PHOSPHORUS DYNAMICS FOR EFFICIENT NUTRIENT MANAGEMENT IN ORGANIC AGRICULTURE

White Paper

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Introduction

There is a growing global trend towards organic agriculture as a result of the increasing demand for organically grown and/or certified products driven by food security concerns (FiBL, 2018; Scialabba and Hattam, 2002; Clark and Tilman, 2017). Organic agriculture is defined by FAO (1999) as "a holistic production management system which promotes and enhances agroecosystem health, including biodiversity, biological cycles and soil biological activity", which is similar to other definitions found in literature (e.g. USDA, IFOAM). However, observable imbalances in phosphorus management in organic farms call into question the conformity of the current organic agriculture to this commonly accepted definition.

Phosphorus (P) is an essential nutrient for all living organisms (Faucon et al.,2015). In plants, it takes part in the most crucial processes such as photosynthesis, respiration, energy storage and transfer and DNA formation (Smil, 2000). Accordingly, sufficient phosphorus is necessary for plants to maintain a high level of crop productivity. However, since nitrogen (N) is the primary limiting nutrient for plants and they generally respond immediately to N deficiencies, the majority of organic farms will only take crop N needs into consideration for their nutrient management without considering soil P dynamics (Heinrich et al., 2018; Cooper et al., 2018; Clark and Tilman, 2017). P deficiencies, unlike N, are not immediately visible or marked by specific signs (Qian and Schoenau, 2000; Smil, 2000). Studies show that the N based approach in organic agriculture commonly results in wide range of P inefficiencies: either excessive P or P deficiencies (Heinrich et al., 2018; Nelson and Janke, 2007; Mezenes et al., 2017; Cooper et al., 2017; Komiyama et al., 2014; Clark and Tilman, 2017).

It is not commonly recognized that P dynamics are significantly different than N dynamics in the environment. As opposed to N, P is highly reactive and immobile and cannot be found in gaseous forms (Faucon et al., 2015). These characteristics cause the phosphorus cycle to be naturally very slow, compared to C and N, making P one of the most limiting bioavailable nutrients in nature, especially in aquatic ecosystems (Smil, 2000; Chik, 2017). For aquatic ecosystems, even a small amount of P reaching to the water bodies can negatively affect these ecosystems substantially, primarily by promoting toxic algal blooms. The subsequent decomposition of these algae, and depletion of dissolved oxygen in the water causes common water quality problems in many parts of the world, in a process called eutrophication (Smil, 2000; Chik, 2017). P discharges from agricultural fields constitute the predominant non-point sources for many eutrophication issues and organic agriculture is found to have a relatively higher eutrophication potential than conventional agriculture (Chik, 2018; Clark and Tilman, 2017).

In organic agriculture, unlike N that has a wide range of sources, primary organically approved P sources are limited to manure and manure-based products and non-processed phosphate rocks (Nelson and Jange, 2007). Extensive mining and processing of phosphate rocks to produce chemical P fertilizers for conventional agriculture is causing rapid depletion of these non-renewable reserves (Schröder et al., 2011; Smil,2000; Faucon et al., 2016). In organic agriculture, since the solubility of non-processed rocks and thus the release of plant available P is very low (Cooper et al., 2017), manure and manure products are generally the main P sources. N and P content of manure and manure products are decoupled from plant needs; when manure or a manure product is added according to plant N requirements, P is generally excessively added to the soil, due to their relatively higher P content (Nelson and Janke, 2007; Heinrich et al., 2018). In general, organic farms that rely on manure and manure-based products generally result in excessive P addition (Cornish and Oberson, 2008; Clark and Tilman, 2017). On the other hand, organic farms that have no or limited access to manure and manure products are likely to have soil P deficiencies due to the limited P input and depletion of accessible soil P reserves over time. Depending on various factors, including soil characteristics and variabilities in P forms added with manure, P behaves differently in soil. Potentially, P can be fixed within the soil where it becomes strictly unavailable to plants and to other organisms; or it can be lost from the soil and potentially causes water quality issues (Schröder et al., 2011). Referring to the finite global P rock reserves and these potential consequences where reusing P is not possible, the current approach of organic agriculture for P management is not sustainable and is dependent on the existing P sources.

Considering the trend towards organic agriculture, there is an urgent need to decrease nutrient inefficiencies related to P. Even though manure has an unbalanced nutrient content and P is a nutrient with limited mobility in nature, the main cause of P inefficiencies in organic agriculture is the the strong focus on meeting plant N needs. With an understanding of P dynamics and factors affecting these dynamics, it is possible to decrease P inefficiencies through promoting soil P recycling and decrease excessive P addition to the soil (Schröder et al., 2011; Cornish and Oberson, 2008; Clark and Tilman, 2017).

Accordingly; the objective of this paper is to increase the understanding of P dynamics to enable the development of site specific management practices for increasing the P efficiency in organic agriculture.

In this paper, firstly, the essential concepts related to P dynamics will be reviewed, including P forms and behaviors within the soil and within the manure and manure-based products. Secondly, management implications of the concepts reviewed will be provided, for increasing the efficiency of nutrient management, together with the related management recommendations. And lastly, a case study will be included, where an organic farm was visited to observe their nutrient management methods and the feasibilities of the management implications.

