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MODELING AN IMPROVEMENT IN PHOSPHORUS UTILIZATION IN TROPICAL AGRICULTURE

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ABSTRACT

Studies of Terra Preta soils have generated interest in recreating their fertility elsewhere. Much of the research has focused on soil amendment charcoal (“biochar”). Terra Preta also contains bone fragments, producing a high concentration of phosphorus. Some forecast worldwide declines in phosphorus supplies, and better agricultural system management is required to improve phosphorus use efficiency. A conceptual model is offered to consider the influence of charcoal on bioavailability of phosphorus. The model describes a system where improvements in the chemical and biological condition of the soil result in increased phosphorus availability and cycling. Mechanisms of phosphorus/charcoal interaction are considered, and an

assessment is made of the potential impact on African subsistence agriculture from the incorporation of biogenic, allogenic phosphorus through biochar.

KEYWORDS

Phosphorus, Biochar, Entropy, Agricultural Systems, Nutrient Cycles

INTRODUCTION

Phosphorus (P) is one of the three macronutrients required for plant growth (the others, of course, being nitrogen [N] and potassium [K]). Phosphorus is especially important for root growth, flowering, fruiting, and seed formation (Smil, 2000). There are no substitutes for P since it is essential to all living things, being a central component of DNA and ATP. Natural P cycling includes erosion of sedimentary rocks into soil, uptake by plants from soil and consumption of plants by animals. Terrestrially, P can be recycled back into soil via decomposition of animal wastes and plant materials, but erosion eventually transports P into aquatic environments. There it is eventually incorporated into sediments, which over hundreds of millions of years may again become terrestrial rock, bearing P (Liu et al., 2008).

Human needs have accelerated portions of this cycle because without continual P inputs current rates of food production would not be possible (Cordell et al., 2009). Approximately 50 MT of phosphate rock is mined each year from a few concentrated sources (van Vuuren et al., 2010) and distributed over the world's cultivated land, an area which exceeds one billion hectares (Smil, 2000), a classic description of an entropic resource use. Process choices in the human P cycle further lead to entropy increases, beginning with wasteful mining practices and including the recycling of less than 50% of human excreta (Cordell et al., 2009; Liu et al., 2008). Erosion, the primary transport process of P to the sea and its ultimate loss from agricultural systems, is accelerated by agriculture (Liu et al. 2008).

Modern agricultural practices have distorted P distributions, so that P is generally accumulating in some first world agricultural soils and has been lost from nearly all subsistence farming areas, so that eutrophic and oligotrophic concerns both need to be addressed, albeit in distinctly different arenas (Liu et al. 2008). The acceleration of P cycling has led some to apply

Hubbert modeling to P usage, with price spikes in the late 2000s leading to estimations that global P production peaks have already been reached (Dery & Anderson, 2007) or are soon to be achieved (Cordell et al., 2009); others, while mindful of the finite extent of rock P deposits, believe peak P is several hundred years in the future (van Vuuren et al. 2010; Cornish 2010).

But no participant in the debate on P resources believes current practices are sustainable. It is clear that addressing P-overuse in industrial agriculture and P-deficiencies throughout the developing world requires large-scale changes in current practices, which should be driven by scientific, systematic awareness of the differing drivers of these conditions (Simpson et al., 2011). The synchronicity of resource overuse and underuse has led some to have hope that rebalancing the system could allow for increased yields without additional overall resource consumption (Carpenter and Bennett 2011), because while humans consume approximately 3 MT P per year in food, approximately 15 MT P is mined and applied for food production (Cordell et al., 2009), suggesting that optimization of usage could address many concerns. The key would be to create a human-driven cycling of P with both improved P recycling and reduced loss of P from the agricultural system through process and systemic changes (Cordell et al., 2009; Simpson et al., 2011; Carpenter & Bennett, 2011).

Simpson et al. (2011) laid out a program for idiosyncratic approaches to inefficient P-use. Elements to be considered include:

- Increasing microbial activity in soils through organic inputs (microbes may release soil-sorbed P)
- Ensuring other constraints on crop yields are addressed (if factors other than P-usage are limiting yield, than P is not being used most efficiently)

- Optimizing fertilizer use (soil testing can be used to set optimal fertilization rates), including differential applications
- Managing pasture land better (pasturing is used as a means of increasing soil P for later crop usage, but uneven deposition of manure can create P-loading inefficiencies)
- Priming crop land by building soil P-levels (this prevents recently applied P from being sorbed and being unavailable for immediate plant needs)
- Using fertilizer-N instead of biologically fixed-N (legumes require more P than many other plants)
- Adopting farming systems where processes that accrete soil P (like pasturing) are used in concert with cropping
- Intercropping or phase cropping (so that plant P needs are met by adjacent or earlier plantings that tend to make soil P more available)
- Selecting crops with low P demand

den Herder et al. (2010) and Lynch (2007) add the notion that nutrient uptake could be improved through genetic changes in basic plant root structures, affecting signaling between plants and symbiotic fungi that assist in making soil elements like P available.

