5700 to 600 mg P kg^{-1} in West Africa (Probert et al. 1992). In western Burkina Faso, the variability in the P content of manure produced on-site across 98 farms entailed application rates of 2.2–5.1 t ha^{-1} (Blanchard et al. 2014). Total P ranged from $880 \pm 440 \text{ mg kg}^{-1}$ in low quality manure and $2200 \pm 1320 \text{ mg kg}^{-1}$ in high quality manure, classified as *low* and *high* quality by farmers. Composts were comparable to low-quality manure in P content, with no differences between compost quality classifications. In contrast to manure, compost showed much greater variability in P content relative to N,

likely reflecting stronger effects of feedstock on P, and convergence of C:N during composting. The species and diet of livestock and the manure storage method can significantly affect its quality. This means that organic P amendments based on manure can vary seasonally by livestock diet (Romney, Thorne, and Thomas 1994). Additionally, the bulkiness of organic inputs like manure often means that these are less often used on outfields (Dembélé et al. 2000), a problem that extends to PR (Vanlauwe and Giller 2006).

The lack of manure for appreciable effects on crop yields reflects the nutrient management situation of many smallholders across SSA. For smallholders in East and South Africa, manure production is limited by ownership of cattle and grazing assets (Zingore et al. 2011; Tittonell and Giller 2013). Overall, there is an insufficient cattle population in SSA to meet crop nutrient demand via manure alone (Tittonell and Giller 2013), and nutrient export via harvesting is typically orders of magnitude greater than nutrients that are returned in manure (Bationo and Mkwunye 1991). Furthermore, the high bulk and low P content of such inputs necessitate high application rates for appreciable crop response. For example, applying manure (1800 mg P kg⁻¹) at 17 t ha⁻¹ represented an annual P application rate of 30.6 kg P ha⁻¹ (Zingore et al. 2008). After three seasons at such rates, homefields and outfields on fine and coarse texture soils showed unexpected decreases in Olsen P (e.g., fine-texture outfield 6.6 mg kg⁻¹ soil) relative to the unfertilized control (7.2 mg kg⁻¹ soil). This could reflect the drop in pH from 5.1 to 4.9, resulting in increased P fixation, as well as greater P export of increased harvested yield. Nitrification during manure decomposition may also cause pH decreases (Murwira and Kirchmann 1993). As with inorganic P inputs, when manure is limited, placement application improves its ability to increase P for individual plants (Rusinamhodzi et al. 2013).

8.4.4.3 Plant-Based OM: Residues and Green Manures

Residues and green manures offer farmers a means to scavenge P in marginal or low-fertility lands and conduct P transfers among holdings. However, for this reason, they do not represent a net P input (Jama et al. 2000). Throughout SSA, agroforestry species managed as a source of residues to improve soil P fertility include tithonia (*Tithonia diversifolia*), tephrosia (*Tephrosia vogelii*), and crotalaria (*Crotalaria grahamiana*) (Gachengo et al. 1998; George et al. 2002a). Of these, tithonia has received much attention, particularly in East Africa. Originating in Mesoamerica, tithonia is widespread throughout the tropics and is recognized as a green manure of high potential for P management.

The P availability of green manures depends on residue quality. Relative to other residues, the high P content (3.7 g P kg⁻¹ dry mass) and low C:P (110) of tithonia accounts for its unique ability to provide an appreciable and sustained supply of crop-available P (Mustonen, Oelbermann, and Kass 2011). The residue C:P determines the complementary or the competitive role of the microbial biomass. Under the conditions of limited soil P but nonlimited C, soil microbes can immobilize 20–50% of the soil P during the decomposition of residues (Walbridge 1991). The high P content and the quality of residues like tithonia prevent microbial competition for mineralized P, allowing the accumulation of P in microbial biomass without

decreasing plant-available soil solution P (Nziguheba et al. 1998; Kwabiah et al. 2001; Pypers et al. 2005). On a low-P soil in southern Kenya (pH 5.9, 5 mg kg⁻¹ soil resin-extractable P), tithonia not only replenished resin-extractable P but also met microbial P demands, because the high P content of tithonia facilitated low microbial biomass P:C ratio (Kwabiah et al. 2003).

Due to its local availability and lower cost, tithonia generally offers greater returns compared to other P amendments. When combined with inorganic P, maize yields increased with the increase in proportion of tithonia and showed a nonadditive increase in yield (+0.6 t ha⁻¹) when tithonia provided 36% or more of the total P input (at a rate of 15.5 kg ha⁻¹) (Nziguheba et al. 2002).

Improved fallows entail the intentional planting of uncropped fields with rapidly growing species that capitalize on the intercrop time gap to mobilize the nutrients in biomass that become available in a subsequent growing season following the incorporation of fallow biomass (Sanchez 1999). Although originally designed to improve N management, several fallow species have strong potential for improving soil P status. In Uganda, soil P availability tracked the dry matter production of fallow species (Mubiru and Coyne 2009). Improved fallows produced greater biomass and thus biomass P relative to native fallow (3.2 kg biomass P ha⁻¹), with concurrent greater release of P in the ensuing cropping season. Greatest soil P increases were observed for canavalia (*Canavalia ensiformis*, 10.6 kg biomass P ha⁻¹) across sites and growing seasons, followed by mucuna (*Mucuna pruriens*, 6.5 kg biomass P ha⁻¹) and lablab (*Lablab vulgaris*, 5.6 kg biomass P ha⁻¹). Canavalia is a multipurpose forage legume adapted to drought stress (Douxchamps et al. 2013) and thus poses additional benefits to improving PUE (see Sections 8.4.4.5 and 8.6.2).

Green manures are typically grown on the same farm or area in which they are used, and therefore may not represent a net P input. The use of biomass transfer is limited for a certain time because continued nutrient mining will eventually limit the biomass P. Nutrient mining below critical thresholds for residue production is more likely on marginal soils used for this purpose and therefore already on a thin nutrient balance. The risk is undermining the continued use of off-field biomass. Biomass transfers can lead to P depletion in as quickly as one growing season (George et al. 2002a). In this resulting state of degradation (low P, soil acidity), the poor growth of a tithonia fallow in degraded fields in Rwanda prevented its continued use as green manure source (Bucagu, Vanlauwe, and Giller 2013).

The repeated use of green manures like tithonia grown on marginal lands can also compromise their quality as P amendments. A survey in western Kenya found the potential of tithonia biomass transfer to improve soil P availability to depend on the source of tithonia (George et al. 2001). Specifically, tithonia from nutrient-depleted soils (unfertilized agricultural fields) were a less effective source of P and K, via biomass transfer, than tithonia from unmanaged margins and hedges. Specifically, there was higher leaf P concentration for tithonia from nonmanaged hedges (3.2 g P kg⁻¹) than that from unfertilized fields (2.2 g P kg⁻¹) (George et al. 2001). As a result, the net mineralization of P from tithonia depended on the source, with 90% of the leaves from hedges, but by only 14% from unfertilized fields meeting the critical P concentration of 2.5 g kg⁻¹ for mineralization.

8.4.4.4 Overlooked P Sources: Waste Streams and Ash

Waste streams are a significant gap in the global P cycle and account for the majority of P losses from agroecosystems. An estimated two-thirds of P harvested and exported in biomass is not returned (Karunanithi et al. 2015). For example, bones from livestock slaughter in Ethiopia were estimated to represent 17,000–36,000 t P year⁻¹, which could meet 28–58% of this nation's agricultural P demand with a value of US\$ 50–104 million (Simons et al. 2014). The rapid urbanization in SSA presents a significant gap and an opportunity to improve local and regional P cycling. Urban centers are a sink for P from farmers' fields and a potential source for water pollution and human health hazards. This in part reflects the isolation of agricultural, wastewater, and sanitation sectors in SSA (Timmer and Visker 1998). Waste management in urban areas represents an opportunity to simultaneously improve public and ecosystem health and P deficiencies in surrounding agroecosystems.

The majority of P in urban (and rural) waste streams is contained in food waste and human excreta, chiefly urine. For example, the amount of P lost from human waste streams (excrement and food waste) in Nairobi's district of Kibera (population: 235,000) is estimated at 0.47 kg P person⁻¹ year⁻¹, amounting to 9 t P month⁻¹ (Kelderman et al. 2009). Of this, an estimated 65% is lost as raw sewage effluent or surface runoff, representing an annual P loss of 70.2 t. In general, constraints to the recycling of P from waste streams stem from the potential hygiene risks and infrastructure challenges, such as the high cost of transport from unprocessed waste and wastewater treatment and infrastructure for receiving human waste and storing and delivering recycled P products (Cordell, Drangert, and White 2009). Even so, there are some current opportunities to collect urban P deposits, such as human waste concentrated in pit latrines. In the Bwaise slum in Kampala, Uganda, pit latrines were estimated to retain 99% of P in the waste stream (Nyenje 2014).

Social and cultural challenges to reusing waste streams for agricultural production can stem from the perception of waste, which vary across cultures and may be complicated. For example, in southern Ghana, household interviews and group discussion identified a general negative attitude to interacting with fresh excreta, and despite the acknowledgment of its potential as a fertilizer, participants were unwilling to use it on their own crops or consume crops grown with excreta (Nimoh et al. 2014). Yet in northern Ghana (Tamale and Bolgatanga), farmers recognize the economic and agronomic benefits of using sewage sludge despite social ridicule and potential health hazards from its improper handling (Cofie, Kranjac-Berisavljevic, and Drechsel 2005). As a result, 90% of "night soil" in Tamale is used for agricultural production, and its increased use was concurrent with declining fertilizer imports in Ghana (Owusu-Bennoah and Visker 1994). In contrast, across much of Uganda, human waste is composted and applied to a variety of crops, including root and agroforestry species.

Ash residues from home stoves and agricultural waste are common in SSA (Karekezi and Turyareeba 1995), and its use as a dual P and liming amendment for acid soils in SSA is receiving increased attention (Materechera and Mkhabela 2002; Bougnom et al. 2011; Materechera 2012). Ash may be more useful for its liming effect, attributable to high base cation content and presence of Ca and Mg

(hydr)oxides and carbonates (Lerner and Utzinger 1986; Pitman 2006). The combination of rapidly reacting cation (hydr)oxides and less reactive carbonates produces an immediate and sustained liming effect across the growing season following application (Ulery, Graham, and Amrhein 1993; Materechera 2012). Depending on the feedstock and the burn temperature and duration, ash can be a moderate-quality liming agent (26–59% CCE) (Ohno and Susan Erich 1990).

More so than manure, the P content of ash can greatly vary among feedstocks, e.g., 10.5% for cereals and 1% for straw (Schiemenz et al. 2011) and is not significantly influenced by combustion temperature, in contrast to other nutrients like N (Sarabèr, Cuperus, and Pels 2011). Like manure and other waste-based amendments, the ability of ash to supply sufficient P is limited by amendment availability. For example, P in ashes from cacao residues in Cote D'Ivoire represented only 2.1% of the cacao crop P needs (Sarabèr, Cuperus, and Pels 2011). Beneficial increases in soil pH and P availability are often observed at high ash application rates, such as the addition of 2 t ha⁻¹ for maize in South Africa (Materechera 2012).

When large amounts of vegetative biomass are combusted as in slash-and-burn agriculture, ash can significantly contribute to crop P need. These effects depend on the temperature and the duration of the burn (Galang, Markewitz, and Morris 2010), as well as the amount and the type of biomass burned. Slash-and-burn may also increase P by pyromineralization of litter and organic surface horizons rich in organic P (Giardina et al. 2000). With the increasing temperature of the burn, the negative effects on P cycling include (1) increases in P sorption capacity of surface soil (0–10 cm) due to increased surface area of mineral oxides and free and/or amorphous Fe³⁺ and Al³⁺ (Kwari and Batey 1991; Romanya, Khanna, and Raison 1994; Yusiharni and Gilkes 2012), (2) death of microbial biomass and loss of extracellular phosphatase activity (Saa et al. 1993), and (3) increased risk of soil erosion with concurrent P loss. As a result, increasing burning temperature generally leads to net decreases in soil available P (Yusiharni and Gilkes 2012). In contrast to other nutrients like N, K, and Ca, P levels do not return to pre-slash-and-burn levels but experience a net decrease following abandonment (Kleinman, Pimentel, and Bryant 1995). Since burning can induce mineral changes that enhance P sorption in surface soils over the medium term, once pyromineralized P is consumed, the burning can exacerbate P limitations and increase the need for P inputs (Ketterings, van Noordwijk, and Bigham 2002). P loss can also occur via volatilization at temperatures attainable during burning (280°C) (Raison, Khanna, and Woods 1985), although its airborne export is more commonly via aerosolized particulates or wind-blown ash. At field scales, this can account for substantial P losses of, for example, 11 kg P ha⁻¹ (55% of ash P) (Giardina, Sanford, and Døckersmith 2000) or 8–11 kg P ha⁻¹ (Sommer et al. 2004), and at the global scale accounts for a major P flux from terrestrial to atmospheric pools (1.8 Tg P year⁻¹) (Wang et al. 2015).

8.4.4.5 Crop Rotations: Legume Interactions with P Inputs

In unmanaged tropical forest ecosystems, leguminous species can improve biomass P accumulation because N fixation allows greater investment in N-expensive phosphatases to scavenge P (Wang, Houlton, and Field 2007; Houlton et al. 2008). In managed agroecosystems, integrating legume intercrops with P inputs can provide

greater mileage on such inputs while simultaneously increasing N fixation (Giller 2002). This is a strategy of double dipping a single P input targeted to the legume rotation, because residual P and residual fixed N contribute to the nutrient demands of the following cereal crop. The inclusion of a legume such as mucuna or soybean reduced the need for P application for continuous maize from once every 2 years to once every 3 years (Kihara et al. 2010).

Legume-P interactions for improving maize yield and overall productivity are the basis of specific fertilization packages in East Africa, such as managing beneficial interactions in legume intercrops (MBILI) (Tungani, Mukhwana, and Woomeer 2002). MBILI was modified to include PR as low-cost P input in the PR evaluation project package (PRE-PAC) for P-deficient soils in western Kenya (Rutto et al. 2011). The PREP-PAC package provides sufficient inputs for 25 m² plots at 100 kg P ha⁻¹ as MPR, 40 kg N ha⁻¹, 125 g food grain legume seed (biological N-fixation component), the legume inoculant (*Rhizobium*), a biodegradable adhesive, and lime seed pelleting to favor inoculation (Nekesa et al. 1999).

8.4.5 COMBINING INORGANIC AND ORGANIC AMENDMENTS

Combining organic inputs like tithonia with inorganic P sources can improve overall PUE and crop response through a number of mechanisms. Favorable interactions for soil P by combining inorganic and organic inputs may be mediated by microbial biomass responses, both total biomass and species abundance (Malik, Marschner, and Khan 2012). Generally, higher-quality residues (high P concentration, low C:P) determine whether these interactions are favorable for soil available P. Favorable interactions are generally found at higher P input rates (50–250 kg P ha⁻¹) but are less clear at more realistic lower rates (e.g., 15 kg P ha⁻¹) (Nziguheba et al. 1998).

A specific benefit of combining organic and inorganic P inputs is lifting non-P nutrient limitations to increase the P response. This may explain higher yields with mixtures at the same P rate (Mukuralinda et al. 2009). In Rwandan coffee systems, P inputs explained more variation (74%) in coffee yield in Rwanda over three seasons than N (56%) and K (64%) inputs, and tephrosia mulch significantly increased the coffee yield relative to NPK, although this may reflect greater P content of tephrosia rather than an interaction effect (Bucagu, Vanlauwe, and Giller 2013). The addition of inorganic P may also improve parameters favorable for mineralization of organic P in the OM component, e.g., C:P (Nziguheba et al. 2000). Sanchez et al. (1997) found that the combination of tithonia biomass with 250 kg P ha⁻¹ as MPR increased maize yields fivefold in western Kenya partially due to 60 kg K ha⁻¹ supplied with the plant material.

8.4.6 INDIRECT P MANAGEMENT BY LIMING TO AMELIORATE FIXATION

8.4.6.1 Liming Decreases Sorption of Native and Added P in Soils

Soil acidity is a major constraint to agricultural production on weathered soils, which if managed properly, makes these soil types one of the most potentially productive (Sánchez and Salinas 1981). Lime can be used to improve the availability of native and/or added P by increasing soil pH because mineral oxide binding of P decreases

as the pH increases from 4–7 (Haynes 1982; Havlin et al. 2013). Liming therefore has tremendous potential to improve agricultural production on weathered soils like Oxisols (Sánchez and Salinas 1981; Fageria and Baligar 2008). The amount of lime necessary to improve crop production depends on crop type (species and cultivar), the quality of liming material (measured relative to CaCO_3 as the percentage of CCE), and the current and target soil pH. Liming rates can be determined by soil pH, base saturation or its converse measurement of exchangeable acidity, or Al saturation. An excellent discussion of lime, P, soil, and plant interactions is provided by Haynes (1982).