Soil Phosphorus Dynamics

P can exist in different forms and phases in soil. Plant available forms of P are mainly orthophosphates. These inorganic orthophosphates are negatively charged ions (i.e. $H2PO4^{-}$ and $HPO4^{2-}$) that are found in the soil solution (soil-water), in the liquid phase (Sims et al., 2005). Once in soil solution, orthophosphates can also be taken up by soil organisms such as bacteria and fungi. Due to the higher mobility of nutrients when they are in liquid form, they are relatively more prone to be lost from the soil or any other mediums such as manure or composts (Sims et al., 2005; Sharpley, 1995). However, due to the high reactiveness of orthophosphates -- that is, their tendency to form strong chemically bonded compounds with various surrounding elements, particles and/or other compounds -- they have limited mobility in the environment. Once orthophosphates form these compounds and transform to their solid phase, they are not readily plant available. The limited mobility of P is the most prominent characteristic of P dynamics, that differentiates P dynamics from N. The degree of solubility, thus availability of these compounds, varies according to various factors such as the soil characteristics, chemical composition of the organic amendments and environmental conditions. (Gagnon et al., 2012; Sims et al., 2005).

Figure 1 shows the forms of orthophosphates that can be found within the soil matrix.

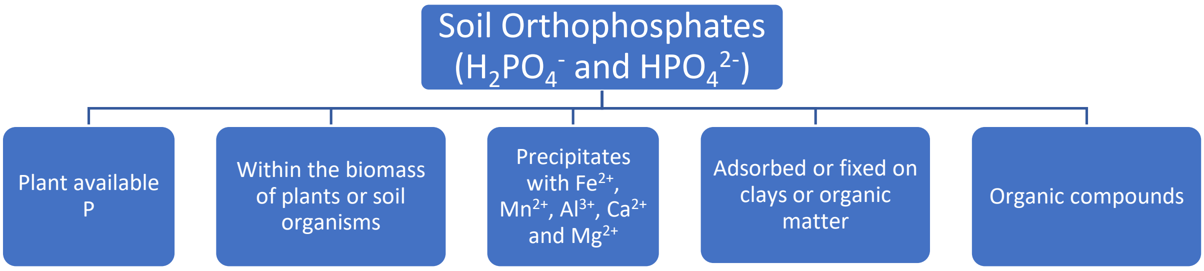

Figure 1

Unless orthophosphates are taken up by plants and/or soil organisms, they can be adsorbed by particles such as certain clays and organic matter that have positive surface charges. They can also form minerals by precipitating with certain metal ions. The precipitates are highly insoluble and are not available to plants. These metal ions can also form bridges between organic compounds and P ions, causing insoluble complexation (i.e. organically complexed metals). Organic forms of P originate from plants and other organisms that are metabolizing P for their metabolic activities, that would eventually be stabilized in soil organic matter through decomposition processes (e.g. within soil humus) (Leytem et al, 2005; Gerke, 2015; Menezes et al., 2017; Broadbent, 1986).

Soil phosphorus equilibrium

Each soil has a phosphorus equilibrium between the liquid and solid phases of P. The complex chemistry of the soil system and its various soil processes are responsible for maintaining this equilibrium. For example, if a certain amount of plant available P is added to the soil, it reverts into a plant unavailable forms of phosphorus until the P equilibrium is reached. Similarly, when plants uptake P from the soil solution, some P is released into the soil solution from the solid fraction. The strength of the chemical bonds and soil conditions, such as pH and moisture content, effect the rates of reactions. (McDowell and Sharpley, 2002; Menzies, 2009; Gagnon et al., 2012; Sims et al., 2005)

Figure 2 illustrates the phosphorus equilibrium, main forms of P within the soil and related soil processes.

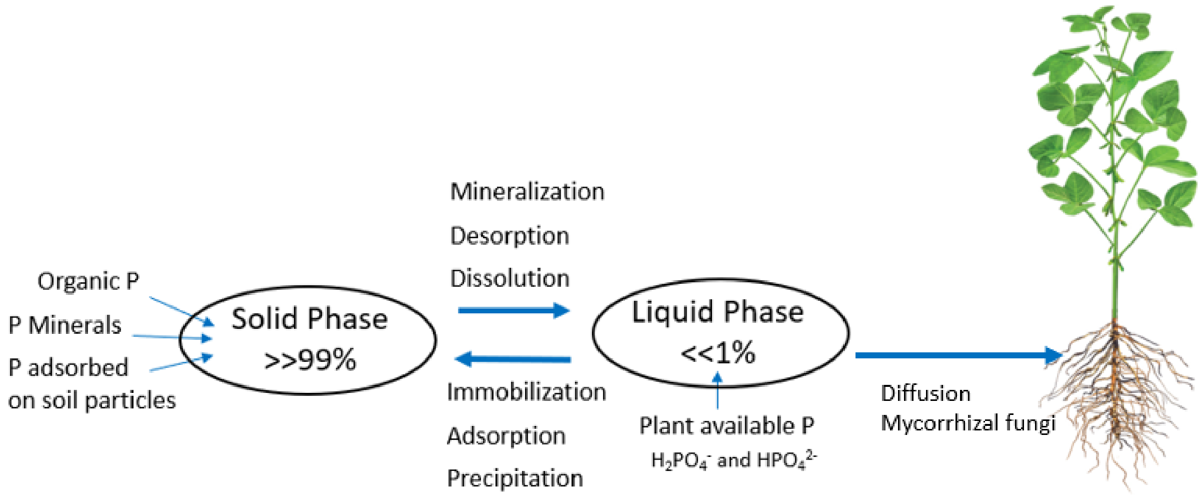

Figure 2

As seen in Figure 2, the equilibrium concentration of plant unavailable forms of P, that is, solid phase of P is very high (>>99%) (Menezes et al., 2017; Condron et al., 2005). Forms of P in solid phase can only be plant available once they are released into the soil solution as orthophosphates whose equilibrium concentration generally forms only a small portion of soil P (<<1%) (Brady and Weil, 2002; Condron et al., 2005).