These prescriptions are not immediately applicable for most subsistence farmers. Soil infertility, including lack of N and P, along with insufficient soil carbon, is clearly a cause of one sixth of the planet not being adequately fed. In sub-Saharan Africa, food shortages affect more than 30% of the population. Poor yields, on the order of one tonne/hectare for grains, are caused by the poor soil conditions (Sanchez, 2010; Kimetu et al., 2008). In essence, farmers on poor soils adopt the prescription of using plants with low P demands, as those are the only plants they can grow (Simpson et al., 2011). Remedies such as fertilizer use are generally unavailable due to

a feedback cycle between poor, over-used soil and rural poverty (Barbier, 2000); not only is poverty a barrier to fertilizer use, but costs for phosphate fertilizers are often 2–6 times greater for an African farmer than a European farmer, due to differences in transport and storage costs (Runge-Metzger, 1995).

Short-range solutions to nutrient deficiencies for subsistence farmers need to be implemented. Subsidized N fertilizers have achieved success in tripling yields (Sanchez, 2010); applications of carbonaceous materials of various kinds along with sources of N also improved yields (Kimetu et al., 2008). But P-deficiencies in soil lead to P deficiencies in crops, so that incorporating field residues and recycling animal and human wastes will not create adequate soil P levels, and a supplementary mineral input is necessary (Roose, 1996), since otherwise there will be a continual cycle of ever-declining amounts of P being returned to the soil. Absent substantial changes in foreign aid policies, it seems unlikely there will be general funding supports to enable widespread applications of mineral fertilizer, which, as discussed below, may not be an efficient use of resources in any case.

Here we present a conceptual model of P-cycling in agricultural soils. The model illustrates why many African soils are deficient in P, and that system functions make it difficult to improve yields without continuing inputs of expensive fertilizers. However, through analogy to Brazilian Terra Preta soil, a demonstration is made that the use of biochars may increase crop P-levels using allogenic resources, which means that farmer education may be the sole resource needed to increase near-term yields for subsistence farmers with P-deficient soils.

P BEHAVIOR IN SOIL—OUR MODEL

Phosphorus is usually the most limiting of soil-supplied elements, and soil P tends to decline when soils are used for agriculture. This is because grain or seed contains the most

significant amounts of phosphorus. A high proportion of the grain becomes human food, and human waste is not returned to the field as often as plant or animal wastes (Buol, 1995). P is also limiting because of its chemistry. The low solubility of phosphates and their rapid transformation to insoluble forms makes P less available or unavailable to crops (Smil, 2000). Al, Fe, Ca, K, and Mg can all react with fertilizer P and produce relatively insoluble compounds (see Table 1) (Kamprath, 1986; Smil, 2000). Crop response to water soluble phosphate fertilizers is thus strongly dependent on the overall capacity of soils to sorb P. Once this sorption capacity is satisfied, additional P applications are needed only to replenish the nutrient removed by the crop and to make up for waterborne and erosional losses (Smil, 2000).

Figure 1 broadly depicts P availability as a function of the quantity of P present in the soil, its interaction with the soil body, and the ability of plants to extract P from the soil. Factors that increase P availability include mineral P (P_i) dissolution, organic P (P_o) mineralization, P desorption from soil surfaces, plant root development, and mycorrhizal infection of plant roots. While increased root development and mycorrhizal activity make P more available, other factors may increase or decrease P concentration in the soil solution:

- 1) P may precipitate in and out of the soil solution, a process that may be affected by microbial activity;

- 2) Microbes incorporate some P into their tissues, but also release P through the decomposition of organic matter;

- 3) P may be sorbed or desorbed from Al and Fe oxides. Strong sorption is sometimes referred to as “P fixation.”

TROPICAL AGRICULTURAL SOILS: A MODIFIED MODEL

Sandy soils and soils with nearly neutral pH have relatively little fixation, whereas acidic, clayey soils with high Fe and Al content have the highest sorption capacity (Olson & Engelstad, 1972; Juo & Adams, 1986; Smil, 2000). Acidic, clayey conditions are typical of tropical soils, which naturally contain phosphates, most of which are strongly fixed or sorbed on soil constituents, so P bioavailability is often the main growth limiting factor. The potential for increasing P availability by water soluble phosphate application is limited by the high P-fixing capacity of highly weathered soils of the tropics with topsoil of loamy or clayey textures (Arca, 1985).

In Fe and Al oxide systems, phosphate sorption is affected by pH, and sorption envelopes have a maximum near pH 4 in solutions containing low P concentrations (Juo & Adams, 1986). Thus, liming the soil to a higher pH has enhanced P availability for crops (Olson & Engelstad, 1972; Kamprath, 1986). Benefits are usually attributed to: an increased rate of decomposition of organic matter, which releases phosphorus to the soil solution; reduced aluminum uptake by plants; and, a blocking of sorption reactions. The pH level above which benefits cease and deleterious effects begin is usually between 5 and 6, at which level most of the exchangeable aluminum has been neutralized (Olson & Engelstad, 1972) and less soluble hydroxyapatite begins to form (Snoeyink & Jenkins, 1980).