Unlike regions with similar soil conditions, e.g., Brazil, liming of acid soils is not prevalent in SSA. This may reflect low awareness and/or knowledge of lime's potential to improve yields, as well as market availability, transport constraints, and economic costs (Okalebo et al. 2009). Research and extension efforts have not sufficiently evaluated and promoted lime as part of P management and an overall soil quality improvement practice in acid soils. Liming can also be useful to correct for soil acidification from inputs such as urea and diammonium phosphate (DAP) (Okalebo et al. 2009).

8.4.6.2 Considerations on the Use of Lime in Acid, P-Deficient Soils

Improvements to soil P fertility with lime can occur in the short term (<1 month), but such changes are generally observed at high applications rates (5–20 t ha⁻¹) (Gichangi and Mnkeni 2009). Rapid increases in available P following the reaction of added lime to desorb fixed P have been termed the *P spring effect* (Mike and Nanthi 2003). Additionally, plants are able to take up more P (along with other nutrients) because of decreased Al³⁺ toxicity. This may entail an increase in rhizosphere mining of organic P since some crop species are able to induce significant mineralization of rhizosphere organic P via phosphatase exudation (George et al. 2002b).

Liming effects on the biological cycling of P are not well characterized but are expected to be favorable for soil P availability, since microbial activity is generally sensitive to low pH. This may account for observed increases in soil organic P and C:P_o with increasing soil acidity (Turner and Blackwell 2013). Liming also affects soil enzyme activities because enzymes have pH optima. Although acid phosphomonoesterase activity decreased with pH increases induced by liming, alkaline phosphomonoesterase and potentially phosphodiesterase were significantly increased, and correlated with microbial biomass C (Acosta-Martínez and Tabatabai 2000; Ekenler and Tabatabai 2003). Consequently, mineralization of organic P occurs with liming and associated pH increase (Haynes 1982), potentially contributing to the P spring effect of lime.

The quality of liming material influences its potential for improving soil P availability. Lime quality can be measured by CCE. Like PR, particle size is a major control on reaction rate, with finer textures offering a more rapid liming effect (Tisdale, Nelson, and Beaton 1985). The particle size efficiency of lime increases with its fineness factor (FF) (Huang, Fisher, and Argo 2007). As a result of these physical properties, there can be lags in lime effects on yield, typically in the first season following application (Tabu et al. 2007). CaO (quicklime or burned lime) will react more rapidly than less-soluble CaCO_3 (limestone or unburned lime). At

lower application rates (1.4 t ha^{-1}), there were greater differences in short-term potato yield between burned and unburned lime sources, but there were no differences at higher rates (4.8 t ha^{-1}) (Nduwumuremyi et al. 2013). Differences in CCE of two local lime sources and their processing by burning resulted in differences in potato yields (Nduwumuremyi et al. 2013). Exchangeable Al^{3+} was decreased below the toxicity threshold of 5% (Abbott 1987) with high application (4.2 t ha^{-1}) of agricultural burned and unburned lime (86% CCE) from 58.4% exchangeable Al^{3+} (Nduwumuremyi et al. 2013). This corresponded to an increase in pH from 4.8 to 5.7 and a 44% increase in Bray-II P to 5.6 mg kg^{-1} soil; potato yields increased by >50% (21.9 t ha^{-1}). The yield benefits of lime applications plateau with increasing application rates and/or time as pH increases. This may reflect non-P nutrient limitations. For example, doubling lime applications from 1.4 to 2.9 t ha^{-1} did not double yields (Nduwumuremyi et al. 2013).

Liming to increase pH benefits soil fertility beyond P supply because the majority of nutrients are less available at low pH (<5) (Havlin et al. 2013), including secondary nutrients and micronutrients. Lime can also provide trace nutrients, depending on the source. The provisioning of base cations such as Ca and Mg by lime has strong effects on the overall fertility of weathered soils (Fageria and Baligar 2008), as well as micronutrients such as Mo and B (Clark 1984), which are limiting in such soils (Vitousek et al. 2010). A meta-analysis of maize yields and P constraints ($n = 2800$) in western Kenya found that the maximum yield obtained in research stations stagnated at 7 t ha^{-1} , well below the 10 t ha^{-1} potential (Smaling and Janssen 1993), likely as a result of secondary nutrient (Ca, Mg) and micronutrient deficiencies (Kihara and Njoroge 2013).

8.4.6.3 Liming for P Management in SSA

Given the expense of concentrated P inputs and the decrease in PUE from geochemical fixation, lime is a way to increase the mileage of P inputs in acid soils. Lime generally decreases P requirements for a given yield threshold because less added P is fixed. The uptake of P and consequent biomass growth of coffee (*Coffea arabica*) was greater with lime additions ($0.69 \text{ g CaCO}_3 \text{ kg}^{-1}$ soil) to acid soils from Rwanda, although soil P was still considered deficient (Bucagu, Vanlauwe, and Giller 2013). Similarly, coffee yields increased with lime additions, strongly correlating with pH (Cyamweshi et al. 2014). In northwest Cameroon, the addition of lime and OM (mucuna residues) on strongly P-sorbing soils reduced P fertilizer requirement by 45–83% for maize, bean, and potato (Yamoah et al. 1996).

In East Africa, liming has been shown to have great potential to alleviate P constraints, as well as offer co-benefits to crop production from amelioration of other nutrient deficiencies and Al^{3+} phytotoxicity. For example, in western Kenya, the majority of soils are weathered and exhibit $\text{pH} < 5.5$ (Smithson et al. 2003). Extension recommendations are $40 \text{ kg P ha}^{-1} \text{ year}^{-1}$, in agreement with optimal rates estimated at 38 kg P ha^{-1} (Kihara and Njoroge 2013). However, a lower rate of 26 kg P ha^{-1} can increase available P above the critical threshold for maize of $10 \text{ mg Olsen P kg}^{-1}$ soil and secure high maize yields (6 t ha^{-1} vs. unfertilized farmer control of 0.5 t ha^{-1}) when co-applied with lime (2 t ha^{-1}), as well as N (75 kg ha^{-1}) (Okalebo

et al. 2009). A single addition of 2 t lime ha⁻¹ increased the pH from 5.8 to 6.5, above the critical pH threshold of P fixation by Al (Figure 8.2).

The negative effects of liming include a potential for increased weed competition and decreased availability of micronutrients such as Zn, as was observed with liming that induced an increase in pH > 5 for Ultisols in Nigeria (Friesen, Juo, and Miller 1980). Since lime increases soil Ca and pH, its use precludes subsequent PR application (Tabu et al. 2007). Lime is better paired with soluble P inputs, whereas PR presents a low-cost alternative to both inputs. In hand-tilled systems, lime incorporation is limited to surface horizons, to which crop root growth may be constrained. The lack of deep lime incorporation can be an issue because P sorption generally increases with depth (Eze and Loganathan 1990).

8.5 ASSESSMENT OF P AVAILABILITY IN SOIL

There are three reasons for measuring soils for available and total P: (1) determine the appropriate application rate for specific soil conditions, (2) adjust subsequent applications rates to account for residual effect of previous inputs, and (3) assess past and predict future management effects on soil P stocks, from available to organic to fixed P.

The comparison of different nutrient management strategies in western Kenya demonstrates the importance of soil testing to determine the need for P inputs over time. In western Kenya, nutrient management interventions can perform poorly (low maize yield) despite soil P increases, suggesting a critical threshold of 15 mg Bray-I P kg⁻¹ soil (Woomer 2007). This threshold is comparable to the Olsen-P threshold of 10 mg P kg⁻¹ soil proposed by Okalebo et al. (2002) assuming an Olsen:Bray-I conversion factor of 2. As a result, fertilization packages in western Kenya should consider multiseasonal effects of repeated P applications. For example, MBILI promoted in Kenya entails an initial 20 kg P ha⁻¹ application as DAP (Tungani, Mukhwana, and Woomer 2002). Other projects, such as the PREP (Nekesa et al. 1999), involve a one-time P recapitalization application of 100 kg P ha⁻¹ as MPR, or in the case of the fertilizer use recommendation project, an initial P application of 100 kg P ha⁻¹ as DAP followed by maintenance applications of 20 kg P ha⁻¹ season⁻¹ (Kenya Agricultural Research Institute 1994).

High P rates are currently recommended for maize in western Kenya by the national extension services (Kenya Agricultural Research Institute [KARI]): 40 kg P ha⁻¹ per year⁻¹ based on 20 kg P ha⁻¹ per crop. This is in close agreement with estimated optimal returns at 38 kg P ha⁻¹ year⁻¹ (Kihara and Njoroge 2013), but the trials used for this estimation were of short term (<10 years). As Woomer et al. (2007) suggested, these rates are often necessary to satisfy the crop requirements initially but in subsequent years are likely too high, necessitating lower maintenance rates. Corroborating Woomer's hypothesis, P additions at these rates for 11 years increased labile P over 200% above minimum thresholds for maize on an Oxisol in western Kenya (Margenot et al. 2014). Even on short-term (<2 years) scales, the recommended application rates are too high for lifting P availability because of other non-P limitations, including micronutrients (Woomer 2007; Kihara and Njoroge 2013).

8.5.1 SOIL PHOSPHORUS TESTS

Soil P tests are commonly used to refer to a soil-appropriate measure of plant-available P. The objective of soil P tests is to develop a relationship between the method of soil P analysis, typically through an extraction, and crop P uptake or more typically crop yield. The soil P test is therefore most meaningful in providing P management guidelines when it is calibrated through P fertilization response trials. Given the strong effect of pH as the master variable on soil P availability, three types of tests are used based on the pH of the measured soils: the Olsen test for alkaline soils using 0.5 M NaHCO_3 (Watanabe and Olsen 1965), Bray test for acid soils using 0.03 M NH_4F and 0.025 M HCl (Bray and Kurtz 1945), and Mehlich test for acid soils using 0.2 N CH_3COOH + 0.25 N NH_4NO_3 + 0.013 N HNO_3 + 0.015 N NH_4F + 0.001 M ethylenediaminetetraacetic acid in Mehlich-III (Mehlich 1984). Additional tests include chelation by organic acids such as oxalate, acetate, or lactate, and salt extractions, such as 0.02 M KCl and 0.01 M CaCl_2 (Menon, Chien, and Hammond 1989). Following extraction, the inorganic P in the solution is quantified by colorimetry or inductively coupled plasma atomic emission spectrometry or optimal emission spectrometry.

The strong effect of pH on soil P speciation and thus its removal by a specific extractant makes paramount the matching of a test method to soil pH. Although soil P test values are generally correlated, pH extremes and the presence of carbonates affect the correlations for the three more commonly employed soil tests, Bray, Mehlich, and Olsen. These tests have the potential to be highly standardized among many different labs (Wolf and Baker 1985). The standardization of soil tests and other soil P analyses is important for providing recommendations, partly because altering the test parameters (e.g., shaking time) can change results depending on soil properties. Such modifications explained the discrepancies among Bray test results in Rwanda (Drechsel, Mutwewingabo, and Hagedorn 1996). Important for this standardization is the use of a control or a lab standard to check for errors or reagent staling.

Soil P test recommendations are specific to crop type (species, potentially cultivar) and soil-climate conditions. Recommendations are for crop response, typically yield, but also crop uptake (e.g., foliar P, total biomass, grain yield and/or nonharvestable yield) P content. Like soil mapping to understand broad edaphic constraints on agricultural use, the establishment of soil test guidelines for P management requires specificity. For example, trials on the response of maize to P fertilization in a single district in Tanzania (Morogoro) found that even among P-deficient sites, optimum P application rates ranged from 16 to 50 kg P ha^{-1} to achieve the critical threshold of 10.5 mg Olsen P kg^{-1} soil (Ussiri et al. 1998). Despite the low pH (<7) of these soils, Olsen P gave stronger predictions of maize yield as compared to other commonly used soil test methods, including Bray-I and Mehlich-III which are considered to be more suitable predictors of plant-available P in acid soils. This again highlights the need for field trials and lab tests to establish site-specific recommendations.

8.5.2 SINK-BASED METHODS

Sink-based soil tests measure P available from the soil to a passive sink, such as a plant root idealized by a positively charged surface such as iron- and/or

aluminum-impregnated or anion exchange surface in the form of membranes or resins. The determination of P availability using anion exchange resin has been shown to better simulate P removal from soil surrounding the rhizosphere environment than other extractants (Cooperband and Logan 1994). Analogous to the roots, as P is removed from the soil solution by adsorption to a sink, P not in the soil solution (e.g., weakly sorbed to mineral or OM) replenishes the soil solution P by equilibrium processes (Qian and Schoenau 2002). Because they measure exchangeable P, sink methods are considered to be a more realistic indication of soil P available for crop uptake. In contrast, extracts represent instantaneous snapshots of P in the soil solution during extraction—P availability at a particular moment, versus available P (Beckett and White 1964). For this reason, sink-based methods typically involve longer assay times (18–24 hours) than extractions (e.g., 5 min for Bray, 30 min for Olsen). Loading sink surfaces with counterions such as carbonate further mimic ion exchange processes in the root uptake of P (Sibbesen 1978; Qian and Schoenau 2002). The use of anion exchange membranes (AEMs) allows more accurate determination of microbial biomass by difference between nonfumigated and fumigated samples in strongly P-fixing soils such as Andosols and Oxisols by competing with soil-binding sites for lysed microbial P (Kouno, Tuchiya, and Ando 1995; Oberson et al. 1997).

8.5.3 P SORPTION MEASUREMENTS

Complementary to soil P tests, sorption of P by a soil can be measured to determine the potential P fixation, or at the other extreme of soil P saturation, estimate the risk of P loss. P sorption can be measured in two ways: exposing soil to a high P spike (single-point sorption) or determining a sorption isotherm by exposing a series of soil samples to different concentrations of P to calculate the maximum P sorption (Q_{\max}) (Essington 2004). P sorption tests can be useful to (1) estimate P additions for maintaining a specific P concentration in soil solution (Fox and Kamprath 1970) or conversely, (2) assess P input efficiency given the proportion of the added P that would become plant unavailable (Nwoke et al. 2003). For example, single-point sorption tests have been used to estimate P fertilization requirements for sugarcane production on P-fixing soils in South Africa (Gichangi, Mnkeni, and Muchaonyerwa 2008). In Guinea, sorption isotherms were used to estimate P application to highly fixing soils based on calculated P fixation for the upper plow horizon (Nwoke et al. 2003).

8.5.4 SEQUENTIAL EXTRACTION: HEDLEY FRACTIONATION

Sequential chemical extraction can be used to divide soil P into different inorganic (P_i) and organic (P_o) fractions, although the translation of these fractions to plant availability is not straightforward and risks chemical reductionism. The Hedley method employs a sequence of chemical extractions that define a series of P_i and P_o fractions by increasing the chemical lability (Hedley, Stewart, and Chauhan 1982): resin exchange membrane or AEM- P_i , NaHCO_3 - P_i and - P_o , NaOH - P_i and - P_o , and HCl - P_i and - P_o . These are broad, operational measures of soil P defined by the

chemical form of P (e.g., Ca-P represented by HCl-P_i) (Cross and Schlesinger 1995; Condrón and Newman 2011). An excellent review on the ability of the Hedley fractionation to provide information on land use and management effects on P cycling is provided by Negassa and Leinweber (2009).

Hedley fractionations have provided insight on management effects on organic P, specifically (1) highlighting the gradual depletion of organic P with continued cultivation and (2) corroborating the significance of P cycling through organic forms in P-limited weathered soils. Decreases in soil available P over time are thought to largely reflect the mineralization of organic P, as has been found across chronosequences and shifting cultivation systems in Nigeria and Tanzania (Adepetu and Corey 1976; Tiessen, Salcedo, and Sampaio 1992; Sugihara et al. 2012). This is consistent with greater decomposition and SOM turnover in tropical zones (Olson 1963; Ayanaba and Jenkinson 1990; Feller and Beare 1997; Six et al. 2002), which would entail greater mineralization of organic P. The application of ³³P labeling demonstrated the potential of the Hedley fractionation to identify differences in P dynamics among managements in a weathered soil (Oxisol) (Buehler et al. 2002). Soils under positive P balance from fertilization accumulated newly added P across all P_i fractions (resin P_i, NaHCO₃-P_i, NaOH-P_i, HCl-P_i), but not P_o fractions. In contrast, soils with low or no fertilization showed preferential accumulation of P in NaOH-P_o and HCl-P_o fractions, indicating that (1) the differences in P cycling in agroecosystems reflect P management history, chiefly P balance, and (2) the organic cycling of P is important under conditions of P limitation.