Once orthophosphates are adsorbed on clays or on organic matter, they can either be held weakly or form insoluble compounds and get fixed (i.e. 'absorbed'), depending mainly on soil pH, that will be discussed below. When they are weakly adsorbed, they form labile compounds, which is a suitable form for supplying orthophosphates ($H2PO4^-$ and $HPO4^{2-}$) to the soil solution. However, in general, soil processes that release plant available forms from inorganic solid P compounds into the soil solution are very slow compared to the rate of adsorption and/or precipitation, since the solubilities

Each soil has its P fixation capacity depending on certain characteristics. The P equilibrium can only be maintained if soil is not P saturated. Adding excessive P to soil that causes P accumulation, increases soil P saturation percentage, which is likely to result in P saturated soil. Once a soil is saturated, any additional soluble phosphorus added to the soil, cannot be 'fixed' or held to the soil particles. Thus, additional P will most likely to stay in the soil solution and be highly prone to leaching (McDowell and Sharpley, 2002).

of most of these compounds tend to be low due to the high reactiveness of P (Cooper et al. 2018; Menezes et al. 2017). Especially for P precipitation of various P minerals, the solubilities are generally too low that they are considered non-reusable (Cooper et al. 2018; Menezes et al. 2017). Accordingly, P transitions into less soluble/insoluble forms are generally called 'P fixation' and soil P build-up (P accumulation) is a common issue especially when excessive amount of P than plants' requirements are added (Nelson and Janke, 2007; Heinrich et al., 2018). Unlike certain inorganic solid P compounds, organic forms of P don't get fixed permanently. Mineralization and immobilization are two processes that are mediated by soil organisms that play a key role for P dynamics through transforming organic P to inorganic P and vice-versa (Alori et al., 2017; Sharpley, 1995).

Soil characteristics affecting P fixation

Soil characteristics such as clay content, clay types, pH, organic matter, soil biology are generally the key regulators of the rate and the extent of soil P fixation (Mezenes et al. 2017; McDowell and Sharpley, 2002). That is, they control the solubility of P compounds in solid phase as well as the kinetics of soil P dynamics (i.e. soil P processes in Figure 1). These characteristics determine the soil's P fixation capacity and the behavior of P within the soil matrix including the rate and extent of plant availability of P, soil P loss and the fate of P added to the soil.

High soil P fixation capacity can lead to plant-P deficiencies, since any additional P would likely get fixed and become unavailable to plants. However, high P fixation capacity can be beneficial in reducing environmental impacts of excessive P addition to the soil, acting as a temporary buffer and holding excessive P that might otherwise cause water quality issues. Low P fixation capacity would become rapidly saturated by excessive P addition and P leaching is more likely to occur, if excessive P addition persists (Zhang et al., 2015; Ehgball, 2003).

Clay fraction of the soil

Clays (particles smaller than 0.002mm) are the most active fraction of soils that serve for holding/exchanging/releasing nutrients and water due to their relatively large and reactive specific surface areas (i.e. adsorption sites) (Gerard, 2016). These adsorption sites are important in terms of the initial rapid removal of orthophosphates from the soil solution and for the rapid maintenance of the P equilibrium. Sandy soils with low clay fraction have relatively low adsorption sites for holding orthophosphates thus, have relatively small P fixation capacity (Zhang et al., 2015; Ehgball, 2003).

Clay fraction of soils can have many different types of clays, including phyllosilicates, crystalline and amorphous hydrous oxides. Clays that have the highest anion adsorption/exchange sites for holding/fixing P, are metal oxides; mainly Al-, Fe-, Mg- or Mn-oxides, (e.g. goethite, gibbsite) followed by certain clay minerals, especially kaolinite. These types of clays, especially metal oxides, are mainly found in old and highly weathered soils such as Oxisols and Ultisols, which leads to P deficiencies to being a common issue in older landscapes (Faucon et al., 2015; Gerard, 2016; Sharpley, 1995).

Soil pH

Soil pH is the most important regulator of the solubility of inorganic P compounds and P availability to plants. Firstly, because surface charges (e.g. anion exchange sites) of metal oxides, certain clay minerals and organic matter are mainly pH dependent. And secondly, pH is an indicator of the concentration of certain metal ions that precipitate with P to form insoluble compounds (e.g. Fe^{2+}, Mn^{2+}, Al^{3+}, Ca^{2+}).

As seen in Figure 3, P availability is mainly controlled by metal oxides in acidic conditions, as once P is adsorbed on these clay particles, it gets fixed and becomes plant unavailable (Gerard, 2016). The concentrations of reactive Fe^{2+}, Mn^{2+}, Al^{3+} also increase in acidic soils, which would precipitate with orthophosphates (Gagnon et al., 2012; Leytem et al., 2005). In alkaline conditions, P availability is controlled mainly by Ca^{2+} concentrations, which precipitates with orthophosphates to form insoluble apatite (Gagnon et al., 2012; Leytem et al., 2005).

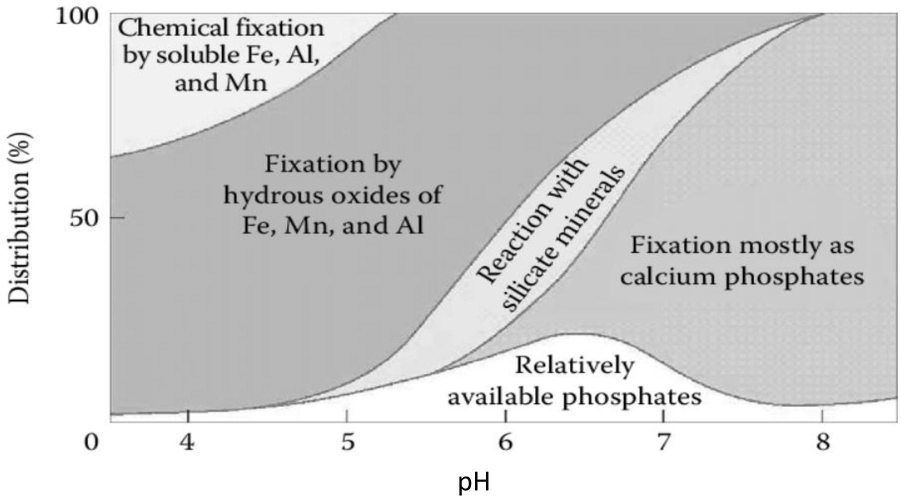

Figure 3 (Schlesinger, 2012)