Organic matter may also play a role in P bioavailability, so that the application of mineral P fertilizer alone may not be sufficient to overcome low soil fertility. Phosphate sorption decreased on Fe and Al oxide surfaces in the presence of organic chelating ions and silicate ions (Juo & Adams, 1986). Thus, organic P was found to increase plant growth in soils with reduced total P contents and high-phosphate sorption capacity (Steiner et al., 2008a).

Long-fallow (20 years per cycle) swidden cultivation in Indonesia, through 2-10 cycles (40-200 years), did not significantly change total P concentrations, but did shift the P from both available and highly recalcitrant inorganic forms to available organic and occluded inorganic forms. Deep-rooting fallow vegetation, with resultant high concentrations of fine roots deep in the soil profile, along with periodic plant death through fire, are likely to cause transfer of P_i to the surface and P_o to deeper horizons; the uptake of P by the deep roots generally increases total P availability (Lawrence & Schlesinger, 2001). Sykes et al. (2008) confirmed that plants are able to scavenge P from low availability pools if they can develop a healthy root system. However, long swidden cycles are no longer a feature of most subsistence farming systems.

Figure 2 indicates the reduction of P availability produced by conditions in many tropical soils. Weathered soils contain high levels of sesquioxides that adsorb P strongly. Plant ability to scavenge P from the soil is reduced by soil acidity, which stunts root growth and decreases mycorrhizal activity. Mineral P dissolution may decline with reduced microbial activity. A hot, humid climate may cause rapid P_o cycling due to increased microbial activity, which makes P_o more available. However, P sorption and low P content in plants and animal wastes mean that only small amounts of P_o accumulate under tropical conditions.

TERRA PRETA AND P: A SYSTEM TO LEARN FROM

Terra Preta Soils

An approach to improved P management is suggested by the relic Anthrosols of Brazil which are known as “Terra Preta.” These soils not only contain higher concentrations and greater amounts of stable soil organic matter (Glaser et al., 2001), but also have higher pH values and moisture-holding capacity than the surrounding soils (Zech et al. 1990). Much attention has focused on the fact that these soils contain large amounts of stable black carbon or charcoal

(Glaser et al., 2001, Glaser et al., 2002, Lehmann et al., 2002, Lehmann et al., 2003, Steiner et al., 2007, Steiner et al., 2008a, Steiner et al., 2008b).

For the discussion here, the most significant aspect of Terra Preta soils is they have extremely high amounts of P (German, 2003) in comparison with the surrounding soils, which have the low P status typical of tropical soils. In one study, Terra Preta topsoil P values were 36 ppm and 71 ppm, compared to a mean of 17.5 ppm (range 11-25 ppm) for adjacent Inceptisols (Eden et al., 1984). Similarly, German (2003) measured P values from 37.4 ppm to 68.6 ppm in Terra Preta soils, compared to no more than 3.6 ppm for adjacent Latosols. Scanning electron microscopic (SEM) observations suggest that most of the phosphorus in these soils is in amorphous/low crystalline forms, associated with bone apatite from fish middens (Lima et al., 2002). Eden et al. (1984) suggest that variability in P concentrations in Brazilian Terra Preta soils reflects differential rates of accumulation of domestic waste, as well as variations in the length of site occupancy.

Higher pH in soils generally implies reduced P sorption and greater P availability. Also, in Terra Preta soils, char can be found to a depth of 1 meter (sometimes more). The deeper portions of Terra Preta soils are thus less acidic and less subject to aluminum toxicity, and have improved bulk density and water-holding characteristics, compared to other tropical soils. This can allow for deeper rooting of fallow plants, and potentially improved available P for crop cycles, per Lawrence & Schlesinger (2001).

Terra Preta soils seem to have an exceptional ability to retain nutrient ions against leaching, even though their nutrient availability is high (Lehmann et al., 2003). This may be due to surface sorption of cations associated with higher pH, but nutrient retention has been attributed also to the high surface area and porosity of the charcoal, and the surface charge that

develops as the charcoal molecules are oxidized. Thus, increased P availability was, in one case, perceived as a factor of P sorption on the charcoal surface rather than the effects of liming (Topoliantz et al., 2005).

Steiner et al. (2007) state that the fertility of Terra Preta is primarily associated with the bone (as a P source) and charcoal in the soil, while Lehmann et al. (2003) specifically associated increased crop growth with greater P bioavailability, measured at more than an order of magnitude greater than what is found in a natural Ferralsol. It is possible that the large amounts of bone in Terra Preta soils sets them at the “critical” P level (where all sorption sites are occupied), which is typically the case for the most heavily fertilized soils of the developed world, where only light applications of P fertilizers are required to replace what is lost in harvest (Cordell et al., 2009). This could explain the popular perception that the fertility of Terra Preta is “not depleted” during agricultural use (e.g., Cornell University, 2006).