8.6 IMPROVING P EFFICIENCY OF CROPS FOR LOW P SOILS

Plants possess a number of adaptive mechanisms to cope with soil P deficiency, leading to changes at morphological, physiological, biochemical, and molecular levels (Zhang, Liao, and Lucas 2014). Developing P-efficient plants by modifying their adaptive strategies represents a sustainable approach that does not compromise environmental quality and limited P resources. From an agronomic point of view, and in an operational sense, the genotypic differences in P efficiency of crop plants need to be defined as the differences in growth or in yield of crops when grown in a P-deficient soil (Marschner 1995; George et al. 2011). A P-efficient plant is able to produce a higher yield in a low P soil compared to a standard genotype (Graham 1984). Higher P acquisition efficiency (PAE) from soils and improved internal PUE are two basic strategies that plants utilize to adapt to soils with low plant-available P (Vance, Uhde-Stone, and Allan 2003; Lynch 2011; Richardson and Simpson 2011; Veneklaas et al. 2012; López-Arredondo et al. 2014; Zhang, Liao, and Lucas 2014).

The differences in P efficiency can be quantified using several measures (Hammond et al. 2009). Agronomic PUE is the increase in yield per unit of added P fertilizer (g DM g⁻¹ P_f). This is equivalent to the product of the increase in plant P content per unit of added P fertilizer (g P g⁻¹ P_f), often referred to as plant P uptake efficiency (PU_pE), and the increase in yield per unit increase in plant P content (g DM g⁻¹ P), or P utilization efficiency. There are four other measures of PUE: (1) P efficiency ratio, which is yield divided by the amount of P in the plant (g DM g⁻¹ P) or

the reciprocal of tissue P concentration if the entire plant is harvested; (2) physiological PUE, which is yield divided by tissue P concentration at a given P concentration in the rooting medium ($\text{g}^2 \text{DM g}^{-1} \text{P}$); (3) the critical value required for 90% yield, which is the amount, or the concentration, of P in the rooting medium required for a given percentage of maximum yield (g P), expressed as the K_m value required for half-maximal yield; and (4) critical tissue P concentration, which is tissue P concentration required for a given percentage of maximal yield.

The genetic variation in plant P efficiency is well documented, and numerous quantitative trait loci (QTL) encoding traits for crop P efficiency have been identified in a variety of crops including rice, maize, common bean, and soybean (for reviews see López-Arredondo et al. 2014 and Zhang, Liao, and Lucas 2014). Although conventional breeding showed significant progress in developing P-efficient cultivars, particularly for soybean in China (Wang, Yan, and Liao 2010), success with marker-assisted breeding has been limited due to significant environmental effects on P efficiency traits. As a result, most identified QTL have made small contributions to overall P efficiency. However, in rice the use of QTL Pup1 (Phosphorus uptake 1) in marker-assisted breeding has led to the development of rice lines showing a dramatic increase in PUE when grown in P-deficient soils (Chin et al. 2010). The increase in rice yield on P-deficient soil was demonstrated by the overexpression of PSTOL1—the gene responsible for Pup1 QTL—indicating high potential for further genetic enhancement of P efficiency in rice (Gamuyao et al. 2012). Although transgenic approaches also yielded significant experimental results in improving P efficiency in different crops (López-Arredondo et al. 2014; Zhang, Liao, and Lucas 2014), there has not yet been a transgenic plant line produced for improving P efficiency that has been released for commercial use.

8.6.1 P ACQUISITION EFFICIENCY

An effective management strategy for soils with low P content and/or P fixation is to enhance the plant's efficiency in acquiring soil P (Lynch 2011). Improved P acquisition by crop plants can be achieved by using three approaches (Ramaekers et al. 2010). First, traditional plant breeding for enhanced P acquisition is a feasible strategy as shown by a range of inheritance studies and the breeding of improved crops with greater P acquisition and better tolerance to low P soils (Ramaekers et al. 2010; Lynch 2011; Gabasawa and Yusuf 2013; Beebe et al. 2014; Kugblenu et al. 2014; Mendes et al. 2014; Leiser et al. 2015). Second, genetic engineering can be used to introduce genes that improve P acquisition and growth of crop plants (López-Arredondo et al. 2014; Zhang, Liao, and Lucas 2014). A third strategy focuses on the use of agricultural practices to enhance plant growth under P-deficient conditions through inoculation with plant growth-promoting rhizobacteria and mycorrhizae (Ramaekers et al. 2010; Richardson and Simpson 2011).

Although enhancing the PAE of crops can improve agroecosystem productivity in the short term, a longer-term consequence is that the increased PAE will lower the total soil P content over time. The rate of this decrease will depend on the initial total P content of the soil, the cropping intensity, and the crop P requirement (Ramaekers et al. 2010). To avoid ending up with overall low P soil contents, it is advisable to add

small amounts of soluble P inputs or less-soluble slow-release forms such as rock phosphate. This strategy avoids the rapid loss of added P through soil leaching in coarse-textured soils that are unable to retain P. In P-fixing soils, this strategy additionally reduces the fixation of applied P not taken up by the plant. Combining this strategy with an improved plant efficiency to acquire P will ensure a higher recovery of applied P, lowering P fertilizer requirements.

One of the key mechanisms to increase plant access to P is greater topsoil exploration resulting from root architectural, morphological, and anatomical traits (Lynch 2011; Richardson and Simpson 2011). The ideotype of topsoil foraging has been proposed for improving the PAE by roots (Lynch 2011; White et al. 2013; Lynch and Wojciechowski 2015). It is possible to breed for this ideotype to develop crops for low P soils (Lynch 2011, 2013; Lynch and Wojciechowski 2015). Enhancing topsoil foraging is essential to improve PAE of crop plants because only 20% of the topsoil is explored by the roots during crop growth and development. Efficient genotypes of common bean and maize have shallow roots in the topsoil, and a shallower root growth angle of the axial or seminal roots increases topsoil foraging and thereby contributing to greater values of PAE.

In addition to root architectural traits, root morphological traits such as root length, diameter, surface area, volume, presence of root hairs, and length of root hairs contribute to inter- and intraspecific variation in PAE. The formation of root cortical aerenchyma, which convert living cortical tissue to air space through programmed cell death, improves the PAE by reducing the metabolic cost of soil exploration (Lynch and Wojciechowski 2015). A cost-benefit analysis of root traits indicated that root hairs have the greatest potential for improving PAE relative to their cost of production (Brown et al. 2013). Greater gains in PAE can be achieved through increased length and longevity of root hairs, as compared to increasing their density. The genetic variation in root hair length can be exploited to develop crop cultivars with improved PAE due to their ability to expand the effective P depletion zone around the root axis (Lynch and Wojciechowski 2015). Dimorphic root architecture of axial roots with a greater range of growth angles could also be considered for improving the PAE of crop plants grown in low P soils. In common bean (*Phaseolus vulgaris* L.), the QTL for root architecture are associated with QTL for PAE (Liao et al. 2004), allowing for breeding favorable traits like drought resistance and tolerance to Al toxicity (Yang, Rao, and Horst 2013).

Increased production and secretion of organic acids and enzymes such as phosphatases and ribonucleases in the rhizosphere can increase PAE by the mobilization of P in the rhizosphere (Zhang, Liao, and Lucas 2014). Purple acid phosphatases are a class of acid phosphatases implicated in plant response to P starvation and encompass a diversity of enzymes with intracellular and extracellular (via secretion) activities to scavenge and recycle P (Tian and Liao 2015). Secreted organic acids solubilize P by chelating Al, Fe, and Ca via carboxylate moieties from insoluble Al-P, Fe-P and Ca-P species, respectively, thereby rendering P soluble. Soil organic P is also not directly available to plants unless hydrolyzed or mineralized into P_i by released root phosphatases. The association between plant roots and AMF is another means of improving PAE in several crops (Ramaekers et al. 2010; Richardson and Simpson 2011). The general understanding is that a major mechanism through which

AMF-associated plants acquire higher growth and drought resistance might be increased P nutrition, although additional processes independent of P nutrition may also be important (Suriyagoda et al. 2014). Further research is needed to exploit the beneficial effects of AMF association in relation to P supply for improving crop adaptation to low P soils.

8.6.2 P USE EFFICIENCY

Plant adaptation to P-limited soils can also be affected by genotypic differences in PUE. A potential strategy to reduce dependency on P fertilizer is to enhance the plant's internal PUE. Plants with enhanced PUE show higher growth for the same amount of P taken up. A comparison of the amount of P taken up by various crops to produce 1 t of yield indicated that common bean and soybean stand out as the most P-demanding crops per unit of economic yield (Rao, Friesen, and Osaki 1999). Modern crop varieties use P more efficiently than older varieties mainly as a result of improvements in harvest index (HI), which is related to plant structural and C allocation traits. Beebe et al. (2008) reported that the selection for drought resistance in common beans through improved partitioning of photosynthates to grain also improved yield under low P soil conditions, indicating the importance of improved HI on improving the P efficiency of this species. Recent work on low-input maize systems indicated that across several maize landraces ($n = 20$), PUE in conditions of low soil P were increased by greater internal P utilization and a high HI (Bayuelo-Jiménez and Ochoa-Cadavid 2014).

Higher values of PUE imply effective partitioning and remobilizing P among organs and tissues, and perhaps more importantly, a capacity to accumulate dry matter as a result of efficient use of P in metabolic processes (Veneklaas et al. 2012). Genotypic differences in PAE confound PUE rankings because genotypes with higher PAE suffer a lower degree of P stress, resulting in lower PUE (Rose et al. 2011). Improved PUE can be achieved by plants that have overall low P concentrations and by optimal distribution and redistribution in the plant allowing maximum growth and biomass allocation to harvestable plant parts (Wang, Yan, and Liao 2010). Significant decreases in plant P pools may be possible through reductions of superfluous ribosomal RNA and replacement of phospholipids by sulfolipids and galactolipids. Improvements in P distribution within the plant may be possible by increased remobilization from tissues with decreased P need such as senescing leaves and reduced partitioning of P to developing grains. These changes are expected to prolong and enhance the productive use of P in photosynthesis and have nutritional and environmental benefits (Veneklaas et al. 2012).

Su et al. (2009) identified six QTL controlling PUE in Chinese winter wheat pot and field trials. Moreover, positive linkages were observed between the QTL for PAE and PUE at two loci, suggesting the possibility of improving PAE and PUE simultaneously. Field research on the genetic architecture of PUE in maize cultivated in a low P soil showed that approximately 80% of QTL mapped for PAE co-localized with those for PUE, indicating that the efficiency in acquiring P is the main determinant of PUE (Mendes et al. 2014). Measurements of PAE, PUE, and grain yield in the same environments risk autocorrelations that may mask underlying genotypic

relations. Recently, Leiser et al. (2015) tested the value of PAE and PUE traits for a selection of sorghum for performance in P-limited environments and found that PAE and PUE traits independent of HI were of similar importance for grain yield under low P conditions in statistically independent trials.

A comprehensive understanding of plant adaptive responses is required to simultaneously improve PAE and PUE, together with agronomic approaches that can collectively help meet the sustainability challenge of P delivery to crops. Targeted research is needed to quantify the magnitude of PAE and PUE gains that may be obtained through different mechanisms and their variation associated with genetic and environmental factors. Recent approaches such as genome-wide expression (transcription) QTL analyses and genome-wide association studies using next-generation sequencing could help to identify loci related to and controlling plant PAE and PUE (Veneklaas et al. 2012; Zhang, Liao, and Lucas 2014). Greater focus on plant-based P management (“feed the crop, not the soil”) offers a means to markedly decrease the need for P inputs to agroecosystems by averting low-efficiency P additions to soils and instead use low, crop-targeted P inputs (Withers et al. 2014).

8.6.3 PRECISION AGRICULTURE

Precision agriculture holds a strong potential to improve the agronomic efficiency of P inputs, but the high cost of its technological applications makes it currently untenable for many agroecosystems across SSA. One of the goals of precision agriculture is to improve the efficiency of inputs by targeting inputs to temporal and spatial variabilities in soil nutrient concentration and uptake by crops. This is predicated on quantifying the in-field variability of soil properties, typically by spectroscopic and/or remote-sensing technologies, in order to appropriately match inputs (Mulla 2013). The intensive use of technology in precision agriculture (Stafford 2000) engenders high capital costs, and as a result, its application is largely nonexistent across SSA (Seelan et al. 2003). However, limited case studies have demonstrated a strong potential of spatial mapping of variable, if low soil fertility in small-scale fields in SSA, such as millet production in the West Sahel (Florax, Voortman, and Brouwer 2002). On the other hand, microdosing P fertilizer (see Section 8.4.3) arguably represents a low-technology manifestation of precision agriculture because it can improve the agronomic efficiency of added P by spatial and temporal targeting of inputs to individual crop plants. A second constraint to precision agriculture for P management is that methods such as near-infrared spectroscopy used to characterize the spatial variability of soil nutrients have limited ability to quantify predict available soil P (see Section 8.2.4) (Chang et al. 2001).

8.7 MODELING CROP RESPONSE TO P

Field research on crop response to P inputs is time and labor intensive. Such research also has its limitations where the scaling of results beyond the particular soil, field, region, and/or agroecosystem is concerned. On the other hand, the theoretical understanding of P processes in soils, especially under tropical conditions where the organic fraction of P plays a crucial role, has steadily improved over the past

decades. It is therefore not surprising that scientists attempt to describe soil P processes, P crop uptake, and the influence of environment (e.g., soils, climate, and management) on these with the aid of computer simulation models. Besides scientific curiosity, the goal has been to employ models to determine P dynamics in a predictive fashion (spatially as well as temporarily) beyond the system under study.

Initial work to describe the P movement in soils and plant uptake by computer models began in the late 1960s with the work of Nye and Marriott (1969). The Barber and Cushman model followed in the late 1970s/early 1980s (Barber 1995), the concept of which was incorporated into the model of nutrient uptake (Claassen and Steingrobe 1999), as well as the phosmod model (Greenwood, Karpinets, and Stone 2001) and the model by Mollier et al. (2001, 2008). Further details about these models can be found in the study by Ryan et al. (2012). These models all have one thing in common: they never made it into wider use. None of these models has been frequently applied the model developers themselves.

Mollier et al. (2008) modeled maize P uptake well under nonlimiting conditions in southwestern France, but the results under P-deficient conditions were less promising. In agroecosystems where P fertilizer is available and abundantly applied, there is low need for detailed crop models to evaluate alternative P management (Probert and Keating 2000), even though recognized environmental damage of decades of high P inputs merit such modeling. The opposite is true for P-limited soils and for regions where P fertilizer is not applied in sufficient quantities—often two co-occurring scenarios in many regions of SSA.

In comparison to the wealth of research publications dealing with N dynamics, crop N uptake, and approaches to optimize N management, P model development and application has been notably lagging behind. Not surprisingly, there are few additional widely known models that are capable of simulating soil P dynamics and crop responses.

The first one is the erosion-productivity impact calculator (Jones et al. 1984) and the second, the CENTURY model (Parton 1996). A number of studies have been published on the application of CENTURY, yet the majority address OM turnover only. CENTURY's P routine includes five inorganic P (P_i) pools (labile, sorbed, strongly sorbed, occluded, and parent) and six organic P (P_o) pools (passive, slow, active, microbial, soil litter, surface litter) (Figure 8.5). The CENTURY model was used by Gijssman et al. (1996) to simulate the C, N, and P dynamics of a highly weathered Oxisol under savanna grassland in Colombia. The authors were unable to do so satisfactorily and consequently pointed out that the various P pools would need revision to better reflect tropical conditions. It also turned out problematic to evaluate the results of a model that builds on conceptual pools rather than soil P fractions that can actually be measured.