Soil organic matter content and soil organisms

P in soil organic matter, i.e. organic forms of P, generally constitutes 30 to 85% of total phosphorus in soils, which is largely composed by soil phytate, phosphomonoesters, phytin, nucleic acids and phospholipids that are relatively more complex compounds than organic N compounds that are primarily amides, amino acids, amino sugars (Broadbent, 1986; Alori et al., 2017). Even though P release from organic P compounds is not as easy as N release, studies show that this microbial transformation of organic forms of P significantly contributes to the release of plant available P into soil solution (Condron et al., 2005). The rate and the extent of the release of P into the soil solution are related to the complexity of organic compounds, soil organisms and other soil conditions such as temperature and moisture (Condron et al., 2005).

For their own needs, soil organisms require certain amount of C, N and P with maintained C:N:P ratios (Brady and Weil, 2008; Dao and Schwartz, 2010). Soils should provide adequate amount of C, N and P for organisms to release the excess amount of nutrients to the soil solution for plant uptake. Otherwise, if N and/or P is limited, organisms tend to immobilize plant available N and/or P forms in their biomass, limiting plants' access to P (Menzies, 2009). For obtaining P, they can use both P from the organic matter through decomposition and use P directly from the soil solution (e.g. orthophosphates), similar to plants.

Storage of orthophosphates within the microbial biomass as well as within the soil organic matter are highly beneficial since P is protected from permanent fixation by various soil components as discussed above.

Plant P uptake

Due to the high limited mobility of P and low percentage of plant available forms in the soil solution (<<1%), plants cannot take P through mass actions unlike N uptake, which forms the majority of plant N uptake. Diffusion is the main process by which plant P uptake which usually results in a P depletion zone just around the roots. For coping with P deficiencies, plants have developed various strategies for adapting to P deficiencies, such as excreting specific enzymes e.g. phosphatase for solubilizing P compounds, developing specific root structures such as root hairs and/or clustered roots increasing root interception), and forming symbiotic mycorrhizal fungi relationships that increases plant access to nutrient (Nelson and Mikkelsen, 2008; Zhang et al., 2014; Menzies, 2009; Bradbent, 1986; Mikkelsen, 2013).

Additionally, soil organisms are also found in relatively high concentrations just around the roots for easier access to carbon for their own needs. This can be both beneficial, since organisms can release plant available forms of P to the depletion zones, and maleficent since they are better nutrient scavengers than plants and would immobilize nutrients in case of a nutrient deficiency (Dao and Schwartz, 2010).

Phosphorus in manure and manure products

Manure is a commonly used nutrient source in organic agriculture, either as raw manure or processed manure that results in various manure products. Raw manure has a relatively high concentrations of soluble plant available forms of P and N. Using raw manure can be difficult to handle; transportation is difficult, it can introduce weeds and pathogens, and it may contribute to salinity issues. In addition, N content of raw manure can volatize relatively quickly, before it can be used by plants and/or soil organisms. There are various manure handling, storage and treatment methods, such as composting, that aim to reduce these adverse effects (Rosen and Bierman, 2005; Eghball, 2002; Schröder et al., 2011).

Unlike chemical fertilizers, manure and manure products are complex and have high variabilities, which complicates the decision-making processes related to efficient nutrient management (Dao and Schwartz, 2010). Their chemical composition contains various forms of P that could interact differently with soil constituents once they are added to the soil. Total P concentration, as well as different P forms and their availability, are highly variable according to factors such as animal type, feed (e.g. P concentration in animal feed), manure storage, treatment and composting methods and materials (Nelson and Jange, 2007; Sharpley and Moyer, 2000; Pagliari and Laboski, 2013).

For grouping P compounds with similar degrees and conditions of solubilities, i.e. plant availabilities, there exist various fractions of P within manure and manure products as seen in figure 4.

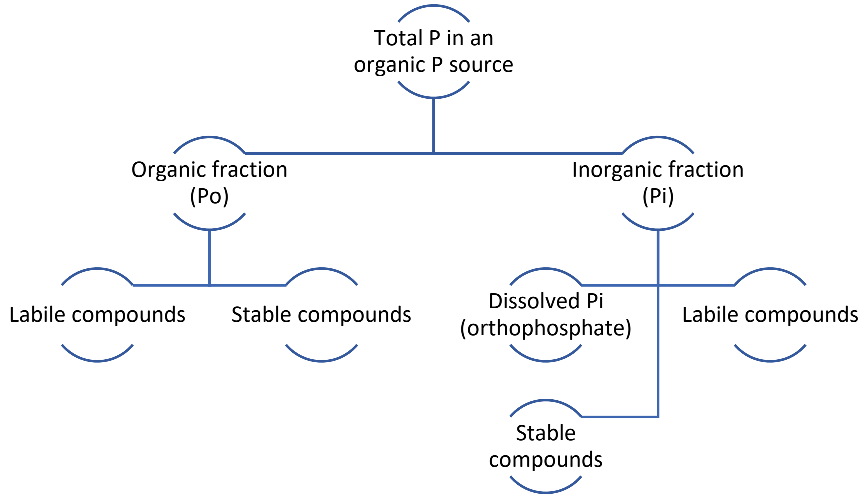

Figure 4

The two major fractions are organic and inorganic forms of P which can be further fractionated into labile (soluble) and stable (insoluble) compounds. Solubilities (or bioavailability) of these P compounds and their concentrations are the key for accurate prediction of the fate and potential P dynamics once added to the soil (Komiyama et al., 2014; Li et al., 2014).