Biochar and P

Agriculture tends to deplete soil fertility, causing losses in pre-agricultural levels of nutrients and carbon in most cases. Modern, first world farming has found cost-effective means of replacing lost nutrients. The loss of soil C, since the lost C may not appreciably affect yield in industrial farming, has not been as universally addressed (McLauchlan, 2006). The realization that soil C reservoirs can be important in addressing climate change (e.g., Lal, 2003; Sohi et al., 2010) has helped to foster general appreciations of the value of organic carbon in agricultural soils (e.g., Fowles, 2007; Mondini & Sequi, 2008). Terra Preta, as its charcoal C appears to be recalcitrant, has been viewed as a potentially important public policy model for improving soil quality for agriculture and serving as a means of redressing anthropogenic releases of C to the atmosphere (e.g., Day & Hawkins, 2007; Navia & Crowley, 2010; Sohi et al., 2010).

The charcoal created for use in soils is usually called biochar. The nature of biochar varies considerably, depending on source material for the charcoal and methods of production. High temperature biochars (created at $T > 550^{\circ}\text{C}$) usually have greater surface areas and are more resistant to decay, as they have more aromatic constituents (Joseph et al., 2010), although all biochars are more resistant to decay than unpyrolyzed carbon sources. Enhanced production has been reported for soils amended with biochar, both for tropical, subsistence farming (Glaser et al., 2002; Lehmann et al., 2003; Steiner et al., 2008b; Kimetu et al., 2008; Major et al., 2010), and in other settings (Joseph et al., 2010). In general, combining fertilizers with a carbon source, such as biochar, has a synergistic effect in tropical soils, causing increased efficiency of fertilizer applications (Lehmann et al., 2003; Steiner et al., 2008b; Kimetu et al., 2008), and supplying minerals that might otherwise be recalcitrant in native soils (Major et al., 2010).

The source material for biochar affects the composition of the product (Sohi et al., 2010); most studies find chars do not retain N, although this is not universally the case (Joseph et al., 2010), especially for low-temperature biochars (Gaskin et al., 2008). Because P does not volatilize until approximately 700°C , even high temperature biochars tend to retain source material P, and can actually increase P concentrations since C and other materials are volatilized in the charring process (DeLuca et al., 2009). Nevertheless, most biochars do not contain much in the way of fertilizer nutrients, even for P, Ca, and Mg (Lehmann et al., 2003). The sorbent potential of the large C surface area can mean that biochars take up more P than they make available to plants (Steiner et al., 2007). “Weathering” biochar (the suite of processes including oxidation, microbial decay, dissolution, etc., that occurs with many biochars either in contact with the atmosphere or soil) reduces the uptake of crop-important compounds and makes the

biochar more stable. More weathering occurs with low temperature biochar. These alterations mean the properties of a biochar may be change over time (Joseph et al., 2010).

Generally, however, P appears to be much more available in soils amended with charcoal than those that are not (Lehmann et al., 2003; Asai et al., 2009). DeLuca et al. (2009) offered four mechanisms for the effect:

1) the release of P salts from woody tissues during charring (but although char does contain small amounts of P, char applications alone do not seem to increase plant P uptake, growth, or biomass yield [Lehmann et al., 2003, Steiner et al, 2008a]).

2) biochar interference with P sorption to Al and Fe oxides, especially in acid soils (biochar raises soil pH by increases in alkaline metal oxides, so that with the reduced presence of free Al^{3+} and Fe^{3+} near root surfaces [Steiner et al., 2007], the solubility of phosphate salts and the pH-dependent activities of ions in those salts are increased [Snoeyink & Jenkins, 1980]);

3) biochar-induced changes in the soil ion exchange capacity (biochar can have a high ion exchange capacity [Liang et al., 2006], and therefore may alter P availability by providing anion exchange capacity);

4) biochar sorption of plant and microbial chelates (in strongly acidic, low activity clay soils, soil organic constituents may form complexes with Fe and Al ions (Juo and Adams, 1986), suggesting biochars will sorb the ions that would otherwise react with P).

Biochar may create a beneficial environment for soil microorganisms, especially the mycorrhizal associations thought to control P-cycling (Smil, 2000; Warnock et al., 2007; Arca, 1985). This could occur because biochar alters soil physico-chemical properties, affects other soil microbes so that they do not inhibit mycorrhizae, creates plant–fungus signaling interference and detoxifies allelochemicals, and/or provides refugia from fungal grazers (Warnock et al.,

2007; Joseph et al., 2010), and so increases soil fertility (Steiner et al., 2008a; DeLuca et al., 2009). It is clear that P availability is affected by cycling of P from organic and insoluble inorganic pools (Smil, 2000; Steiner et al., 2008a; De Luca et al., 2009), and P-uptake is largely controlled by mycorrhizae (Warnock et al., 2007).

Biochar containing bone

Charcoal amended tropical soils tend to have P concentrations of approximately 30 mg/kg, but P in Terra Preta soils tends to be higher (Eden et al., 1984; German et al. 2003) and can be much greater—up to 100-300 mg/kg (Glaser et al., 2002). Terra Preta charcoals are marked by inclusion of bone, and most of the P in the soil appears to be from animal, not plant, sources (Lima et al., 2002).