As far as more widely used crop models that are still maintained and updated on a regular basis are concerned, a P module was first integrated into Crop Environment Resources Synthesis (CERES) and Crop Growth (CROPGRO) models within the decision support system for agrotechnology transfer (DSSAT) software in early 2000 (Daroub et al. 2003). This P module included datasets from Tanzania but did not involve substantial further testing. Using maize datasets from Ghana, Dzotsi et al. (2010) modified the P module in DSSAT. Specifically, the authors separated the

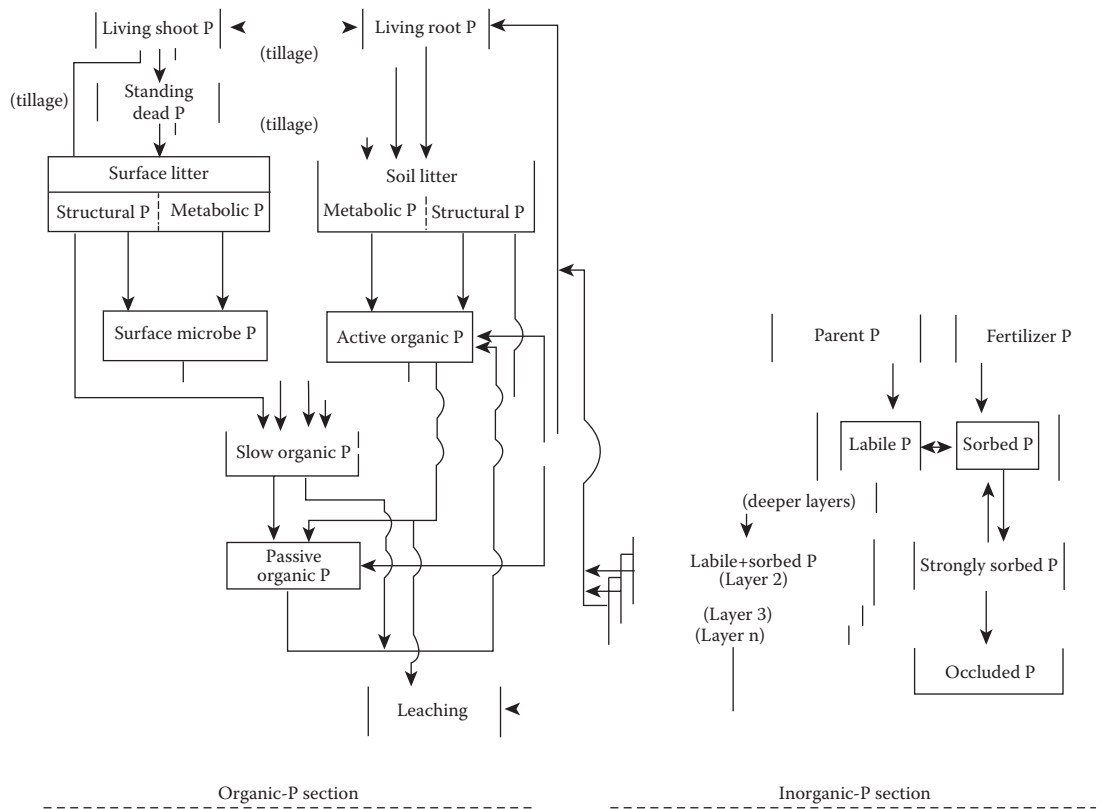


FIGURE 8.5 The conceptual layout of the P module of CENTURY. (From Gijsman, A. J., A. Oberson, H. Tiessen, and D. K. Friesen, *Agronomy Journal*, 88, 894–903, 1996. With permission.)

inorganic P pool into two spatially distinct pools, a pool close to the root zone (i.e., available for plant uptake) and a second pool beyond plant root reach. To facilitate ease of use, the authors developed a set of regression equations to relate equilibrium P concentrations and P transformation rates to soil properties (e.g., texture, water content, organic matter). This version is currently applicable to maize, sorghum, and, as of recently, peanut (Naab et al. 2015). However, the bulk of studies on the application of DSSAT in SSA focus on trials where P is nonlimiting due to fertilization. A few studies employing DSSAT use the built-in rudimentary soil fertility limitation factor, and whereas other studies simply ignore P limitations, even if these are present. Thus, the module remains to be thoroughly tested with datasets for representative agroecosystems in SSA to improve model predictions, as well as to mainstream P simulations to the same level as N.

Besides DSSAT, the agricultural production systems simulator (APSIM) is the second best known and widely applied crop model. A P module was introduced into APSIM in early 2000 (Keating et al. 2003; Probert 2004) and was tested on contrasting soil types (Delve et al. 2009). As is the case for DSSAT, there have been only a limited number of publications building on the P module in APSIM. Past and ongoing participatory modeling work in SSA (Dimes, Twomlow, and Carberry 2003), ignore P limitations, despite the goal of advising farmers on resource use and optimization; certainly a problematic approach.

Ongoing research by the CIAT deals with a more sophisticated way of quantifying P pools. Using soils across a variety of land uses in Malawi and Tanzania, CIAT scientists are working to relate P fractions obtained by sequential extraction (Tiessen, Stewart, and Moir 1983) to land use history, and to predict fractions using mid-infrared spectroscopy (MIRS). The idea behind this is to explain land-use driven changes in P fractions as well as develop a rapid and sophisticated method to initialize DSSAT P pools by MIRS, bypassing tedious and expensive lab fractionations (see Section 8.5.4) or error-prone application of default regression equations to derive these pools.

8.8 CONCLUSIONS AND RESEARCH PERSPECTIVES

As a result of the interactions of soil properties, cropping demands and resources, and socioeconomic conditions unique to the subcontinent, P is a key limiting nutrient for agroecosystem productivity in SSA. Net P inputs to recapitalize soils in SSA are ultimately necessary to lift P limitations. To this end, there are substantial opportunities and low-hanging fruit that offer high mileage on small investments to improve P management. SSA has not only limited but also underexplored P resources, including PR and lime. As current inputs rates in SSA are the lowest of any global region, even minor increases in net P inputs will lessen P limitations in SSA. Biological mechanisms can contribute to crop P uptake but are generally significantly in low-input systems with low soil P. Liming holds a significant potential to decrease P fixation, improve PUE of costly inputs, and ameliorate additional non-P nutrient and toxicity limitations on PUE. Despite the proven efficacy of liming to improve the soil P status in similar soil-climate conditions such as South America and East Africa, there is limited work and even less implementation of pH management to address P deficiency.

Additional research on the affordability and the accessibility of much needed inputs is a critical but oft-overlooked component of P management in SSA. Temporal and spatial specificities of P management hold strong if underutilized potential to maximize the effect of limited P inputs. There is certainly a role that can be played by computer modeling of crop P responses, but a wider-scale application of available tools is yet to come. Breeding efforts to reduce the demand of crops for P show promise, and there are advancements in identifying the genetic basis of traits involved in P uptake and utilization by crops. PAE and PUE can be improved at numerous points along the soil–microbe–plant pathway(s) of P transformation. Increased productivity will require that organic matter inputs be supplemented with inorganic P inputs for crops to provide net P inputs to soils with negative P balances. The combined use of mineral fertilizers (rapid nutrient release) with organic fertilizers (slow nutrient release) is capable of synchronizing P supply with demand, thereby maximizing PUE and minimizing environmental impacts of P loss.

Although input-based strategies are inevitable to improve soil P status and general soil fertility in SSA, there exist considerable economic, social, and even political roadblocks, as well as knowledge constraints. The complexity of these, and their traditional separation from agronomic approaches to soil fertility management, constrains the implementation of well-established knowledge.

ACKNOWLEDGMENTS

This work was partially supported by a U.S. Borlaug Fellowship in Global Food Security and the Consultative Group for International Agricultural Research Program on Grain Legumes.

REFERENCES

- Aainaa, H. N., O. H. Ahmed, S. Kasim, and N. M. Ab Majid. 2014. Reducing Egypt rock phosphate use in *Zea mays* cultivation on an acid soil using clinoptilolite zeolite. *Sustainable Agriculture Research* 4 (1):56.
- Abbott, T. S. 1987. *BCRI Soil Testing: Methods and Interpretation*. Biological and Chemical Research Institute, NSW Agriculture and Fisheries, Orange, New South Wales.
- Achat, D. L., C. Morel, M. R. Bakker, L. Augusto, S. Pellerin, A. Gallet-Budynek, and M. Gonzalez. 2010. Assessing turnover of microbial biomass phosphorus: Combination of an isotopic dilution method with a mass balance model. *Soil Biology and Biochemistry* 42 (12):2231–2240.
- Acosta-Martínez, V., and M. A. Tabatabai. 2000. Enzyme activities in a limed agricultural soil. *Biology and Fertility of Soils* 31 (1):85–91.
- Adepetu, J. A., and R. B. Corey. 1976. Organic phosphorus as a predictor of plant-available phosphorus in soils of southern Nigeria. *Soil Science* 122 (3):159–164.
- Adesanwo, O. O., M. T. Adetunji, and S. Diatta. 2012. Effect of legume incorporation on solubilization of Ogun phosphate rock on slightly acidic soils in SW Nigeria. *Journal of Plant Nutrition and Soil Science* 175 (3):377–384.
- Akande, M. O., F. I. Oluwatoyinbo, J. A. Adediran, K. W. Buari, and I. O. Yusuf. 2004. Soil amendments affect the release of P from rock phosphate and the development and yield of okra. *Journal of Vegetable Crop Production* 9 (2):3–9.

- Allen, S. C., V. D. Nair, D. A. Graetz, S. Jose, and P. K. Ramachandran Nair. 2006. Phosphorus loss from organic versus inorganic fertilizers used in alleycropping on a Florida Ultisol. *Agriculture, Ecosystems & Environment* 117 (4):290–298.
- Alloush, G. A., S. K. Zeto, and R. B. Clark. 2000. Phosphorus source, organic matter, and arbuscular mycorrhiza effects on growth and mineral acquisition of chickpea grown in acidic soil. *Journal of Plant Nutrition* 23 (9):1351–1369.
- Amery, F., and E. Smolders. 2012. Unlocking fixed soil phosphorus upon waterlogging can be promoted by increasing soil cation exchange capacity. *European Journal of Soil Science* 63 (6):831–838.
- Ayaga, G., A. Todd, and P. C. Brookes. 2006. Enhanced biological cycling of phosphorus increases its availability to crops in low-input sub-Saharan farming systems. *Soil Biology and Biochemistry* 38 (1):81–90.
- Ayanaba, A., and D. S. Jenkinson. 1990. Decomposition of carbon-14 labeled ryegrass and maize under tropical conditions. *Soil Science Society of America Journal* 54 (1):112–115.
- Bâ, A. M., and T. Guissou. 1996. Rock phosphate and vesicular-arbuscular mycorrhiza effects on growth and nutrient uptake of *Faidherbia albida* (Del.) seedlings in an alkaline sandy soil. *Agroforestry Systems* 34 (2):129–137.
- Barber, S. A. 1995. *Soil Nutrient Bioavailability: A Mechanistic Approach*. John Wiley & Sons, New York.
- Bationo, A., and A. U. Mokwunye. 1991. Role of manures and crop residue in alleviating soil fertility constraints to crop production: With special reference to the Sahelian and Sudanian zones of West Africa. In *Alleviating Soil Fertility Constraints to Increased Crop Production in West Africa*, edited by Mokwunye, A. U. Springer, Amsterdam.
- Bationo, A., S. K. Mughogho, and U. Mokwunye. 1986. Agronomic evaluation of phosphate fertilizers in tropical Africa. In *Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa*. Springer, Amsterdam, the Netherlands.
- Bationo, S., E. Hartemink Alfred, O. Lungo, M. Naimi, P. Okoth, E. M. A. Smaling, and L. Thiombiano. 2006. African soils: Their productivity and profitability of fertilizer use. Paper read at *African Fertilizer Summit, Abuja, Nigeria*.
- Bayuelo-Jiménez, J. S., and I. Ochoa-Cadavid. 2014. Phosphorus acquisition and internal utilization efficiency among maize landraces from the central Mexican highlands. *Field Crops Research* 156 (0):123–134.
- Beckett, P. H. T., and R. E. White. 1964. Studies on the phosphate potentials of soils. *Plant and Soil* 21 (3):253–282.
- Beebe, S. E., I. M. Rao, C. Cajiao, and M. Grajales. 2008. Selection for drought resistance in common bean also improves yield in phosphorus limited and favorable environments. *Crop Science* 48 (2):582–592.
- Beebe, S. E., I. M. Rao, M. J. Devi, and J. Polania. 2014. Common beans, biodiversity, and multiple stresses: Challenges of drought resistance in tropical soils. *Crop and Pasture Science* 65 (7):667–675.
- Bekunda, M. A., A. Bationo, and H. Ssali. 1997. Soil fertility management in Africa: A review of selected research trials. In *Replenishing Soil Fertility in Africa*, edited by Buresh, R. J., P. A. Sanchez, and F. Calhoun. Soil Science Society of America and American Society of Agronomy, Madison, WI.
- Bekunda, M., N. Sanginga, and P. L. Woomer. 2010. Restoring soil fertility in Sub-Saharan Africa. In *Advances in Agronomy*, edited by Donald, L. S. Academic Press, Cambridge, MA.
- Blake, R. E., J. R. O'Neil, and A. V. Surkov. 2005. Biogeochemical cycling of phosphorus: Insights from oxygen isotope effects of phosphoenzymes. *American Journal of Science* 305 (6–8):596–620.

- Blanchard, M., K. Coulibaly, S. Bognini, P. Dugue, and É. Vall. 2014. Diversity in the quality of organic manure produced on farms in West Africa: What impact on recommendations for the use of manure? *Biotechnologie, Agronomie, Société et Environnement* 18 (4):512–523.
- Bogrekcı, I., and W. S. Lee. 2005. Spectral soil signatures and sensing phosphorus. *Biosystems Engineering* 92 (4):527–533.
- Bolan, N. S., and M. J. Hedley. 1989. Dissolution of phosphate rocks in soils: 1. Evaluation of extraction methods for the measurement of phosphate rock dissolution. *Fertilizer Research* 19 (2):65–75.
- Bolan, N. S., and M. J. Hedley. 1990. Dissolution of phosphate rocks in soils: 2. Effect of pH on the dissolution and plant availability of phosphate rock in soil with pH dependent charge. *Fertilizer Research* 24 (3):125–134.
- Bonzi, M., F. Lompo, N. Ouandaogo, and P. M. Sédogo. 2011. Promoting uses of indigenous phosphate rock for soil fertility recapitalisation in the Sahel: State of the knowledge on the review of the rock phosphates of Burkina Faso. In *Innovations as Key to the Green Revolution in Africa*, edited by Bationo, A., B. Waswa, J. M. Okeyo, F. Maina, and J. M. Kihara. Springer, Amsterdam.
- Bougnom, B. P., B. A. Knapp, F.-X. Etoa, and H. Insam. 2011. Possible use of wood ash and compost for improving acid tropical soils. In *Recycling of Biomass Ashes*, edited by Insam, H., and B. A. Knapp. Springer, Berlin Heidelberg.
- Bray, R. H., and L. T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59 (1):39–46.
- Brown, L. K., T. S. George, L. X. Dupuy, and P. J. White. 2013. A conceptual model of root hair ideotypes for future agricultural environments: What combination of traits should be targeted to cope with limited P availability? *Annals of Botany* 112 (2):317–330.
- Bucagu, C., B. Vanlauwe, and K. E. Giller. 2013. Managing Tephrosia mulch and fertilizer to enhance coffee productivity on smallholder farms in the Eastern African Highlands. *European Journal of Agronomy* 48 (0):19–29.
- Buehler, S., A. Oberson, I. M. Rao, D. K. Friesen, and E. Frossard. 2002. Sequential phosphorus extraction of a P-labeled Oxisol under contrasting agricultural systems. *Soil Science Society of America Journal* 66 (3):868–877.
- Buresh, R. J., P. C. Smithson, and D. T. Hellums. 1997. Building soil phosphorus capital in Africa. *Replenishing Soil Fertility in Africa*. In *Replenishing Soil Fertility in Africa*, edited by Buresh, R. J., P. A. Sanchez, and F. Calhoun. Soil Science Society of America, Madison, WI.
- Canfield, D. E., E. Erik, and T. Bo. 2005. The phosphorus cycle. In *Advances in Marine Biology*, edited by Donald, E. K., E. Canfield, and T. Bo. Academic Press, Cambridge, MA.
- Celi, L., and E. Barberis. 2005. Abiotic stabilization of organic phosphorus in the environment. In *Organic Phosphorus in the Environment*, edited by Turner, B. L., E. Frossard, and D. S. Baldwin. CABI Publishing, Wallingford, UK. 113–132.
- Chang, C.-W., D. A. Laird, M. J. Mausbach, and C. R. Hurburgh. 2001. Near-infrared reflectance Spectroscopy–Principal components regression analyses of soil properties. *Soil Science Society of America Journal* 65 (2):480–490.
- Chen, Y.-S. R., J. N. Butler, and W. Stumm. 1973. Adsorption of phosphate on alumina and kaolinite from dilute aqueous solutions. *Journal of Colloid and Interface Science* 43 (2):421–436.
- Chien, S. H. 1977a. Dissolution of phosphate rocks in a flooded acid soil. *Soil Science Society of America Journal* 41 (6):1106–1109.
- Chien, S. H. 1977b. Thermodynamic considerations on the solubility of phosphate rock. *Soil Science* 123 (2):117–121.