Inorganic fraction

Studies show that the majority of the total existing P, which may be up to 90% in manure and manure products, is inorganic. The inorganic fraction of manure further increases during the composting process due to microbial mineralization of organic P in the manure. Even though the distribution of this inorganic fraction into labile and stable fractions vary among different manure and manure products, the majority of inorganic P is in labile and dissolved fractions (Nelson and Mikkelson, 2008; Sharpley and Moyer, 2000; Gagnon et al. 2012; Li et al., 2014; Eghball, 2003).

Soluble and dissolved inorganic forms are reactive and they interact with soil constituents relatively fast (NRCS, 2007). Thus, the fate and behavior of P in this fraction of the organic amendments are mainly regulated by the characteristics of the soil, as explained in the previous section (*'Soil Phosphorus Dynamics'*). That is, P can be taken up by plants and by soil organisms, adsorbed on clay sized soil particles or precipitate with certain metal ions. These forms, within a manure or compost, might also be associated with P loss in the form or leachate and/or runoff, especially if the soil has low P fixation capacity, P saturated and/or if manure is surface applied (Sharpley and Moyer, 2000).

P in soluble and dissolved fractions are also prone to be lost during manure handling, storage and/or treatment processes, before its addition to the soil. For example, manure liquid-solid separation systems that are commonly used for easier transportation purposes might reduce P content in manure-solid part. Particularly, if manure has originally a high concentration of dissolved inorganic fraction, a considerable amount of P would stay in manure-liquid part after the separation process. Thus, if manure is not stored properly, dissolved P can leach out from the manure pile (Pagliari and Laboski, 2013).

The stable inorganic fraction (unable to plants) is generally related to the concentration of the elements such as Ca, Fe, Mg of manure that could precipitate with phosphate ions and form insoluble compounds. For example, Li et al. (2014) found that relatively high stable inorganic fraction of swine manure is likely to be related to the diet of the swine. Therefore, if the manure contains Ca^{2+} as the dominating cation it would form stable precipitates with P. This fraction of P would stay insoluble and thus, not plant available. Similarly, this fraction has a low environmental impact, unless it is lost to the water bodies through erosion. (Li et al., 2014; Aboiye et al., 2000).

Organic fraction

Animal manure is the major source of organic P (Dao and Schwarts, 2010). Organic forms of P, which forms relatively smaller portion of P fractions of organic amendments (~<50%), are mainly related to the digestive system of the animals and their diet. The variabilities within organic forms of P affect the dynamics of the organic P compounds within the soil, as well as the ease of decomposition and mineralization, that is, the rate of release of orthophosphates to soil. DNA or nucleic acid, phospholipids and simple phosphomonoesters are common labile compounds whereas phytates and phytic acids are the major stabile organic compounds found in manure (Turner and Leytem, 2004; Aboiye et al.,2000; Pagliari and Laboski, 2012).

As opposed to the dissolved inorganic P fraction that is highly reactive within the soil matrix, most of the labile organic compounds can only be weakly held by soil and thus is highly prone to leaching (Turner and Leytem, 2004; Li et al., 2014). Accordingly, even though the organic fraction of manure and manure products are relatively low; their environmental significance can be relatively high. Studies have reported that these labile compounds dominate the forms of phosphorus in leachate and/or runoff from the soil, which potentially reach water bodies and cause water quality issues (Turner and Leytem, 2004). On the other hand, phytates and phytic acids that are relatively stable organic compounds, are highly reactive in soil, similar to dissolved inorganic P fraction (Leytem et al., 2006; Gerke, 2015; Li et al., 2014). They can be strongly held by clays and form complexes with metals including Fe and Al. Due to their high reactiveness they can significantly contribute to the building of soil organic matter and they have relatively low negative environmental significance (Gerke, 2015).

Phytate is a phosphorus storage form of P found in plant seeds, in cereals and grains (Gerke, 2015). Due to its relatively complex structure, it cannot be fully digested by monogastric animals, such as swine and poultry, unlike ruminants, such as dairy and beef cattle, that have specific enzymes in their digestive system (Gerke, 2015; Abioye et al.,2000). Accordingly, organic P fraction of swine and poultry manure is generally dominated by phytate; unless they are fed by cereals and grains (e.g. grass-fed animals) (Turner and Leytem, 2004; Pagliari and Laboski, 2012). To increase mineral and nutrient absorption of animals, adding the enzyme phytase to the diet of these animals, aids in degrading phytate and releasing P is a common procedure in livestock production. Studies show that phytase addition decreases the amount of phytate in the manure. However, whether the phytase enzyme decreases total P (by increasing P in urea) or increases soluble inorganic fraction of P is inconsistent among studies and among animals (Leytem et al., 2006; Abioye et al., 2000).

Due to the limitedness of the fractionation studies and the high variability of the characteristics of manure and manure products, data from existing fractionation studies would not be valid or feasible for all similar types of organic P sources. However, total N, C and P concentrations can be tested, where C:P and N:P ratios can be used as indicators of nutrient dynamics and availabilities (Dao & Schwartz, 2010).

Importance of C:P and N:P ratios of manures and manure products

Microbial activities play an important role in regulation of the C, N and P dynamics. The rate and extent of the transformation of nutrients through microbial activities is an integral part of the organic matter management (Leytem et al., 2005).