Bone pyrolysis occurs over the approximate temperature range 500–700°C (Purevsuren et al., 2004) which is slightly higher than ordinary charcoal formation temperatures, but clearly within the range of biochar practices (Joseph et al. 2010). Charring bone yields small amounts of tar or liquid, resulting from pyrolysis of the protein network holding the calcium apatite together (Purevsuren et al., 2004), and solid pieces of bone apatite.

Bone apatite may be more soluble than other forms of mineral P. When geogenic and biogenic P compounds in Terra Preta soils were compared, the biogenic Ca-P appeared to be consumed tens of times faster over a few thousand years compared to geogenic Ca-P. Biogenic Ca-P compounds (e.g., animal and fish bones) constituted only 3% of total P for soils that were approximately 2,000 years old, whereas soluble and organic P remained between 58–65% of the total amount of P. This was interpreted as bone-based P being more bioavailable. The continuing high P-availability in Terra Preta soils after the disappearance of bone apatite was

thought to be a base function of biochar-amended soils, which increases active cycling of organic P (Sato et al., 2009).

The formation of bone is an important biological process that concentrates and accumulates P, rather than dispersing it. Thus, the creation of bone in grazing animals, or in fish in local waters, is an undoing of the tendency to increase entropy in P processes. Hydroxyapatite in bones and teeth contains 18.5% P and makes up almost 60% of bone and 70% of teeth (Smil, 2000); a typical African cattle skeleton contains approximately 5-7 kg of P (estimated from Williams et al., 1990, and Stamenkovic, 2005), which is the equivalent of more than 10 kg of P₂O₅ (fertilizer phosphate). Estimates of current annual P use in tropical soils, with poor yields, are approximately 10 kg/ha, meaning the P in one cow could double P availability, and annual P applications of 35 kg/ha have been shown to produce major improvements in crop yield (Sykes et al., 2008). Therefore, it is possible that creating bone biochar from a combination of available organic materials (such as household trash) and cattle carcasses could provide a soil amendment that could increase yields for impoverished farmers, without requiring any foreign aid or non-local resources.

Is it feasible to budget the bones from one cattle carcass per hectare each year in most African settings? Reliable data are sparse; Table 2 shows the most recent FAO (2010) census, for 2000, for the subset of reporting countries. Continent-wide data are dominated by South Africa statistics. Excluding those shows there is a mean of 1.7 cattle/ha, although the data are widely scattered. In some countries, it seems there are a relatively large number of cattle per cultivated hectare, but cattle are not numerous in other areas. In addition, the data do not project mortality rates. Senegal reported more than half of all cattle were 4 years old or older, suggesting the “standing crop” of cattle in many places is relatively long-lived. Schoeman (1989) suggests 80%

of adult female cattle successfully reproduce; since most pastoral herds do not increase in size over time (McPeak & Barrett, 2001), that suggests that approximately 40% of the standing herd either dies or is marketed each year. Thus, a cattle density of more than 3/ha might suffice to provide one carcass/ha, assuming that “marketed” cattle are slaughtered locally, and that cattle bones can be distributed properly to areas of crop cultivation. Therefore, it seems possible for many areas of sub-Saharan Africa (e.g., Botswana, Ethiopia, Guinea, Lesotho, and Madagascar) that sufficient cattle bones will be available to charge the bone biochar system.

Figure 3 indicates the potential impact of for this “Terra Preta” effect to impoverished soils typical of subsistence African agriculture. Mineral P, as bone apatite, is more available, contributing to higher levels of P_o . The most important effects of high levels of charcoal in the soil are reduced soil acidity and the interaction of the char surface with P. Reduced acidity results in less P being fixed to Al and Fe oxides and increased microbial activity. One consequence of the increase in microbial activity may be increased dissolution of sparingly soluble phosphate minerals. Phosphate in the soil solution is retained by the porous biochar surface, where it remains plant available. Reduced acidity means that plant roots can extend through a greater volume of soil. These conditions also favor increased mycorrhizal infection and growth, which further increases root surface area. Inputs of biogenic and allogenic P appear to mean that subsistence farmers can improve yields by adopting biochar additions to soil, providing the bones from locally available cattle are incorporated to decrease entropy in local P-cycling.

CONCLUSIONS

Phosphorus is a key element in agricultural production, but global P scarcity has not been addressed at the international policy level (Cordell et al., 2009). Peak production may occur in as

few as 20 years, even to potential exhaustion of reserves in less than 100 years. Even if P is not depleted in this century, the use of P is unsustainable, as agriculture hastens its dispersion to aquatic sediments, where it cannot be extracted using current technologies. This is happening against a background of ever-increasing food demand which depends on P for its production.