- Chien, S. H., and D. K. Friesen. 2000. Phosphate fertilisers and management for sustainable crop production in tropical acid soils. In *Management and Conservation of Tropical Acid Soils for Sustainable Crop Production*. International Atomic Energy Agency, Vienna, Austria.
- Chien, S. H., L. L. Hammond, and L. A. Leon. 1987. Long-term reactions of phosphate rocks with an Oxisol in Colombia. *Soil Science* 144 (4):257–265.
- Chien, S. H., J. Henao, C. B. Christianson, A. Bationo, and A. U. Mokwunye. 1990. Agronomic evaluation of two unacidulated and partially acidulated phosphate rocks indigenous to Niger. *Soil Science Society of America Journal* 54 (6):1772–1777.
- Chin, J. H., X. Lu, S. M. Haefele, R. Gamuyao, A. Ismail, M. Wissuwa, and S. Heuer. 2010. Development and application of gene-based markers for the major rice QTL Phosphorus uptake 1. *Theoretical and Applied Genetics* 120 (6):1073–1086.
- Claassen, N., and B. Steingrobe. 1999. Mechanistic simulation models for a better understanding of nutrient uptake from soil. In *Mineral Nutrition of Crops: Fundamental Mechanisms and Implications*, edited by Rengel, Z. Haworth Press Inc, New York.
- Clark, R. B. 1984. Physiological aspects of calcium, magnesium, and molybdenum deficiencies in plants. In *Soil Acidity and Liming*, edited by Adams, F. American Society of Agronomy and Crop Science Society of America, Madison, WI.
- Cofie, O. O., G. Kranjac-Berisavljevic, and P. Drechsel. 2005. The use of human waste for peri-urban agriculture in Northern Ghana. *Renewable Agriculture and Food Systems* 20 (02):73–80.
- Condron, L. M., and S. Newman. 2011. Revisiting the fundamentals of phosphorus fractionation of sediments and soils. *Journal of Soils and Sediments* 11 (5):830–840.
- Cooperband, L. R., and T. J. Logan. 1994. Measuring in situ changes in labile soil phosphorus with anion-exchange membranes. *Soil Science Society of America Journal* 58 (1):105–114.
- Cordell, D., J.-O. Drangert, and S. White. 2009. The story of phosphorus: Global food security and food for thought. *Global Environmental Change* 19 (2):292–305.
- Cozzolino, V., V. Di Meo, and A. Piccolo. 2013. Impact of arbuscular mycorrhizal fungi applications on maize production and soil phosphorus availability. *Journal of Geochemical Exploration* 129 (0):40–44.
- Cross, A. F., and W. H. Schlesinger. 1995. A literature review and evaluation of the Hedley fractionation: Applications to the biogeochemical cycle of soil phosphorus in natural ecosystems. *Geoderma* 64 (3–4):197–214.
- Cyamweshi, R. A., N. L. Nabahungu, A. Mukashema, V. Ruganzu, M. C. Gatarayiha, A. Nduwumuremyi, and J. J. Mbonigaba. 2014. Enhancing nutrient availability and coffee yield on acid soils of the central plateau of southern Rwanda. *Global Journal of Agricultural Research* 2 (2):44–55.
- Daroub, S. H., A. Gerakis, J. T. Ritchie, D. K. Friesen, and J. Ryan. 2003. Development of a soil-plant phosphorus simulation model for calcareous and weathered tropical soils. *Agricultural Systems* 76 (3):1157–1181.
- Delve, R. J., M. E. Probert, J. G. Cobo, J. Ricaurte, M. Rivera, E. Barrios, and I. M. Rao. 2009. Simulating phosphorus responses in annual crops using APSIM: Model evaluation on contrasting soil types. *Nutrient Cycling in Agroecosystems* 84 (3):293–306.
- Dembélé, I., D. Koné, A. Soumaré, D. Coulibaly, Y. Koné, B. Ly, and L. Kater. 2000. Fallows and field systems in dryland Mali. In *Nutrients on the Move: Soil Fertility Dynamics in African Farming Systems*, edited by Hilhorst, T., and F. M. Muchena. International Institute for Environment and Development, London.
- Dieter, D., H. Elsenbeer, and B. L. Turner. 2010. Phosphorus fractionation in lowland tropical rainforest soils in central Panama. *CATENA* 82 (2):118–125.

- Dimes, J., S. Twomlow, and P. S. Carberry. 2003. Application of new tools: Exploring the synergies between simulation models and participatory research in smallholder farming systems In *Global Theme 3: Water, Soil and Agrodiversity Management for Ecosystem Resilience*. International Crops Research Institute for the Semi-Arid Tropic, Bulawayo, Zimbabwe.
- Dobermann, A. 2004. A critical assessment of the system of rice intensification (SRI). *Agricultural Systems* 79 (3):261–281.
- Douxchamps, S., I. M. Rao, M. Peters, R. Van Der Hoek, A. Schmidt, S. Martens, J. Polania et al. 2013. Farm-scale tradeoffs between legume use as forage versus green manure: The case of *Canavalia brasiliensis*. *Agroecology and Sustainable Food Systems* 38 (1):25–45.
- Drechsel, P., B. Mutwewingabo, and F. Hagedorn. 1996. Effect of modifications of the P-Bray no. 1 method on soil test results. *Zeitschrift für Pflanzenernährung und Bodenkunde* 159 (4):409–410.
- Dzotsi, K. A., J. W. Jones, S. G. K. Adiku, J. B. Naab, U. Singh, C. H. Porter, and A. J. Gijsman. 2010. Modeling soil and plant phosphorus within DSSAT. *Ecological Modelling* 221 (23):2839–2849.
- Ekenler, M., and M. A. Tabatabai. 2003. Responses of phosphatases and arylsulfatase in soils to liming and tillage systems. *Journal of Plant Nutrition and Soil Science* 166 (3):281–290.
- Esberg, C., B. du Toit, R. Olsson, U. Ilstedt, and R. Giesler. 2010. Microbial responses to P addition in six South African forest soils. *Plant and Soil* 329 (1–2):209–225.
- Essington, M. E. 2004. *Soil and Water Chemistry: An Integrative Approach*. Taylor & Francis, Abingdon-on-Thames.
- Eswaran, H., R. Almaraz, E. van den Berg, and P. Reich. 1997. An assessment of the soil resources of Africa in relation to productivity. *Geoderma* 1.77:1–18.
- Eze, I. C., and P. Loganathan. 1990. Effects of pH on phosphate sorption of some paleudults of southern Nigeria. *Soil Science* 150 (3):613–621.
- Fageria, N. K., and V. C. Baligar. 2008. Ameliorating soil acidity of tropical Oxisols by liming for sustainable crop production. In *Advances in Agronomy*, edited by Donald, L. S. Academic Press, Cambridge, MA.
- Fairhurst, T., R. Lefroy, E. Mutert, and N. Batjes. 1999. The importance, distribution and causes of phosphorus deficiency as a constraint to crop production in the tropics. *Agroforestry Forum* 9:2–8.
- Feller, C., and M. H. Beare. 1997. Physical control of soil organic matter dynamics in the tropics. *Geoderma* 79 (1):69–116.
- Florax, R. J. G. M., R. L. Voortman, and J. Brouwer. 2002. Spatial dimensions of precision agriculture: A spatial econometric analysis of millet yield on Sahelian coversands. *Agricultural Economics* 27 (3):425–443.
- Fox, R. L., and E. J. Kamprath. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soils. *Soil Science Society of America Journal* 34 (6):902–907.
- Fredeen, A. L., I. Madhusudana Rao, and N. Terry. 1989. Influence of phosphorus nutrition on growth and carbon partitioning in *Glycine max*. *Plant Physiology* 89 (1):225–230.
- Friesen, D. K., A. S. R. Juo, and M. H. Miller. 1980. Liming and lime-phosphorus-zinc interactions in two Nigerian Ultisols: I. Interactions in the soil. *Soil Science Society of America Journal* 44 (6):1221–1226.
- Gabasawa, A. I., and A. A. Yusuf. 2013. Genotypic variations in phosphorus use efficiency and yield of some groundnut cultivars grown on an Alfisol at Samaru, Nigeria. *Journal of Soil Science and Environmental Management* 4 (3):54–61.
- Gachengo, C. N., C. A. Palm, B. Jama, and C. Othieno. 1998. Tithonia and senna green manures and inorganic fertilizers as phosphorus sources for maize in Western Kenya. *Agroforestry Systems* 44 (1):21–35.

- Galang, M. A., D. Markewitz, and L. A. Morris. 2010. Soil phosphorus transformations under forest burning and laboratory heat treatments. *Geoderma* 155 (3–4):401–408.
- Gamuyao, R., J. H. Chin, J. Pariasca-Tanaka, P. Pesaresi, S. Catausan, C. Dalid, I. Slamet-Loedin, E. M. Tecson-Mendoza, M. Wissuwa, and S. Heuer. 2012. The protein kinase Pst11 from traditional rice confers tolerance of phosphorus deficiency. *Nature* 488 (7412):535–539.
- George, T. S., A.-M. Fransson, J. P. Hammond, and P. J. White. 2011. Phosphorus nutrition: Rhizosphere processes, plant response and adaptations. In *Phosphorus in Action*. Springer, Amsterdam.
- George, T. S., P. J. Gregory, J. S. Robinson, R. J. Buresh, and B. A. Jama. 2001. *Tithonia diversifolia*: Variations in leaf nutrient concentration and implications for biomass transfer. *Agroforestry Systems* 52 (3):199–205.
- George, T. S., P. J. Gregory, J. S. Robinson, R. J. Buresh, and B. Jama. 2002a. Utilisation of soil organic P by agroforestry and crop species in the field, western Kenya. *Plant and Soil* 246 (1):53–63.
- George, T. S., P. J. Gregory, M. Wood, D. Read, and R. J. Buresh. 2002b. Phosphatase activity and organic acids in the rhizosphere of potential agroforestry species and maize. *Soil Biology and Biochemistry* 34 (10):1487–1494.
- Giardina, C. P., R. L. Sanford, and I. C. Døckersmith. 2000. Changes in soil phosphorus and nitrogen during slash-and-burn clearing of a dry tropical forest. *Soil Science Society of America Journal* 64 (1):399–405.
- Giardina, C. P., R. L. Sanford, I. C. Døckersmith, and V. J. Jaramillo. 2000. The effects of slash burning on ecosystem nutrients during the land preparation phase of shifting cultivation. *Plant and Soil* 220 (1–2):247–260.
- Gichangi, E. M., and P. N. S. Mnkeni. 2009. Effects of goat manure and lime addition on phosphate sorption by two soils from the Transkei region, South Africa. *Communications in Soil Science and Plant Analysis* 40 (21–22):3335–3347.
- Gichangi, E. M., P. N. S. Mnkeni, and P. C. Brookes. 2010. Goat manure application improves phosphate fertilizer effectiveness through enhanced biological cycling of phosphorus. *Soil Science & Plant Nutrition* 56 (6):853–860.
- Gichangi, E. M., P. N. S. Mnkeni, and P. Muchaonyerwa. 2008. Phosphate sorption characteristics and external P requirements of selected South African soils. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)* 109 (2):139–149.
- Gijsman, A. J., A. Oberson, H. Tiessen, and D. K. Friesen. 1996. Limited applicability of the CENTURY model to highly weathered tropical soils. *Agronomy Journal* 88 (6):894–903.
- Giller, K. E. 2002. Targeting management of organic resources and mineral fertilizers: Can we match scientists' fantasies with farmers' realities? In *Integrated Plant Nutrient Management in Sub-Saharan Africa*, edited by Vanlauwe, B., N. Sanginga, J. Diels, and R. Merckx. (Bevat: Balanced Nutrient Management Systems for the Moist Savanna and Humid Forest Zones of Africa.) CAB International, Wallingford.
- Graham, R. D. 1984. Breeding for nutritional characteristics in cereals. In *Advances in Plant Nutrition*, edited by Tinker, P. B., and A. Lauchli. Praeger Publishers, New York.
- Grant, C., S. Bittman, M. Montreal, C. Plenchette, and C. Morel. 2005. Soil and fertilizer phosphorus: Effects on plant P supply and mycorrhizal development. *Canadian Journal of Plant Science* 85 (1):3–14.
- Greenwood, D. J., T. V. Karpinets, and D. A. Stone. 2001. Dynamic model for the effects of soil P and fertilizer P on crop growth, P uptake and soil P in arable cropping: Model description. *Annals of Botany* 88 (2):279–291.
- Guppy, C. N., N. W. Menzies, F. P. C. Blamey, and P. W. Moody. 2005a. Do decomposing organic matter residues reduce phosphorus sorption in highly weathered soils? *Soil Science Society of America Journal* 69 (5):1405–1411.

- Guppy, C. N., N. W. Menzies, P. W. Moody, and F. P. C. Blamey. 2005b. Competitive sorption reactions between phosphorus and organic matter in soil: A review. *Soil Research* 43 (2):189–202.
- Hammond, J. P., M. R. Broadley, P. J. White, G. J. King, H. C. Bowen, R. Hayden, M. C. Meacham et al. 2009. Shoot yield drives phosphorus use efficiency in *Brassica oleracea* and correlates with root architecture traits. *Journal of Experimental Botany* 60 (7):1953–1968.
- Haque, I., N. Z. Lupwayi, and H. Ssali. 1999. Agronomic evaluation of unacidulated and partially acidulated Minjingu and Chilembwe phosphate rocks for clover production in Ethiopia. *European Journal of Agronomy* 10 (1):37–47.
- Harrison, A. F. 1987. *Soil Organic Phosphorus: A Review of World Literature*. CAB International, Wallingford.
- Havlin, J., S. L. Tisdale, W. L. Nelson, and J. D. Beaton. 2013. *Soil Fertility and Fertilizers*. Pearson, New York.
- Hawke, D., P. D. Carpenter, and K. A. Hunter. 1989. Competitive adsorption of phosphate on goethite in marine electrolytes. *Environmental Science & Technology* 23 (2):187–191.
- Haynes, R. J. 1982. Effects of liming on phosphate availability in acid soils. *Plant and Soil* 68 (3):289–308.
- Hedley, M. J., J. W. B. Stewart, and B. S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal* 46 (5):970–976.
- Houlton, B. Z., Y.-P. Wang, P. M. Vitousek, and C. B. Field. 2008. A unifying framework for dinitrogen fixation in the terrestrial biosphere. *Nature* 454 (7202):327–330.
- Hu, X.-Y. 2013. Application of visible/near-infrared spectra in modeling of soil total phosphorus. *Pedosphere* 23 (4):417–421.
- Huang, J., P. R. Fisher, and W. R. Argo. 2007. Container substrate-pH response to differing limestone type and particle size. *HortScience* 42 (5):1268–1273.
- International Fertilizer Industry Association. 2015. *Production and International Trade Statistics*. International Fertilizer Industry Association, Paris.
- Iyamuremye, F., and R. P. Dick. 1996. Organic amendments and phosphorus sorption by soils. In *Advances in Agronomy*, edited by Donald, L. S. Academic Press, Cambridge, MA.
- Jama, B., and A. Kiwia. 2009. Agronomic and financial benefits of phosphorus and nitrogen sources in western Kenya. *Experimental Agriculture* 45 (03):241–260.
- Jama, B., and P. Van Straaten. 2006. Potential of East African phosphate rock deposits in integrated nutrient management strategies. *Anais da Academia Brasileira de Ciências* 78 (4):781–790.
- Jama, B., C. A. Palm, R. J. Buresh, A. Niang, C. Gachengo, G. Nziguheba, and B. Amadalo. 2000. *Tithonia diversifolia* as a green manure for soil fertility improvement in western Kenya: A review. *Agroforestry Systems* 49 (2):201–221.
- Janssen, B. H. 2011. Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments: I. New soil organic matter and residual effect of P from fertilizers and farmyard manure in Kabete, Kenya. *Plant and Soil* 339 (1–2):3–16.
- Jayne, T. S., and S. Rashid. 2013. Input subsidy programs in sub-Saharan Africa: A synthesis of recent evidence. *Agricultural Economics* 44 (6):547–562.
- Jayne, T. S., D. Mather, N. Mason, and J. Ricker-Gilbert. 2013. How do fertilizer subsidy programs affect total fertilizer use in sub-Saharan Africa? Crowding out, diversion, and benefit/cost assessments. *Agricultural Economics* 44 (6):687–703.
- Jemo, M., O. J. Jayeoba, T. Alabi, and A. Lopez Montes. 2014. Geostatistical mapping of soil fertility constraints for yam based cropping systems of North-central and Southeast Nigeria. *Geoderma Regional* 2–3 (0):102–109.
- Jobbágy, E. G., and R. B. Jackson. 2001. The distribution of soil nutrients with depth: Global patterns and the imprint of plants. *Biogeochemistry* 53 (1):51–77.