Even though there is no unique critical C:N:P ratio for soil organisms (Gusewell and Freeman, 2005), Tipping et al. (2016) showed that this ratio is constrained to some extent. Accordingly, C:N:P ratio of the organic amendments are good indicators of the amount and rate of release of plant available P. The ratios are based on total C, N and P concentrations, which does not provide information about different fractions that were discussed above.

C:P Ratio

C:P ratio of the organic amendments is one of the most important and useful indicators of the fate of P within the organic amendment (Dao and Schwartz, 2010; Gagnon et al., 2012; Sharpley and Moyer, 2000). Research has shown that the C:P ratio of the organic amendment is inversely related to the increase in soils' plant available P, similar to C:N ratio and consequent increase in soils' plant available N (Nelson and Janke, 2007; Leytem et al., 2005; Pagliari and Laboski, 2013). When the C:P of the organic source is high (>300:1), net P immobilization tends to occur, which might further decrease the concentration of plant available P, after the addition of the organic amendment (Sharpley and Moyer, 2000). In general, C:P of all manure and composts are lower than 200:1 (Sharpley and Moyer, 2000).

For distinguishing manures with different C:P ratios that are under 200:1, the most important consideration is that the addition of a manure with relatively narrow C:P ratio would stimulate higher P mineralization and thus release of plant available P into the soil solution (Sharpley and Moyer, 2000; Leytem et al., 2005), Comparatively, a wider C:P would lead to a relatively higher microbial P stabilization in their biomass, since they require P for decomposing organic matter with the higher C:P ratio (Zhang et al., 2014; Dao and Schwartz, 2010). During the decomposition process, after adding the organic amendment, C:P will decrease by releasing organic carbon into the atmosphere and stabilizing P within the microbial biomass, which results in the total P to remain constant.

From a management perspective, a narrower manure C:P ratio can be interpreted as beneficial, providing a relatively higher increase in plant available P in a relatively shorter amount of time (Dao and Schwartz, 2010). Whereas, a wider manure C:P ratio would be beneficial for storing nutrients in microbial biomass, decreasing nutrient loss and promoting slow nutrient release (Gagnon et al., 2012; Zhang et al., 2014). Microbial stabilization of P might also be beneficial for preventing P fixing by soil clays, especially for soils with high P fixing capacity (Zhang et al., 2014). Microbial stabilization occurs irrespective of soil P fixing characteristics (Leytem et al., 2006).

N:P Ratio

For the decomposition process, microorganisms require both N and P. For organic amendments with similar C:P ratios, decomposition rate is expected to be lower with lower N content, that is, a lower N:P ratio. Also, considering the high mobility of N that can be lost from the soil and organic amendments in many ways such as volatilization, denitrification and leaching, N:P ratio is expected to decrease over time due to the N loss, before and/or after a manure is applied to the soil, depending on the management practices. Consequently, decomposition rates would decrease as concentration of N decreases (Dao and Schwartz, 2010; Leytem et al.,2005).

From a management perspective, choosing a manure, or manure products, that has a relatively higher N:P ratio, would decrease the rate of P accumulation in soil. For example, in the study conducted by Leytem et al. (2005), P accumulation changed up to 2-3 folds through the manipulation of swine feed by introducing low phytic acid barley to their diet (i.e. lower P concentrations in their feed).

These ratios are rough estimations. If it is possible to make specific comment on the P fractions of an organic source, it would be more valuable information than the ratios. For example, even though composts tend to have lower C:P ratios, composting process stabilizes nutrients (Gagnon et al., 2012; Eghball, 2002) and P release would not be as fast as a manure with a similar C:P ratio.

Management Implications and Recommendations

Once full understanding of P forms in soils and organic amendments, P dynamics and factors affecting the dynamics has been accomplished, it is important to develop strategies for efficient nutrient management in organic agriculture. In previous sections, P forms and dynamics in soil and in manure and manure products were discussed relative to how they are affected by a range of variables and factors. Accordingly, for management decisions and developing strategies for increasing P efficiency, it is crucial to have site specific considerations that include relevant soil characteristics and characteristics of the organic amendments. Considering these site-specific characteristics in nutrient management enable the prediction of potential interactions of soil and organic amendments, That is, prediction of the behavior and fate of various P forms added to soil. This is useful for decision making for efficient management practices as well as for type, amount, rate and method of organic amendment application.

For example, the addition of a manure with relatively high concentration of dissolved inorganic P (plant available forms) to a soil with relatively high P fixation capacity, would quickly transform P into plant unavailable forms and become fixed in the soil, if not taken up by plants or soil organisms. In contrast, if an organic farm has a sandy soil with relatively low amount of clay, that is, soil with very low P fixation capacity, addition of the same organic source with relatively higher dissolved P would most likely result in P loss. Accordingly, the focus of the management for the soil with the high P fixing capacity should be on minimizing P fixation by practices such as manipulating pH and/or decreasing the concentration of dissolved inorganic P in manure through composting so that P is relatively more stabilized (Gagnon et al., 2012). On the other hand, for soils with low P fixing capacity, focus should be on minimizing the amount of input and/or maximizing nutrient retention through increasing the soil organic matter content.

Testing soils and organic amendments mainly in terms of their nutrient content is highly beneficial for site-specific management decisions for increasing nutrient efficiencies.

In order to achieve efficient nutrient management, the main goal is to maximize the efficiency of using nutrient sources and reserves and to minimize nutrient inputs and outputs to/from the farm. Accordingly, based on this analysis, the main management recommendations are to increase P recycling in soils and decrease excessive P input, without negatively affecting crop yield. And as stated, any management practice focusing on P recycling and minimizing excessive P input, should consider site-specific conditions and characteristics of P source used.