Phosphorus efficiency in agriculture must be enhanced. Terrestrial recycling holds promise as it is almost completely untried. However, a relatively small fraction of the P used in agriculture is recoverable. It is likely to be more effective to improve P use efficiency, and improve distribution of P resources so that the bipolar situation of soils awash in excess P contributing to aquatic pollution and impoverished soils lacking sufficient P that fail to address local agricultural needs can be better balanced, as outlined by Simpson et al. (2011).

Most of the approaches limned there are not available to or are inappropriate for African farmers living crop-to-crop. The Terra Preta soils of the Amazon, much more fertile than neighboring soils because of their exceptionally high P bioavailability, may indicate an interim solution that relies on local, available resources. The unusual Terra Preta P resources appear to be due to the incorporation of bone P as well as organic matter in the biochar. Bone P appears to longer lasting than manufactured P fertilizers, but somewhat more labile than rock P. A combination of geochemical and biological processes may account for long-term P availability in Terra Preta soils.

If P availability can be increased through the incorporation of apparently unused cattle bones into locally produced biochar, soil fertility can be increased. Since the incorporation of P into the bones of grazing animals decreases system entropy, this increases the overall efficiency of P use. Each head of African cattle appears to be a potential source of 10 kg of P. By incorporating the bone P into biochar, it should be more available to crops because of other soil

effects associated with chars. Thus, bone biochars could directly support increased yields, or could, as suggested by Runge-Metzger (1995), be used to support increased cultivation of leguminous plants in crop rotation so that soil fertility is raised without requiring the use of expensive fertilizers.

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Table 1. Solubilities of phosphate salts (Snoeyink and Jenkins, 1980)

Salt	pK_{so}
Hydroxyapatite (Ca ₅ (PO ₄) ₃ (OH))	+55.9
□-tricalcium phosphate	+24.0
Ferric phosphate	+21.9
Aluminum phosphate	+21.0

Table 2. African cattle census (FAO, 2010)

Country	Cultivated Area (ha)	Cattle	Cattle/ha
Botswana	96,840	1,305,092	13.5
Cote D'Ivoire	4,351,663	1,135,196	0.3
Ethiopia	11,047,249	41,527,142	3.8
Gambia	304,856	323,167	1.1
Guinea	1,370,145	4,019,583	2.9
Lesotho	~250,000*	755,134	3.0
Madagascar	2,083,590	9,687,342	4.6
Mali	~4,000,000*	6,811,473	1.7
Mozambique	3,925,324	722,199	0.2
Namibia	295,632	707,246	2.4
Senegal	1,877,684	2,838,336	1.5
South Africa	315,128,000	8,248,000	0.0
Tanzania	11,997,071	16,999,793	1.4
Togo	842,124	217,221	0.3
Uganda	12,455,124	6,282,507	0.5
Zambia	Not reported	230,967	N/A
All reporting Africa	~375,000,000	100,000,000	0.3
Reporting Africa w/o South Africa	55,000,000	94,000,000	1.7