- Jones, D. L., and E. Oburger. 2011. Solubilization of phosphorus by soil microorganisms. In *Phosphorus in Action*, edited by Bünemann, E., A. Oberson, and E. Frossard. Springer, Berlin Heidelberg.
- Jones, C. A., C. V. Cole, A. N. Sharpley, and J. R. Williams. 1984. A simplified soil and plant phosphorus model: I. Documentation. *Soil Science Society of America Journal* 48 (4):800–805.
- Jungk, A., and N. Claassen. 1997. Ion diffusion in the soil-root system. *Advances in Agronomy* 61:53–110.
- Kalvig, P., N. Fold, J. B. Jønsson, and E. Elisaimon Mshiu. 2012. Rock phosphate and lime for small-scale farming in Tanzania, East Africa. *Geological Survey of Denmark and Greenland Bulletin* 26:85–88.
- Kanabo, I. A. K., and R. J. Gilkes. 1988. The effect of the level of phosphate rock application on its dissolution in soil and on bicarbonate-soluble phosphorus. *Fertilizer Research* 16 (1):67–85.
- Karekezi, S., and P. Turyareeba. 1995. Woodstove dissemination in Eastern Africa—A review. *Energy for Sustainable Development* 1 (6):12–19.
- Karunanithi, R., A. A. Szogi, N. Bolan, R. Naidu, P. Loganathan, P. G. Hunt, M. B. Vanotti, C. P. Saint, Y. S. Ok, and S. Krishnamoorthy. 2015. Phosphorus recovery and reuse from waste streams. In *Advances in Agronomy*. Academic Press, Cambridge, MA.
- Keating, B. A., P. S. Carberry, G. L. Hammer, M. E. Probert, M. J. Robertson, D. Holzworth, N. I. Huth et al. 2003. An overview of APSIM: A model designed for farming systems simulation. *European Journal of Agronomy* 18 (3–4):267–288.
- Kelderman, P., D. K. Koech, B. Gumbo, and J. O’Keeffe. 2009. Phosphorus budget in the low-income, peri-urban area of Kibera in Nairobi (Kenya). *Water Science and Technology* 60 (10):2669–2676.
- Kenya Agricultural Research Institute. 1994. *Fertilizer Use Recommendations*. Kenya Agricultural Research Institute, Nairobi.
- Ketterings, Q. M., M. van Noordwijk, and J. M. Bigham. 2002. Soil phosphorus availability after slash-and-burn fires of different intensities in rubber agroforests in Sumatra, Indonesia. *Agriculture, Ecosystems & Environment* 92 (1):37–48.
- Khasawneh, F. E., and E. C. Doll. 1979. The use of phosphate rock for direct application to soils. *Advances in Agronomy* 30:159–206.
- Kibunja, C. N., F. B. Mwaura, D. N. Mugendi, P. T. Gicheru, J. W. Wamungo, and A. Bationo. 2012. Strategies for maintenance and improvement of soil productivity under continuous maize and beans cropping system in the sub-humid highlands of Kenya: Case study of the long-term trial at Kabete. In *Lessons Learned from Long-term Soil Fertility Management Experiments in Africa*, edited by Bationo, A., B. Waswa, J. Kihara, I. Adolwa, B. Vanlauwe, and K. Saidou. Springer, Amsterdam.
- Kihara, J., and S. Njoroge. 2013. Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. *Field Crops Research* 150 (0):1–8.
- Kihara, J., B. Vanlauwe, B. Waswa, J. M. Kimetu, J. Chianu, and A. Bationo. 2010. Strategic phosphorus application in legume-cereal rotations increases land productivity and profitability in western Kenya. *Experimental Agriculture* 46 (01):35–52.
- Kleinman, P. J. A., D. Pimentel, and R. B. Bryant. 1995. The ecological sustainability of slash-and-burn agriculture. *Agriculture, Ecosystems & Environment* 52 (2–3):235–249.
- Kouno, K., Y. Tuchiya, and T. Ando. 1995. Measurement of soil microbial biomass phosphorus by an anion exchange membrane method. *Soil Biology and Biochemistry* 27 (10):1353–1357.
- Koutika, L.-S., T. E. Crews, G. Ayaga, and P. C. Brookes. 2013. Microbial biomass P dynamics and sequential P fractionation in high and low P fixing Kenyan soils. *European Journal of Soil Biology* 59 (0):54–59.

- Kugblenu, Y. O., F. K. Kumaga, K. Ofori, and J. J. Adu-Gyamfi. 2014. Evaluation of cowpea genotypes for phosphorus use efficiency. *Journal of Agricultural and Crop Research* 2 (10):202–210.
- Kwabiah, A. B., C. A. Palm, N. C. Stoskopf, and R. P. Voroney. 2003. Response of soil microbial biomass dynamics to quality of plant materials with emphasis on P availability. *Soil Biology and Biochemistry* 35 (2):207–216.
- Kwabiah, A. B., N. C. Stoskopf, R. P. Voroney, and C. A. Palm. 2001. Nitrogen and phosphorus release from decomposing leaves under sub-humid tropical conditions. *Biotropica* 33 (2):229–240.
- Kwari, J. D., and T. Batey. 1991. Effect of heating on phosphate sorption and availability in some north-east Nigerian soils. *Journal of Soil Science* 42 (3):381–388.
- Lamers, J. P. A., M. Bruentrup, and A. Buerkert. 2015a. Financial performance of fertilisation strategies for sustainable soil fertility management in Sudano–Sahelian West Africa 1: Profitability of annual fertilisation strategies. *Nutrient Cycling in Agroecosystems* 102:137–148.
- Lamers, J. P. A., M. Bruentrup, and A. Buerkert. 2015b. Financial performance of fertilization strategies for sustainable soil fertility management in Sudano–Sahelian West Africa. 2: Profitability of long-term capital investments in rock phosphate. *Nutrient Cycling in Agroecosystems* 102:149–165.
- Larson, B. A., and G. B. Frisvold. 1996. Fertilizers to support agricultural development in sub-Saharan Africa: What is needed and why. *Food Policy* 21 (6):509–525.
- Leenaars, J. G. B. 2013. *Africa Soil Profiles Database: Version 1.1 A Compilation of Geo-Referenced and Standardized Legacy Soil Profile Data for Sub Saharan Africa*. Africa Soil Information Service (AFSIS) project. ISRIC—World Soil Information, Wageningen.
- Leiser, W. L., H. F. W. Rattunde, H.-P. Piepho, E. Weltzien, A. Diallo, A. Toure, and B. I. G. Haussmann. 2015. Phosphorous efficiency and tolerance traits for selection of sorghum for performance in phosphorous-limited environments. *Crop Science* 55 (3):1152–1162.
- Lerner, B. R., and J. D. Utzinger. 1986. Wood ash as soil liming material. *Hortscience* 21 (1):76–78.
- Liao, H., X. Yan, G. Rubio, S. E. Beebe, M. W. Blair, and J. P. Lynch. 2004. Genetic mapping of basal root gravitropism and phosphorus acquisition efficiency in common bean. *Functional Plant Biology* 31 (10):959–970.
- Liu, A., C. Hamel, T. Spedding, T.-Q. Zhang, R. Mongeau, G. R. Lamarre, and G. Tremblay. 2008. Soil microbial carbon and phosphorus as influenced by phosphorus fertilization and tillage in a maize-soybean rotation in south-western Quebec. *Canadian Journal of Soil Science* 88 (1):21–30.
- Liverpool-Tasie, L. S. O., B. T. Omonona, A. Sanou, and W. Ogunleye. 2015. Is increasing inorganic fertilizer use in sub-Saharan Africa a profitable proposition? Evidence from Nigeria (February 1, 2015). World Bank Policy Research Working Paper (7201). World Bank Group, Washington, DC.
- López-Arredondo, D. L., M. A. Leyva-González, S. I. González-Morales, J. López-Bucio, and L. Herrera-Estrella. 2014. Phosphate nutrition: Improving low-phosphate tolerance in crops. *Annual Review of Plant Biology* 65 (1):95–123.
- Lynch, J. P. 2011. Root phenes for enhanced soil exploration and phosphorus acquisition: Tools for future crops. *Plant Physiology* 156 (3):1041–1049.
- Lynch, J. P. 2013. Steep, cheap and deep: An ideotype to optimize water and N acquisition by maize root systems. *Annals of Botany* 112 (2):347–357.
- Lynch, J. P., and T. Wojciechowski. 2015. Opportunities and challenges in the subsoil: Pathways to deeper rooted crops. *Journal of Experimental Botany* 66:2199–2210.
- Lynch, J., A. Läuchli, and E. Epstein. 1991. Vegetative growth of the common bean in response to phosphorus nutrition. *Crop Science* 31 (2):380–387.

- Mackay, A. D., J. K. Syers, R. W. Tillman, and P. E. H. Gregg. 1986. A simple model to describe the dissolution of phosphate rock in soils. *Soil Science Society of America Journal* 50 (2):291–296.
- Maheshwari, D. K. 2011. *Bacteria in Agrobiolgy: Plant Nutrient Management*. Springer, Amsterdam.
- Mahimairaja, S., N. S. Bolan, and M. J. Hedley. 1994. Dissolution of phosphate rock during the composting of poultry manure: An incubation experiment. *Fertilizer Research* 40 (2):93–104.
- Malik, M. A., P. Marschner, and K. Saifullah Khan. 2012. Addition of organic and inorganic P sources to soil—Effects on P pools and microorganisms. *Soil Biology and Biochemistry* 49 (0):106–113.
- Margenot, A. J., and R. Sommer. 2014. Amplifying investments in phosphorus by site-specific soil fertility management. In *Visions for a Sustainable Phosphorus Tomorrow*. European Sustainable Phosphorus Platform, Brussels, Belgium.
- Margenot, A. J., R. Sommer, N. Jelinski, J. Mukulama, and S. J. Parikh. 2014. Soil phosphorus (P) fractions and lability in western Kenya Oxisols after a decade of P inputs of different quality and response to simulated liming: Implications for cost-effective P management. Paper read at *Soil Science Society of America Annual Meeting, November 2, 2014, at Long Beach, CA*.
- Marschner, H. 1995. *Mineral Nutrition of Higher Plants*. Academic Press, Cambridge, MA.
- Materechera, S. A. 2012. Using wood ash to ameliorate acidity and improve phosphorus availability in soils amended with partially decomposed cattle or chicken manure. *Communications in Soil Science and Plant Analysis* 43 (13):1773–1789.
- Materechera, S. A., and T. S. Mkhabela. 2002. The effectiveness of lime, chicken manure and leaf litter ash in ameliorating acidity in a soil previously under black wattle (*Acacia mearnsii*) plantation. *Bioresource Technology* 85 (1):9–16.
- Mehlich, A. 1984. Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. *Communications in Soil Science and Plant Analysis* 15 (12):1409–1416.
- Mendes, F. F., L. J. M. Guimarães, J. C. Souza, P. E. O. Guimarães, J. V. Magalhaes, A. A. F. Garcia, S. N. Parentoni, and C. T. Guimaraes. 2014. Genetic architecture of phosphorus use efficiency in tropical maize cultivated in a low-P soil. *Crop Science* 54 (4):1530–1538.
- Menon, R. G., S. H. Chien, and L. L. Hammond. 1989. Comparison of Bray I and Pi tests for evaluating plant-available phosphorus from soils treated with different partially acidulated phosphate rocks. *Plant and Soil* 114 (2):211–216.
- Mike, J. H., and S. B. Nanthi. 2003. Role of carbon, nitrogen, and sulfur cycles in soil acidification. In *Handbook of Soil Acidity*: CRC Press, Boca Raton, FL.
- Minasny, B., G. Tranter, Al. B. McBratney, D. M. Brough, and B. W. Murphy. 2009. Regional transferability of mid-infrared diffuse reflectance spectroscopic prediction for soil chemical properties. *Geoderma* 153 (1–2):155–162.
- Miyasaka, S. C., and M. Habte. 2001. Plant mechanisms and mycorrhizal symbioses to increase phosphorus uptake efficiency. *Communications in Soil Science and Plant Analysis* 32 (7–8):1101–1147.
- Mnkeni, P. N. S., J. M. R. Semoka, and J. B. B. S. Buganga. 1991. Effectiveness of Minjingu phosphate rock as a source of phosphorus for maize in some soils of Morogoro, Tanzania. *Zimbabwe Journal of Agricultural Research* 29 (1):27–37.
- Mollier, A., P. de Willigen, S. Pellerin, and M. Heinen. 2001. A two dimensional simulation model of phosphorus uptake including crop growth and P response. In *Plant Nutrition*, edited by Horst, W. J., M. K. Schenk, A. Bürkert, N. Claassen, H. Flessa, W. B. Frommer, H. Goldbach et al. Springer, Amsterdam.

- Mollier, A., P. De Willigen, M. Heinen, C. Morel, A. Schneider, and S. Pellerin. 2008. A two-dimensional simulation model of phosphorus uptake including crop growth and P-response. *Ecological Modelling* 210 (4):453–464.
- Morris, M. L. 2007. *Fertilizer Use in African Agriculture: Lessons Learned and Good Practice Guidelines: Directions in Development—Agriculture and Rural Development 39037*. The World Bank, Washington, DC.
- Mowo, J. G. 2000. *Effectiveness of Phosphate Rock on Ferralsols in Tanzania and the Influence of Within-Field Variability*. Landbouwniversiteit Wageningen (Wageningen Agricultural University), Wageningen.
- Msolla, M. M., J. M. R. Semoka, and O. K. Borggaard. 2005. Hard Minjingu phosphate rock: An alternative P source for maize production on acid soils in Tanzania. *Nutrient Cycling in Agroecosystems* 72 (3):299–308.
- Mubiru, D. N., and M. S. Coyne. 2009. Legume cover crops are more beneficial than natural fallows in minimally tilled Ugandan soils. *Agronomy Journal* 101 (3):644–652.
- Mukuralinda, A., J. S. Tenywa, L. Verchot, J. Obua, and S. Namirembe. 2009. Decomposition and phosphorus release of agroforestry shrub residues and the effect on maize yield in acidic soils of Rubona, southern Rwanda. *Nutrient Cycling in Agroecosystems* 84 (2):155–166.
- Mulla, D. J. 2013. Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering* 114 (4):358–371.
- Murwira, H. K., and H. Kirchmann. 1993. Nitrogen dynamics and maize growth in a Zimbabwean sandy soil under manure fertilisation. *Communications in Soil Science and Plant Analysis* 24 (17–18):2343–2359.
- Mustonen, P. J., M. Oelbermann, and D. C. L. Kass. 2011. Using *Tithonia diversifolia* (Hemsl.) gray in a short fallow system to increase soil phosphorus availability on a Costa Rican Andosol. *Journal of Agricultural Science* 4 (2):91.
- Mwangi, W. M. 1996. Low use of fertilizers and low productivity in sub-Saharan Africa. *Nutrient Cycling in Agroecosystems* 47 (2):135–147.
- Naab, J. B., K. J. Boote, J. W. Jones, and C. H. Porter. 2015. Adapting and evaluating the CROPGRO-peanut model for response to phosphorus on a sandy-loam soil under semi-arid tropical conditions. *Field Crops Research* 176 (0):71–86.
- Nakamura, S., M. Fukuda, F. Nagumo, and S. Tobita. 2013. Potential utilization of local phosphate rocks to enhance rice pin sub-Saharan Africa. *Japan Agricultural Research Quarterly: JARQ* 47 (4):353–363.
- Nannipieri, P., L. Giagnoni, L. Landi, and G. Renella. 2011. Role of phosphatase enzymes in soil. In *Phosphorus in Action*. Springer, Amsterdam.
- Ndung'u, K. W., J. R. Okalebo, C. O. Othieno, M. N. Kifuko, A. K. Kipkoech, and L. N. Kimenye. 2006. Residual effectiveness of minjingu phosphate rock and fallow biomass on crop yields and financial returns in western Kenya. *Experimental Agriculture* 42 (03):323–336.
- Nduwumuremyi, A., V. Ruganzu, J. N. Mugwe, and A. C. Rusanganwa. 2013. Effects of unburned lime on soil pH and base cations in acidic soil. *ISRN Soil Science* 2013:7.
- Negassa, W., and P. Leinweber. 2009. How does the Hedley sequential phosphorus fractionation reflect impacts of land use and management on soil phosphorus: A review. *Journal of Plant Nutrition and Soil Science* 172 (3):305–325.
- Nekesa, P., H. K. Maritim, J. R. Okalebo, and P. L. Woome. 1999. Economic analysis of maize-bean production using a soil fertility replenishment product (PREP-PAC) in western Kenya. *African Crop Science Journal* 7 (4):585–590.
- Nekesa, A. O., J. R. Okalebo, C. O. Othieno, M. N. Thuita, M. Kipsat, A. Bationo, and N. Sanginga. 2005. The potential of Minjingu phosphate rock from Tanzania as a liming material: Effect on maize and bean intercrop on acid soils of western Kenya. *African Crop Science Conference Proceedings* 7:1121–1128.