Increasing phosphorus recycling

P fixation to various soil particles is an important problematic for both farms with excessive P and P deficiencies. Once P is fixed, it is not possible to reuse effectively that P and these inaccessible P compounds tend to accumulate in soils. Fixed P compounds, that are mainly composed of P minerals and complexed P by metal oxides (i.e. complexation with mainly Fe or Al), are inorganic compounds. On the other hand, organic P compounds that are found either in living biomass or in soil organic matter can be reused by plants and other soil organisms through the decomposition process. During decomposition, these organic forms are transformed into plant available orthophosphates by microorganisms. Also, when a manure or manure product is added to a soil, the majority of the forms of P tend to be in inorganic soluble forms that are directly plant and organism available. Promoting the use of soil P by soil organisms and plans and promoting its storage within the soil organic matter is highly beneficial, since P recycling would protect P from getting fixed within the soil.

Accordingly, management practices that aim to increase P recycling should promote plant and other organisms' access to soil P so that P would be added to living biomass and potentially increases soil organic matter content. Increasing soil organic matter content serves as an accessible P reserve and for slow release of available P.

Accessing soil P

Plants uptake P largely by diffusion, which causes P depletion just around the root surfaces. It is possible to increase P use efficiency without adding additional P sources by accessing and/or remobilizing existing soil P (Nelson and Mikkelsen, 2008). A useful strategy that enhances soil P utilization is the promotion of plant-mycorrhizal fungi symbiosis and increasing root density through incorporating a diversity of plants as cover cropping and/or a part of crop rotation to the production system (Nelson and Mikkelsen, 2008).

The majority of higher plants can form a symbiotic relationship with mycorrhizal fungi. This symbiont increases access to the soil matrix through mycorrhizal hyphae up to several centimeters out from the roots into the soil (Gerke, 2015; Mikkelsen, 2013). Management practices that promote this symbiotic relationship include reducing soil disturbance (e.g. reduced tillage) and incorporation as certain cover crops and/or perennials into the management regime that enhances mycorrhizal fungi (Nelson and Janke, 2007). Incorporating certain cover crops and/or plants in crop rotation can be highly beneficial for not only for this symbiosis but also for enhanced P recycling in soil, that might otherwise be fixed by the soil and/or be lost (Löbermann et al., 2016). As cover crops with varying root systems grow, P and other nutrients accumulate in their biomass and when the crops are incorporated into the soil, P is released back into the soil through decomposition. For cover cropping and crop rotation, using plants with high nutrient acquisition should be preferred for maximizing nutrient recycling, without limiting the nutrient acquisition of cash crops (Löbermann et al., 2016). Additionally, some cover crops can excrete root exudates (e.g. enzymes) that can increase P availability, such as some Brassicaceae and some Fabaceae (Wendling et al., 2016; Kamh et al., 1999).

Soil organic matter content

Soil organic matter is an important source (i.e. reservoir) for P for slower, long term acquisition of nutrients, depending on the complexity of the compounds, unlike chemical fertilizers that are generally 100% plant available in a relatively short period of time. Thus, in organic agriculture, it is crucial to maintain or increase soil organic matter content for reserving nutrients as well as for enhancing a healthy soil biology. Not all organic farms are building soil organic matter and/or have high organic matter content. Certain practices such as intensive tillage, heavy manure additions and inefficient crop residue management may lead to an increase in carbon emission (contributing to CO_2 in the atmosphere) which would eventually reduce soil organic matter (Nelson and Mikkelsen, 2008).

Management practices such as such as conservation tillage and crop residue retention contribute to an increase in soil organic matter. If possible, preferring organic matter sources with wider C:P ratios will be beneficial for increasing microbial stabilization of P, which plays an important role especially in short term dynamics of organic P transformations (Sharpley, 1995). Composting the manure before addition for stabilizing the dissolved P forms or separating liquid-solid fractions of manure is beneficial for decreasing P fixation (P accumulation) (Rosen and Bierman, 2005).

Storing P in the form of soil organic matter is also beneficial in that less P input will be needed for the subsequent growing seasons (Schröder et al., 2011). The release of plant available nutrients is negatively correlated with the stability of P compounds in an organic source. The more stable an organic source, the more nutrients are reserved for releasing during the subsequent growing seasons. Accordingly, the requirement for nutrient addition is expected to decrease over time in organic agriculture, which is essential for the sustainability of the farms.

Decreasing excessive phosphorus addition

Other than increasing soil organic matter content, which would decrease the need for the addition of organic matter in subsequent growing seasons, there are other strategies for decreasing the excessive P addition to the soil. Studies show that excessive P addition to the soil is positively correlated with the increase in soil's soluble inorganic P (Leytem et al., 2005). Even though the management practices that are increasing P recycling promote the use of this increased fraction of P by soil organisms and plants, there is a limit for P uptake of these organisms. If excessive P addition persists, the negative environmental consequences such as soil P saturation and P loss from the farm are inevitable.

N-based addition of organic amendments, especially manure and manure products that have lower N:P ratio than the plant requirements, causes excessive P addition to soil (Nelson and Janke, 2007; Heinrich et al., 2018). Moreover, N content in these sources are calculated as 'Potentially Available N

(PAN)’, which is lower than original N content, due to the high N mobility and potentially N loss before and after the application, unlike the P content (Nelson and Janke, 2007). For example, once manure is added to soil. If not incorporated immediately into the soil, N (i.e. ammonium) can volatilize within hours in the form of ammonia gas; if applied during rainy season, soluble form of N (i.e. nitrate) can readily leach into receiving water bodies and if anaerobic conditions occur caused by compaction or flooding, N (i.e. nitrate) can be denitrified and released into the atmosphere in the form of NO, N2O and/or N2. On the other hand, for all these cases, P is likely to stay within the soil matrix. Thus, relatively high amounts of manure added in order to avoid any N deficiencies, increases P concentration in the soil.