* Estimated based on landholder census and farm size distributions

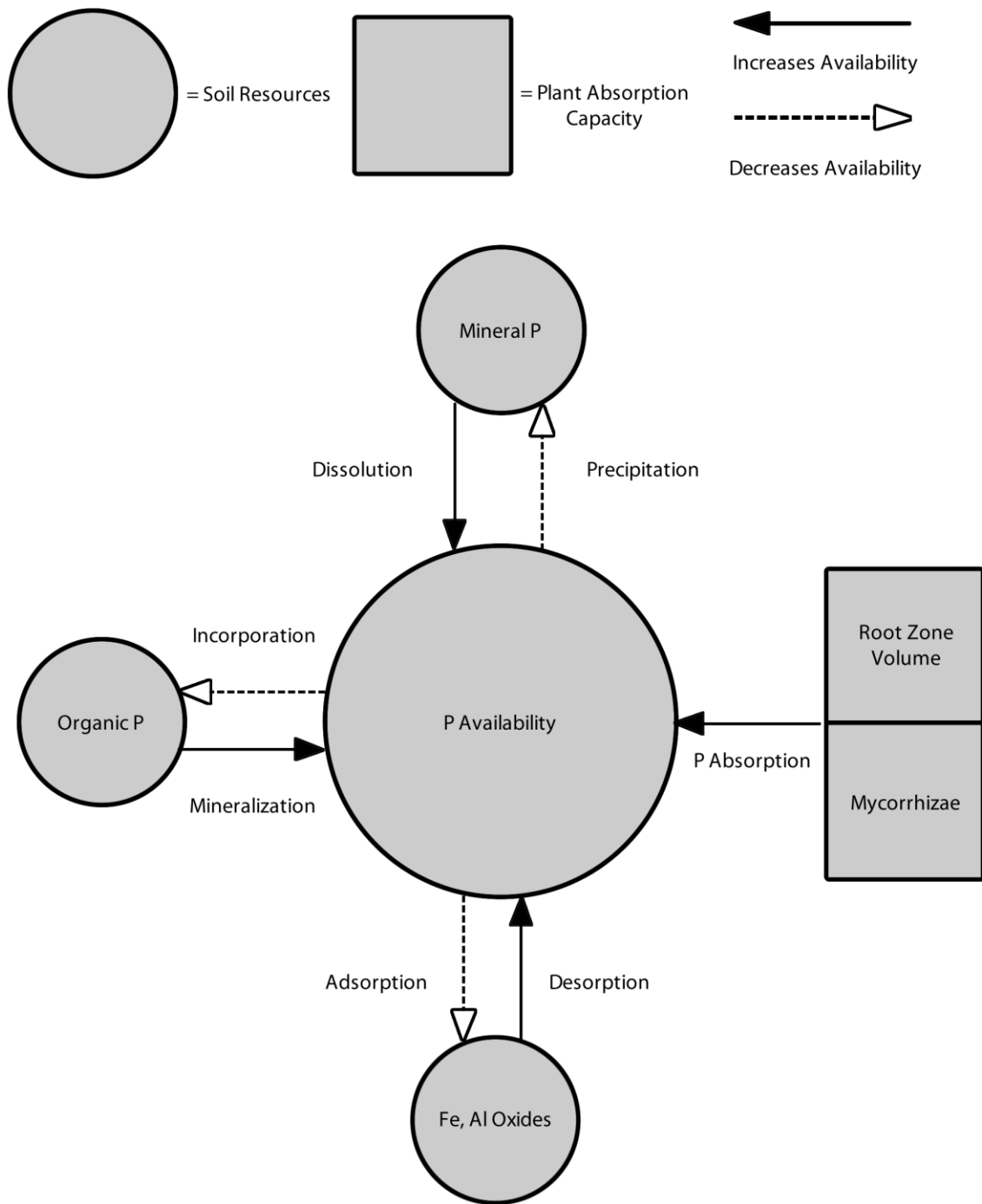


Figure 1: P availability in soil is influenced by soil reserves of P, their bioavailability, and the ability of plants and mycorrhizae to scavenge P from the soil solution