- Nimoh, F., K. Ohene-Yankyera, K. Poku, F. Konradsen, and R. C. Abaidoo. 2014. Farmers' perception on excreta reuse for peri-urban agriculture in southern Ghana. *Journal of Development and Agricultural Economics* 6 (10):421–428.
- Njui, N. A., and A. A. O. Musandu. 1999. Response of maize to phosphorus fertilisation at selected sites in western Kenya. *African Crop Science Journal* 7 (4):397–406.
- Notholt, A. J. G. 1994. Phosphate rock: Factors in economic and technical evaluation. *Geological Society, London, Special Publications* 79 (1):53–65.
- Nwoke, O. C., B. Vanlauwe, J. Diels, N. Sanginga, O. Osonubi, and R. Merckx. 2003. Assessment of labile phosphorus fractions and adsorption characteristics in relation to soil properties of West African savanna soils. *Agriculture, Ecosystems & Environment* 100 (2–3):285–294.
- Nye, P. H., and F. H. C. Marriott. 1969. A theoretical study of the distribution of substances around roots resulting from simultaneous diffusion and mass flow. *Plant and Soil* 30 (3):459–472.
- Nyenje, P. 2014. *Fate and Transport of Nutrients in Groundwater and Surface Water in an Urban Slum Catchment Kampala, Uganda*. Delft University of Technology, Delft.
- Nziguheba, G. 2007. Overcoming phosphorus deficiency in soils of Eastern Africa: Recent advances and challenges. In *Advances in Integrated Soil Fertility Management in Sub-Saharan Africa: Challenges and Opportunities*. Springer, Amsterdam.
- Nziguheba, G., R. Merckx, C. A. Palm, and P. Mutuo. 2002. Combining *Tithonia diversifolia* and fertilizers for maize production in a phosphorus deficient soil in Kenya. *Agroforestry Systems* 55 (3):165–174.
- Nziguheba, G., R. Merckx, C. A. Palm, and M. R. Rao. 2000. Organic residues affect phosphorus availability and maize yields in a Nitisol of western Kenya. *Biology and Fertility of Soils* 32 (4):328–339.
- Nziguheba, G., C. A. Palm, R. J. Buresh, and P. C. Smithson. 1998. Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. *Plant and Soil* 198 (2):159–168.
- Oberson, A., and E. J. Joner. 2005. Microbial turnover of phosphorus in soil. In *Organic Phosphorus in the Environment*. CABI, Wallingford, pp. 133–164.
- Oberson, A., D. K. Friesen, C. Morel, and H. Tiessen. 1997. Determination of phosphorus released by chloroform fumigation from microbial biomass in high P sorbing tropical soils. *Soil Biology and Biochemistry* 29 (9–10):1579–1583.
- Oberson, A., D. K. Friesen, I. M. Rao, P. C. Smithson, B. L. Turner, and E. Frossard. 2006. Chapter 37: Improving phosphorus fertility in tropical soils through biological interventions. In *Biological Approaches to Sustainable Soil Systems*, edited by Uphoff, N. (ed.). Marcel Dekker, New York.
- Oberson, A., P. Pypers, E. K. Bünemann, and E. Frossard. 2011. Management impacts on biological phosphorus cycling in cropped soils. In *Phosphorus in Action*, edited by Bünemann, E., A. Oberson, and E. Frossard. Springer, Berlin Heidelberg.
- Oehl, F., A. Oberson, M. Probst, A. Fliessbach, H.-R. Roth, and E. Frossard. 2001. Kinetics of microbial phosphorus uptake in cultivated soils. *Biology and Fertility of Soils* 34 (1):31–41.
- Ohno, T., and M. S. Erich. 1990. Effect of wood ash application on soil pH and soil test nutrient levels. *Agriculture, Ecosystems & Environment* 32 (3–4):223–239.
- Ojo, O. D., E. A. Akinrinde, and M. O. Akoroda. 2010. Residual effects of phosphorus sources in grain amaranth production. *Journal of Plant Nutrition* 33 (5):770–783.
- Okalebo, J. R., K. W. Gathua, and P. L. Woomer. 2002. *Laboratory Methods of Soil and Plant Analysis: A Working Manual*. Second ed. Sustainable Agriculture Centre for Research Extension and Development in Africa (SACRED), Nairobi.
- Okalebo, J. R., C. O. Othieno, A. O. Nekesa, K. W. Ndungu-Magiroy, and M. N. Kifuko-Koeh. 2009. Potential for agricultural lime on improved soil health and agricultural production in Kenya. *Ninth African Crop Science, Conference Proceedings, Cape Town, South Africa, 28 September–2 October 2009*, pp. 339–341.

- Okalebo, J. R., P. L. Woome, C. O. Othieno, N. K. Karanja, S. Ikerra, A. O. Esilaba, A. O. Nekesa et al. 2007. Potential for agricultural lime on improved soil health and agricultural production in Kenya. Paper read at *African Crop Science Proceedings, Egypt*.
- Oliveira, S. M., and A. S. Ferreira. 2014. Change in soil microbial and enzyme activities in response to the addition of rock-phosphate-enriched compost. *Communications in Soil Science and Plant Analysis* 45 (21):2794–2806.
- Olson, J. S. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44 (2):322–331.
- Osorio, N. W., and M. Habte. 2013a. Synergistic effect of a phosphate-solubilizing fungus and an arbuscular mycorrhizal fungus on leucaena seedlings in an Oxisol fertilized with rock phosphate. *Botany* 91 (4):274–281.
- Osorio, N. W., and M. Habte. 2013b. Phosphate desorption from the surface of soil mineral particles by a phosphate-solubilizing fungus. *Biology and Fertility of Soils* 49 (4):481–486.
- Osorio, N. W., and M. Habte. 2015. Effect of a phosphate-solubilizing fungus and an arbuscular mycorrhizal fungus on *Leucaena* seedlings in tropical soils with contrasting phosphate sorption capacity. *Plant and Soil* 389 (1–2):375–385.
- Owusu-Benoah, E., and C. Visker. 1994. Organic wastes hijacked. *ILEIA Newsletter* 10 (3):12–13.
- Parton, W. J. 1996. The CENTURY model. In *Evaluation of Soil Organic Matter Models*, edited by Powlson, D., P. Smith, and J. Smith. Springer, Berlin Heidelberg.
- Pearson, R. W. 1975. *Soil Acidity and Liming in the Humid Tropics*. New York State College of Agriculture and Life Sciences, Cornell University, Ithaca, NY.
- Peters, J. B. 1996. Choosing between liming materials. In *University of Wisconsin Extension*. University of Wisconsin-Madison, Madison, WI.
- Pitman, R. M. 2006. Wood ash use in forestry—A review of the environmental impacts. *Forestry* 79 (5):563–588.
- Probert, M. E. 2004. A capability in APSIM to model phosphorus responses in crops. Paper read at *Nutrient Management in Tropical Cropping Systems, Canberra, Australia*.
- Probert, M. E., and B. A. Keating. 2000. What soil constraints should be included in crop and forest models? *Agriculture, Ecosystems & Environment* 82 (1–3):273–281.
- Probert, M. E., J. R. Okalebo, J. R. Simpson, and R. K. Jones. 1992. The role of boma manure for improving soil fertility. Paper read at *A Search for Strategies for Sustainable Dryland Cropping in Semi-arid Eastern Kenya. ACIAR Proceedings*. Nairobi, Kenya.
- Pur'Homme, M. 2010. World phosphate rock flows, losses, and uses. In *Phosphates International Conference*. International Fertilizer Industry Association, Brussels.
- Pypers, P., S. Verstraete, C. P. Thi, and R. Merckx. 2005. Changes in mineral nitrogen, phosphorus availability and salt-extractable aluminium following the application of green manure residues in two weathered soils of South Vietnam. *Soil Biology and Biochemistry* 37 (1):163–172.
- Qian, P., and J. J. Schoenau. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. *Canadian Journal of Soil Science* 82 (1):9–21.
- Raison, R. J., P. K. Khanna, and P. V. Woods. 1985. Transfer of elements to the atmosphere during low-intensity prescribed fires in three Australian subalpine eucalypt forests. *Canadian Journal of Forest Research* 15 (4):657–664.
- Rajan, S. S. S., J. H. Watkinson, and A. G. Sinclair. 1996. Phosphate rocks for direct application to soils. *Advances in Agronomy* 57:77–159.
- Ramaekers, L., R. Remans, I. M. Rao, M. W. Blair, and J. Vanderleyden. 2010. Strategies for improving phosphorus acquisition efficiency of crop plants. *Field Crops Research* 117 (2–3):169–176.

- Rao, I. M., and N. Terry. 1989. Leaf phosphate status, photosynthesis, and carbon partitioning in sugar beet: I. Changes in growth, gas exchange, and calvin cycle enzymes. *Plant Physiology* 90 (3):814–819.
- Rao, I. M., D. K. Friesen, and M. Osaki. 1999. Plant adaptation to phosphorus-limited tropical soils. *Handbook of Plant and Crop Stress*. Marcel Dekker, Inc., New York, pp. 61–96.
- Richardson, A. E., and R. J. Simpson. 2011. Soil microorganisms mediating phosphorus availability update on microbial phosphorus. *Plant Physiology* 156 (3):989–996.
- Robinson, J. S., and J. K. Syers. 1990. A critical evaluation of the factors influencing the dissolution of Gafsa phosphate rock. *Journal of Soil Science* 41 (4):597–605.
- Robinson, J. S., and J. K. Syers. 1991. Effects of solution calcium concentration and calcium sink size on the dissolution of Gafsa phosphate rock in soils. *Journal of Soil Science* 42 (3):389–397.
- Romanya, J., P. K. Khanna, and R. J. Raison. 1994. Effects of slash burning on soil phosphorus fractions and sorption and desorption of phosphorus. *Forest Ecology and Management* 65 (2):89–103.
- Romney, D. L., P. J. Thorne, and D. Thomas. 1994. Some animal-related factors influencing the cycling of nitrogen in mixed farming systems in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 49 (2):163–172.
- Rose, T. J., M. T. Rose, J. Pariasca-Tanaka, S. Heuer, and M. Wissuwa. 2011. The frustration with utilization: Why have improvements in internal phosphorus utilization efficiency in crops remained so elusive? *Frontiers in Plant Science* 2:73.
- Roy, A. H., and G. H. McClellan. 1986. Processing phosphate ores into fertilizers. In *Management of Nitrogen and Phosphorus Fertilizers in Sub-Saharan Africa*, edited by Mokwunye, A. U., and P. G. Vlek. Springer, Amsterdam.
- Rusinamhodzi, L., M. Corbeels, S. Zingore, J. Nyamangara, and K. E. Giller. 2013. Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research* 147 (0):40–53.
- Rutto, E. C., R. Okalebo, C. O. Othieno, M. J. Kipsat, A. Bationo, and K. Girma. 2011. Effect of PREP-PAC application on soil properties, maize, and legume yields in a Ferralsol of Western Kenya. *Communications in Soil Science and Plant Analysis* 42 (20):2526–2536.
- Ryan, J., H. Ibrikli, A. Delgado, J. Torrent, R. Sommer, and A. Rashid. 2012. Significance of phosphorus for agriculture and the environment in the West Asia and North Africa region. In *Advances in Agronomy*, edited by Donald, L. S. Academic Press, Cambridge, MA.
- Saa, A. M., C. Trasar-Cepeda, F. Gil-Sotres, and T. Carballas. 1993. Changes in soil phosphorus and acid phosphatase activity immediately following forest fires. *Soil Biology and Biochemistry* 25 (9):1223–1230.
- Sabiha, J., T. Mehmood, M. M. Chaudhry, M. Tufail, and N. Irfan. 2009. Heavy metal pollution from phosphate rock used for the production of fertilizer in Pakistan. *Microchemical Journal* 91 (1):94–99.
- Sale, P. W. G., and A. U. Mokwunye. 1993. Use of phosphate rocks in the tropics. *Fertilizer Research* 35 (1–2):33–45.
- Sanchez, P. A. 1999. Improved fallows come of age in the tropics. *Agroforestry Systems* 47 (1–3):3–12.
- Sanchez, P. A. 2002. Soil fertility and hunger in Africa. *Science (Washington)* 295 (5562):2019–2020.
- Sanchez, P. A., and T. J. Logan. 1992. Myths and science about the chemistry and fertility of soils in the tropics. In *Myths and Science of Soils of the Tropics*, edited by Lal, R., and P. A. Sanchez. Soil Science Society of America and American Society of Agronomy, Madison, WI.

- Sánchez, P. A., and J. G. Salinas. 1981. Low-input technology for managing Oxisols and Ultisols in tropical America. *Advances in Agronomy* 34:279–406.
- Sanchez, P. A., S. Ahamed, F. Carré, A. E. Hartemink, J. Hempel, J. Huising, P. Lagacherie et al. 2009. Digital soil map of the world. *Science* 325 (5941):680–681.
- Sanchez, P. A., K. D. Shepherd, M. J. Soule, F. M. Place, R. J. Buresh, A.-M. N. Izac, A. U. Mokwunye, F. R. Kwesiga, C. G. Ndiritu, and P. L. Woomer. 1997. Soil fertility replenishment in Africa: An investment in natural resource capital. In *Replenishing Soil Fertility in Africa*, edited by Buresh, R. J., P. A. Sanchez, and F. Calhoun. Soil Science Society of America, Madison, WI. 1–46.
- Sanginga, N., and P. L. Woomer. 2009. *Integrated Soil Fertility Management in Africa: Principles, Practices, and Developmental Process*: International Center for Tropical Agriculture, Palmira.
- Sarabèr, A., M. Cuperus, and J. Pels. 2011. Ash from combustion of cacao residues for nutrient recycling: A case study. In *Recycling of Biomass Ashes*, edited by Insam, H., and B. A. Knapp. Springer, Berlin Heidelberg.
- Satter, M. A., M. M. Hanafi, T. M. M. Mahmud, and H. Azizah. 2006. Role of arbuscular mycorrhiza and phosphorus in acacia mangium-peanut agroforestry system for rejuvenation of tin tailings. *Journal of Sustainable Agriculture* 28 (4):55–68.
- Scalenghe, R., A. C. Edwards, E. Barberis, and F. Ajmone-Marsan. 2014. Release of phosphorus under reducing and simulated open drainage conditions from overfertilised soils. *Chemosphere* 95 (0):289–294.
- Schiemenz, K., J. Kern, H.-M. Paulsen, S. Bachmann, and B. Eichler-Löbermann. 2011. Phosphorus fertilizing effects of biomass ashes. In *Recycling of Biomass Ashes*, edited by Insam, H., and B. A. Knapp. Springer, Berlin Heidelberg.
- Seelan, S. K., S. Laguette, G. M. Casady, and G. A. Seielstad. 2003. Remote sensing applications for precision agriculture: A learning community approach. *Remote Sensing of Environment* 88 (1–2):157–169.
- Sharpley, A. N. 1995. Soil phosphorus dynamics: Agronomic and environmental impacts. *Ecological Engineering* 5 (2–3):261–279.
- Sheldon, R. P., and D. F. Davidson. 1987. Discovery and development of phosphate rock resources in phosphate-deficient third world countries. *Natural Resources Forum* 11 (1):93–98.
- Sibbesen, E. 1978. An investigation of the anion-exchange resin method for soil phosphate extraction. *Plant and Soil* 50 (1–3):305–321.
- Sikora, F. J. 2002. Evaluating and quantifying the liming potential of phosphate rocks. *Nutrient Cycling in Agroecosystems* 63 (1):59–67.
- Simons, A., D. Solomon, W. Chibssa, G. Blalock, and J. Lehmann. 2014. Filling the phosphorus fertilizer gap in developing countries. *Nature Geoscience* 7 (1):3–3.
- Simpson, J. R., J. R. Okalebo, and G. A. S. Lubulwa. 1996. The problem of maintaining soil fertility in Eastern Kenya: A review of relevant research. In *ACIAR Monograph*. Australian Centre for International Agricultural Research, Canberra.
- Sinsabaugh, R. L., and J. J. Follstad Shah. 2012. Ecoenzymatic stoichiometry and ecological theory. *Annual Review of Ecology, Evolution, and Systematics* 43 (1):313–343.
- Sinsabaugh, R. L., B. H. Hill, and J. J. Follstad Shah. 2009. Ecoenzymatic stoichiometry of microbial organic nutrient acquisition in soil and sediment. *Nature* 462 (7274):795–798.
- Six, J., C. Feller, K. Denef, S. Ogle, J. C. De Moraes Sa, and A. Albrecht. 2002. Soil organic matter, biota and aggregation in temperate and tropical soils—Effects of no-tillage. *Agronomie* 22 (7–8):755–775.
- Smaling, E. M. A., and B. H. Janssen. 1993. Calibration of quefts, a model predicting nutrient uptake and yields from chemical soil fertility indices. *Geoderma* 59 (1–4):21–44.
- Smaling, E. M. A., S. M. Nandwa, and B. H. Janssen. 1997. Soil fertility in Africa is at stake. In *Replenishing Soil Fertility in Africa*, edited by Buresh, R. J., P. A. Sanchez, and F. Calhoun. Soil Science Society of America and American Society of Agronomy, Madison, WI.