There exist various ways of preserving N in these sources during storage (e.g. covered storage), by various treatments (e.g. composting) and/or through appropriate application methods (e.g. incorporation). Accordingly, management practices that aim to decrease N losses would enable growers to decrease the amount of organic amendments they add to the soil.

Moving away from N-based addition of manure and manure products is another strategy for decreasing excessive P inputs. Even though it is not a common practice to add organic amendments according to plants’ P requirements, (i.e. P-based nutrient management), studies show that the P-based management approach can effectively control P buildup in agricultural soils while maintaining crop yields and decreasing P in the runoff (Komiyama et al., 2014; Maguire, 2009; Eghball, 2003). This approach is likely to require additional N sources for maintaining crop yields (Olson and Paterson, 2005). However, manipulation of organic N sources is relatively easier than organic P sources. Using a variety of organic amendments in addition to manure and manure products such as incorporating N fixers to the system as cover crops, adding urea as an immediate N source and blood meal as long-term N source. Even though this approach is more demanding, labor intensive and potentially costlier, especially for the farms that have reached soil P saturation levels it is important to decrease P input substantially and enhance P use efficiency.

Case Study

For the case study, an organic farm in the Westham Island in the Delta Municipality, BC, was visited. The objective was to understand the feasibility of the management implications discussed in the previous section by gaining information on how a certified organic farm conducts its nutrient management, what types of organic amendments they use and how the management affects the P situation in the soils.

The farm visited was a 50-acre farm growing more than 50 different crops. The soils in that region are generally poorly drained, with high water and nutrient holding capacity, moderately fine-texture and a dense impervious sub-layer. For reversing the disadvantages of the soils, there was an artificial drainage system installed on the farm. Additionally, for overcoming adverse soil structure due to high clay content, the farmers' aim was to increase soil organic matter. Using compost and incorporating cover crops were the two main practices conducted.

The farm was using chicken compost as their main organic nutrient source. Other than its advantages of increasing soil organic matter content, it was also the most convenient source available in the region, in terms of its economic value. Due to the high number of crops and the variabilities in their nutrient requirements, for applying the compost, they had 2 main application amounts of these manures: heavy or light. For example, brassicas would require heavy application, while legumes would require light application. Light application was 30 tons/acre, whereas heavy application was 60 tons /acre. They were also using nitrogen fixers as cover cropping, that serve for additional N source to the crops.

They regularly test their soils. They have reported that their cash crops have N deficiencies. They were using additional N sources such as blood meal and feather meal only in their greenhouse, since using these sources are not feasible to apply to larger areas and expensive for the field application. Following the test results, they are aware of P accumulation in their soils, increasing P content over time. However, they were not concerned about the excessive P content in their soils.

Considering the previous section where management implications of P dynamics are discussed, the existing management practices including cover cropping and increasing soil organic matter content are beneficial for recycling P in the soil. However, mainly due to the excessive P addition through the addition of compost with the focus on meeting plant N requirements, P is accumulating in the soil. Based on the recommendations given for decreasing the excessive P addition in the previous section, including lowering the N loss from the organic matter source and the transition into P-based application of organic amendments, none of the recommended practices seemed practical and/or beneficial for the farm. Accordingly, the feasibility of the management implications requires additional practical information and/or solutions mainly related to the organic amendments.

Conclusion and Future Enhancements

Current approach to the nutrient management in organic agriculture is not sustainable in terms of P inefficiencies and their potential consequences including the eutrophication. Based on the review of the essential concepts related to P dynamics and their management implications; it is possible to increase P efficiency through understanding P dynamics. The three key findings related to P dynamics for increasing P efficiency are as follows:

i. Understanding the soil characteristics affecting P behavior and availability within the soil, including the pH, clay amount and type, P saturation percentage through soil testing,
ii. Understanding the characteristics of an organic amendment including various P fractions and/or total C:N:P ratios for decision making process related to the organic amendments, and
iii. Developing site-specific practices for increasing soil P recycling and decreasing excessive P addition to the soil, by considering the characteristics of the soil and the organic amendments.

In the case study which was conducted for feasibility of the implications of these findings, it is observed that there is a gap between the findings and their practical feasibilities. Increasing P efficiency might require complex considerations and changes in the farm management system, that potentially will require additional costs, labor or risk potential yields; none of which are preferred consequences for farmers, considering that excessive P is not causing any issues for their crops.

In conclusion, even though it is scientifically possible to increase P efficiencies in various ways, there is a need for more practical information or alternatives for managing the complexities.

Accordingly, following areas should be encouraged and incorporated into agriculture:

- Connecting science-based findings from research and projects to the organic farms through practical information: This communication between science-based findings and organic farms would be especially beneficial if focused on managing the wide range of variabilities in organic nutrient management, such as P fractions in manure that differ according to a range of factors.
- Developing alternative methods for releasing or mobilizing inaccessible soil P or extracting P from manure or other organic sources: These methods would be beneficial for both decreasing P concentrations in soils and/or in organic sources and for providing alternative and recycled P sources for farms that have P deficiencies.

Acknowledgements

I would like to express my gratitude to my supervisor and my professor Dr. Les Lavkulich for his expert advices, valuable remarks and enthusiastic encouragement and support throughout the course of this white paper as well as throughout the MLWS program.

Furthermore, I would like to use this opportunity to thank to all my professors, especially to Dr. Sandra Brown and Dr. Hans Schreier, for equipping me with valuable knowledge and for their continuous support throughout the program.

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