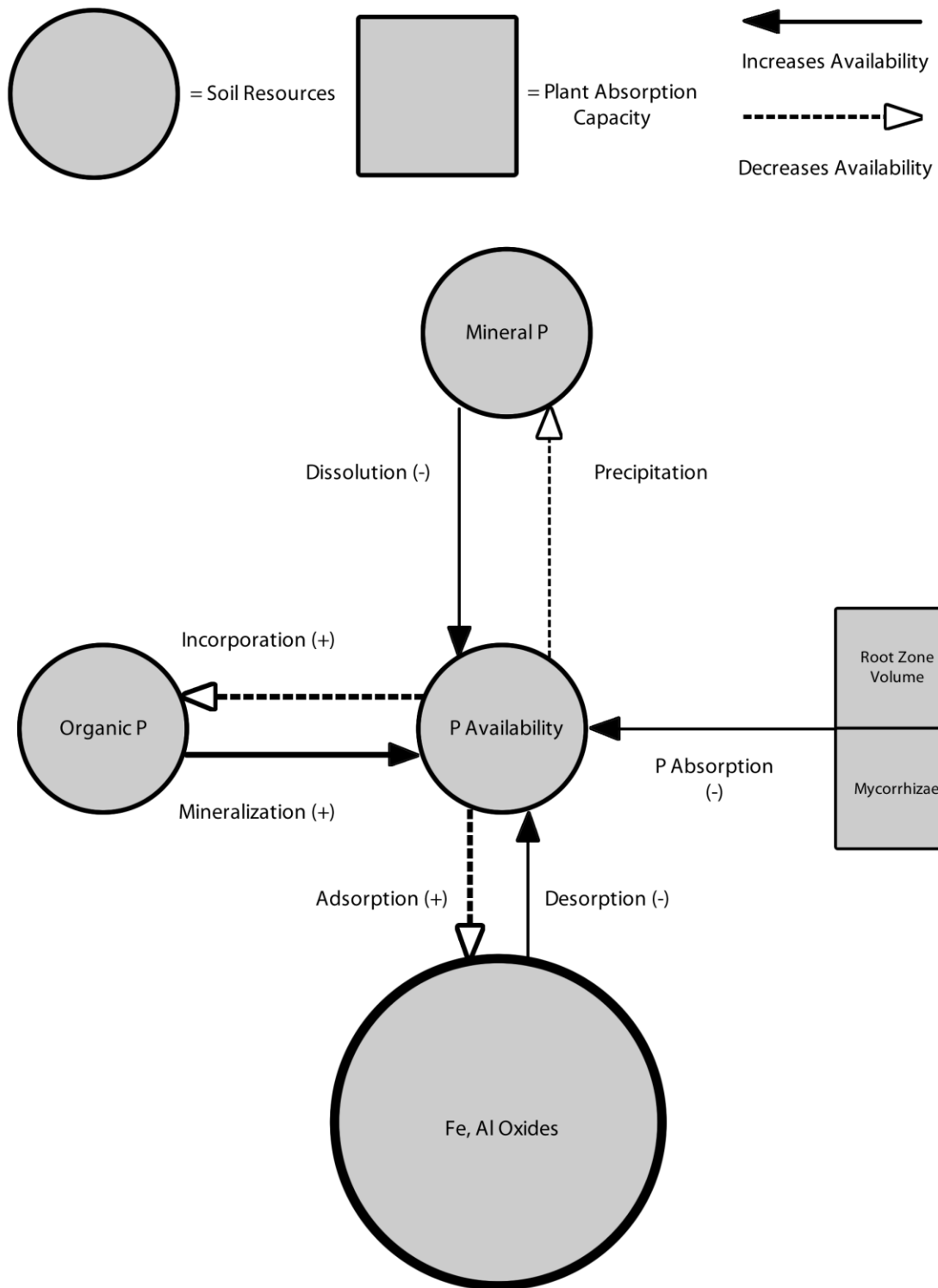


Figure 2: Phosphorus availability in weathered tropical soils is greatly reduced by soil acidity and high concentrations of Fe and Al oxides

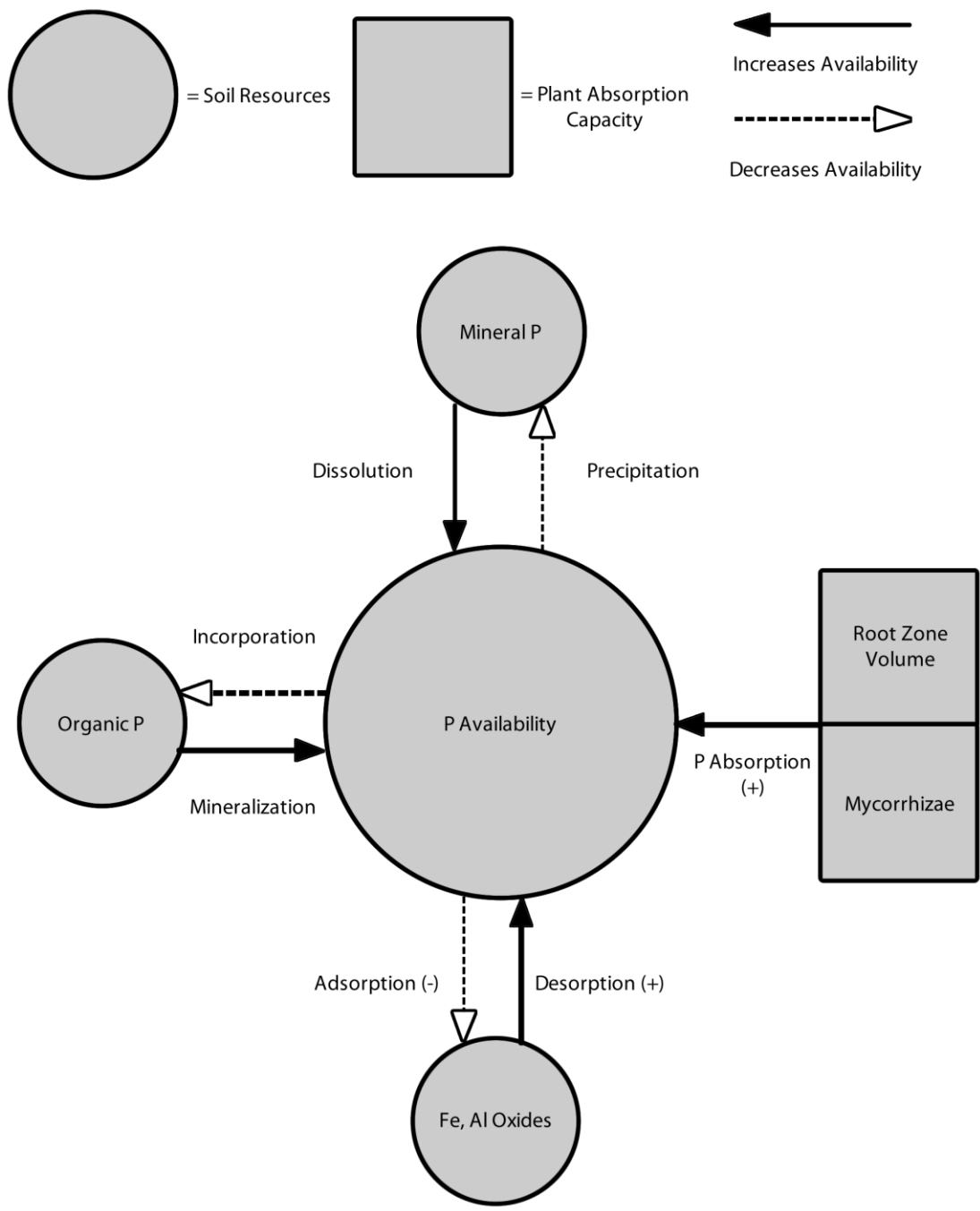


Figure 3: High concentrations of charcoal and bone apatite in Terra Preta soils make P bioavailable through a variety of possible mechanisms.