- Smithson, P., B. Jama, R. Delve, P. van Straaten, R. Buresh, S. S. S. Rajan, and S. H. Chien. 2003. East African phosphate resources and their agronomic performance. Paper read at *Direct Application of Phosphate Rock and Related Appropriate Technology—Latest Developments and Practical Experiences. Proceedings of an International Meeting, Kuala Lumpur, Malaysia, 16–20 July 2001*.
- Soil Survey Staff. 2015. *Web Soil Survey*, edited by Natural Resources Conservation Service, U. S. Department of Agriculture, Washington, DC.
- Sombroek, W. G., H. M. H. Braun, and B. J. A. van der Pouw. 1982. Exploratory soil map and agro-climatic zone map of Kenya, 1980. National Agricultural Laboratories, Ministry of Agriculture, Nairobi.
- Sommer, R., D. Bossio, L. Desta, J. Dimes, J. Kihara, S. Koala, N. Mango, D. Rodriguez, C. Thierfelder, and L. Winowiecki. 2013. Profitable and sustainable nutrient management systems for east and southern African smallholder farming systems—Challenges and opportunities. International Centre for Tropical Agriculture, Valle del Cauca.
- Sommer, R., P. L. G. Vlek, T. D. de Abreu Sá, K. Vielhauer, R. de Fátima Rodrigues Coelho, and H. Fölster. 2004. Nutrient balance of shifting cultivation by burning or mulching in the Eastern Amazon—Evidence for subsoil nutrient accumulation. *Nutrient Cycling in Agroecosystems* 68 (3):257–271.
- Soriano-Disla J. M., L. J. Janik, R. A. V. Rossel, L. M. Macdonald, and M. J. McLaughlin. 2013. The performance of visible, near-, and mid-infrared reflectance spectroscopy for prediction of soil physical, chemical, and biological properties. *Applied Spectroscopy Reviews* 49 (2):139–186.
- Stafford, J. V. 2000. Implementing precision agriculture in the 21st century. *Journal of Agricultural Engineering Research* 76 (3):267–275.
- Stoorvogel, J. J., E. M. A. Smaling, and B. H. Janssen. 1993. Calculating soil nutrient balances in Africa at different scales. *Fertilizer Research* 35 (3):227–235.
- Stursova, M., and R. L. Sinsabaugh. 2008. Stabilization of oxidative enzymes in desert soil may limit organic matter accumulation. *Soil Biology and Biochemistry* 40 (2):550–553.
- Su, J.-Y., Q. Zheng, H.-W. Li, B. Li, R.-L. Jing, Y.-P. Tong, and Z.-S. Li. 2009. Detection of QTLs for phosphorus use efficiency in relation to agronomic performance of wheat grown under phosphorus sufficient and limited conditions. *Plant Science* 176 (6):824–836.
- Sugihara, S., S. Funakawa, T. Nishigaki, M. Kilasara, and T. Kosaki. 2012. Dynamics of fractionated P and P budget in soil under different land management in two Tanzanian croplands with contrasting soil textures. *Agriculture, Ecosystems & Environment* 162 (0):101–107.
- Suriyagoda, L. D. B., M. H. Ryan, M. Renton, and H. Lambers. 2014. Plant responses to limited moisture and phosphorus availability: A meta-analysis. In *Advances in Agronomy*, edited by Donald, L. S. Academic Press, Cambridge, MA.
- Szilas, C., J. M. R. Semoka, and O. K. Borggaard. 2007. Establishment of an agronomic database for Minjingu phosphate rock and examples of its potential use. *Nutrient Cycling in Agroecosystems* 78 (3):225–237.
- Tabo, R., A. Bationo, B. Gerard, J. Ndjunga, D. Marchal, B. Amadou, M. Garba Annou et al. 2007. Improving cereal productivity and farmers' income using a strategic application of fertilizers in West Africa. In *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities*, edited by Bationo, A., B. Waswa, J. Kihara, and J. Kimetu. Springer, Amsterdam.
- Tabu, I. M., A. Bationo, R. K. Obura, and J. K. Masinde. 2007. Effect of rock phosphate, lime and green manure on growth and yield of maize in a non productive niche of a rhodic Ferralsol in farmer's fields. In *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities*, edited by Bationo, A., B. Waswa, J. Kihara, and J. Kimetu. Springer, Amsterdam.

- Terhoeven-Urselmans, T., O. Spaargaren, T.-G. Vagen, and K. D. Shepherd. 2010. Prediction of soil fertility properties from a globally distributed soil mid-infrared spectral library. *Soil Science Society of America Journal* 74 (5):1792–1799.
- Tian, J., and H. Liao. 2015. The role of intracellular and secreted purple acid phosphatases in plant phosphorus scavenging and recycling. In *Annual Plant Reviews*, vol. 28. John Wiley & Sons, Inc, New York.
- Tiessen, H., I. H. Salcedo, and E. V. S. B. Sampaio. 1992. Nutrient and soil organic matter dynamics under shifting cultivation in semi-arid northeastern Brazil. *Agriculture, Ecosystems & Environment* 38 (3):139–151.
- Tiessen, H., J. W. B. Stewart, and J. O. Moir. 1983. Changes in organic and inorganic phosphorus composition of two grassland soils and their particle size fractions during 60–90 years of cultivation. *Journal of Soil Science* 34 (4):815–823.
- Timmer, L., and C. Visker. 1998. Possibilities and impossibilities of the use of human excreta as fertiliser in agriculture in sub-Saharan Africa. Royal Tropical Institute and University of Amsterdam, Amsterdam.
- Tisdale, S. L., W. L. Nelson, and J. D. Beaton. 1985. *Soil Fertility and Fertilizers*. Collier Macmillan Publishers, New York.
- Tittonell, P., and K. E. Giller. 2013. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. *Field Crops Research* 143 (0):76–90.
- Tittonell, P., A. Muriuki, C. J. Klapwijk, K. D. Shepherd, R. Coe, and B. Vanlauwe. 2013. Soil heterogeneity and soil fertility gradients in smallholder farms of the East African highlands. *Soil Science Society of America Journal* 77 (2):525–538.
- Tungani, J. O., E. J. Mukhwana, and P. L. Woome. 2002. MBILI is number 1: A handbook for innovative maize-legume intercropping. Sustainable Agriculture Centre for Research Extension and Development in Africa (SACRED), Nairobi.
- Turner, B. L. 2010. Variation in pH optima of hydrolytic enzyme activities in tropical rain forest soils. *Applied and Environmental Microbiology* 76 (19):6485–6493.
- Turner, B. L., and M. S. A. Blackwell. 2013. Isolating the influence of pH on the amounts and forms of soil organic phosphorus. *European Journal of Soil Science* 64 (2):249–259.
- Turner, B. L., and B. M. J. Engelbrecht. 2011. Soil organic phosphorus in lowland tropical rain forests. *Biogeochemistry* 103 (1–3):297–315.
- Turner, B. L., E. Frossard, and D. S. Baldwin. 2005. *Organic Phosphorus in the Environment*. CAB International, Wallingford.
- Turner, B. L., M. J. Papházy, P. M. Haygarth, and I. D. Mckelvie. 2002. Inositol phosphates in the environment. *Philosophical Transactions of the Royal Society of London B* 357 (1420):449–469.
- Turner, B. L., A. E. Richardson, and E. J. Mullaney. 2007. *Inositol Phosphates: Linking Agriculture and the Environment*. CAB International, Wallingford.
- Twomlow, S., D. Rohrbach, J. Dimes, J. Rusike, W. Mupangwa, B. Ncube, L. Hove, M. Moyo, N. Mashingaidze, and P. Mahposa. 2011. Micro-dosing as a pathway to Africa's Green Revolution: Evidence from broad-scale on-farm trials. In *Innovations as Key to the Green Revolution in Africa*, edited by Bationo, A., B. Waswa, J. M. Okeyo, F. Maina, and J. M. Kihara. Springer, Amsterdam.
- Ulery, A. L., R. C. Graham, and C. Amrhein. 1993. Wood-ash composition and soil pH following intense burning. *Soil Science* 156 (5):358–364.
- Ussiri, D. A., P. N. S. Mkeni, A. F. MacKenzie, and J. M. R. Seraoka. 1998. Soil test calibration studies for formulation of phosphorus fertilizer recommendations for maize in Morogoro district, Tanzania: II. Estimation of optimum fertilizer rates. *Communications in Soil Science and Plant Analysis* 29 (17–18):2815–2828.
- Vågen, T. G., K. D. Shepherd, M. G. Walsh, L. Winowiecki, L. T. Desta, and J. E. Tondoh. 2010. AFSIS technical specifications: Soil health surveillance. *World Agroforestry Centre*, Nairobi, Kenya.

- van der Eijk, D., Bert. H. Janssen, and O. Oenema. 2006. Initial and residual effects of fertilizer phosphorus on soil phosphorus and maize yields on phosphorus fixing soils: A case study in south-west Kenya. *Agriculture, Ecosystems & Environment* 116 (1–2):104–120.
- van der Velde, M., C. Folberth, J. Balkovič, P. Ciaias, S. Fritz, I. A. Janssens, M. Obersteiner et al. 2014. African crop yield reductions due to increasingly unbalanced nitrogen and phosphorus consumption. *Global Change Biology* 20 (4):1278–1288.
- van der Waals, J. H., and M. C. Laker. 2008. Micronutrient deficiencies in crops in Africa with emphasis on Southern Africa. In *Micronutrient Deficiencies in Global Crop Production*, edited by Alloway, B. Springer, Amsterdam.
- Van Kauwenbergh, S. J. 1991. Overview of phosphate deposits in East and Southeast Africa. *Fertilizer Research* 30 (2–3):127–150.
- van Straaten, P. 2002. *Rocks for Crops: Agrominerals of sub-Saharan Africa*. International Center for Research in Agroforestry, Nairobi.
- Vance, C. P., C. Uhde-Stone, and D. L. Allan. 2003. Phosphorus acquisition and use: Critical adaptations by plants for securing a nonrenewable resource. *New Phytologist* 157 (3):423–447.
- Vanlauwe, B., and K. E. Giller. 2006. Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 116 (1–2):34–46.
- Vanlauwe, B., D. Coyne, J. Gockowski, S. Hauser, J. Huising, C. Masso, G. Nziguheba, M. Schut, and P. Van Asten. 2014. Sustainable intensification and the African smallholder farmer. *Current Opinion in Environmental Sustainability* 8 (0):15–22.
- Vanlauwe, B., N. Sanginga, J. Diels, and R. Merckx. 2006. Case studies related to the management of soil acidity and infertility in the West-African moist savannah. In *Management Practices for Improving Sustainable Crop Production in Tropical Acid Soils*. Results of a coordinated research project organized by the Joint FAO/IAEA Programme of Nuclear Techniques in Food and Agriculture. Vienna, Austria.
- Veneklaas, E. J., H. Lambers, J. Bragg, P. M. Finnegan, C. E. Lovelock, W. C. Plaxton, C. A. Price et al. 2012. Opportunities for improving phosphorus-use efficiency in crop plants. *New Phytologist* 195 (2):306–320.
- Vitousek, P. M., S. Porder, B. Z. Houlton, and O. A. Chadwick. 2010. Terrestrial phosphorus limitation: Mechanisms, implications, and nitrogen–phosphorus interactions. *Ecological Applications* 20 (1):5–15.
- Waigwa, M. W., C. O. Othieno, and J. R. Okalebo. 2003. Phosphorus availability as affected by the application of phosphate rock combined with organic materials to acid soils in western Kenya. *Experimental Agriculture* 39 (4):395–407.
- Walbridge, M. R. 1991. Phosphorus availability in acid organic soils of the lower North Carolina coastal plain. *Ecology* 72 (6):2083–2100.
- Walker, T. W., and J. K. Syers. 1976. The fate of phosphorus during pedogenesis. *Geoderma* 15 (1):1–19.
- Wang, R., Y. Balkanski, O. Boucher, P. Ciaias, J. Penuelas, and S. Tao. 2015. Significant contribution of combustion-related emissions to the atmospheric phosphorus budget. *Nature Geoscience* 8 (1):48–54.
- Wang, Y.-P., B. Z. Houlton, and C. B. Field. 2007. A model of biogeochemical cycles of carbon, nitrogen, and phosphorus including symbiotic nitrogen fixation and phosphatase production. *Global Biogeochemical Cycles* GB1018. Available at <http://onlinelibrary.wiley.com/doi/10.1029/2006GB002797/full>
- Wang, X., X. Yan, and H. Liao. 2010. Genetic improvement for phosphorus efficiency in soybean: A radical approach. *Annals of Botany* 106 (1):215–222.
- Waring, B. G., S. Rose. Weintraub, and R. L. Sinsabaugh. 2014. Ecoenzymatic stoichiometry of microbial nutrient acquisition in tropical soils. *Biogeochemistry* 117 (1):101–113.
- Watanabe, F. S., and S. R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and NaHCO₃ extracts from soil. *Soil Science Society of America Journal* 29 (6):677–678.

- White, P. J., T. S. George, L. X. Dupuy, A. J. Karley, T. A. Valentine, L. Wiesel, and J. Wishart. 2013. Root traits for infertile soils. *Frontiers in Plant Science* 4:1–7.
- Withers, P. J. A., R. Sylvester-Bradley, D. L. Jones, J. R. Healey, and P. J. Talboys. 2014. Feed the crop not the soil: Rethinking phosphorus management in the food chain. *Environmental Science & Technology* 48 (12):6523–6530.
- Wolf, A. M., and D. E. Baker. 1985. Comparisons of soil test phosphorus by Olsen, Bray P1, Mehlich I and Mehlich III methods. *Communications in Soil Science and Plant Analysis* 16 (5):467–484.
- Woomer, P. L. 2007. Costs and returns of soil fertility management options in Western Kenya. In *Advances in Integrated Soil Fertility Management in sub-Saharan Africa: Challenges and Opportunities*, edited by Bationo, A., B. Waswa, J. Kihara, and J. Kimetu. Springer, Amsterdam.
- Yamoah, C., M. Ngueguim, C. Ngong, and D. K. W. Dias. 1996. Reduction of P fertilizer requirement using lime and Mucuna on high P-sorption soils of NW Cameroon. *African Crop Science Journal* 4 (4):441–451.
- Yampracha, S., T. Attanandana, A. Sidibe, A. Srivihok, and R. S. Yost. 2006. Predicting the dissolution of four rock phosphates in flooded acid sulfate soils of Thailand. *Soil Science* 171 (3):200–209.
- Yang, Z.-B., I. M. Rao, and W. J. Horst. 2013. Interaction of aluminium and drought stress on root growth and crop yield on acid soils. *Plant and Soil* 372 (1–2):3–25.
- Yusiharni, E., and R. J. Gilkes. 2012. Short term effects of heating a lateritic podzolic soil on the availability to plants of native and added phosphate. *Geoderma* 191 (0):132–139.
- Zhang, Z., H. Liao, and W. J. Lucas. 2014. Molecular mechanisms underlying phosphate sensing, signaling, and adaptation in plants. *Journal of Integrative Plant Biology* 56 (3):192–220.
- Zingore, S., R. J. Delve, J. Nyamangara, and K. E. Giller. 2008. Multiple benefits of manure: The key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. *Nutrient Cycling in Agroecosystems* 80 (3):267–282.
- Zingore, S., P. Tittonell, M. Corbeels, M. T. van Wijk, and K. E. Giller. 2011. Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: A case from Murewa District, Zimbabwe. *Nutrient Cycling in Agroecosystems* 90 (1):87–103.