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Review Article

Managing phosphorus in terrestrial ecosystem: a review

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ABSTRACT

Increasing human population placed stress on the environment, as well as shifting in land use pattern to increase food production, significantly influence the dynamics of soil organic matter and associated nutrients (phosphorus) in terrestrial ecosystems. This review is based on the published work carried out in recent years and critically examines how the P cycling occurs within different terrestrial ecosystems, possible mechanisms involved in its transformation from one form to another and gaps to be investigated. In terrestrial ecosystems P mainly occurs as phosphate ion; generally precipitated with Ca, Al and Fe under varying pH conditions and become relatively immobile in soils. In agricultural fields, change in inorganic (Pi) and organic (Po) phosphorus are attributed due to fertilization and tillage while in forest and grasslands it is the matter of litter addition and its decomposition by microbes. Afforestation of grassland enhances the mineralization of organic matter and P availability through higher microbial activity, production of low molecular weight organic acids and root associations of mycorrhizae. Phosphorus losses primarily occur due to export in the form of erosion and product removal from ecosystem. Heavy export of P from terrestrial ecosystem accelerated the problem of eutrophication. Future studies should be focused on efficient practices to increase the use of accumulated surface P, estimating P bioavailability in soil and improved methods of runoff control to control P export into aquatic ecosystems. Optimization of practices and exploring novel approaches for sustainable production will maintain the enduring supply of this globally limited nutrient and reduce environmental consequences.

Keywords: Ecosystems; P dynamics; Organic P; Inorganic P; Land use; Litter; Soil microbes.

1. INTRODUCTION

Terrestrial ecosystems, particularly forests, are the major body expected to store a large amount of the increased atmospheric carbon (C) [1]. However, the extent of storage depends on different soil conditions of forests such as soil fertility, moisture and temperature [2]. Carbon (C) sequestration potential of vegetation, to sequester this rising level of CO_2 is checked by the low nitrogen availability in soil [3-4]. Many of the workers ignored P but it is likely to be a major obstacle in enhancing C sequestration, because low P availability can limit nitrogen (N) fixation and plant development [5-6], so it can be considered as a constraint in the sustainable management of ecosystem productivity [7-8]. However, in forest ecosystems, fertilization is not a common practice, especially P fertilizers [9], so there is need to give more emphasis on appropriate management of P resources, as existing P reserves are limited and rapidly going to be used up. However, to cope up with the increased concentration of atmospheric CO_2, there is need to increase the forest productivity which results in depletion of P in surface soil and in response to P insufficiency, trees roots may mine soil deeper to acquire the same. Thus, understanding the P dynamics in soils is necessary to know the processes governing P availability. This manuscript synthesizes the available information regarding P content, factors affecting its dynamics and different fractions present in soils.

Phosphorus (P) is one of the most important macro-nutrient after nitrogen in terrestrial ecosystem productivity [10]. Phosphorus is an essential element and plays an important role in the functioning of all living bodies because, as it is the structural component of nucleic acids, co-enzymes, phosphoproteins, phospholipids and also determines many metabolic processes (provides energy as ADP and ATP). Low solubility of natural P-containing compounds and the slow natural cycle of P are the major constraints to check the availability of this essential nutrient and efficiency of the ecological unit [11-12].

2. FORMS OF PHOSPHORUS IN SOIL

Phosphorus in soils mainly comes from parental rock and fertilizers [10-13]. In soil, there are two major forms of P, inorganic and organic. Inorganic P forms are associated with hydrous sesquioxides and Al and Fe compounds in acidic soils whereas with Ca-compounds in alkaline soils. The inorganic phosphates in soils have been classified into easily soluble phosphate (ES-P), aluminium phosphates (Al-P), iron phosphates (Fe-P), reductant soluble phosphates (RS-P) and calcium phosphates (Ca-P) [14]. According to Brady and Weil [15], organic matter, calcium carbonate and sesquioxides are the key factors, controlling the distribution of different forms of P. Organic P (P_o) can account for 5-95% of the total P (TP) in the soil. P_o is derived mainly from manures, plant material, and products of microbial decomposition. P_o is highest under wetland soils, as characterized by high organic matter. Although a large proportion of TP occur in organic form, of which, only a small portion of this pool may be bioavailable.

There are many chemical fractionation schemes developed to assess the specific P form [16-17]. After that, Bowmen and Cole [18] developed method to fractionate various P_o forms. But there are some difficulties in identifying specific inorganic (Pi) and organic (Po) forms which include: modification of unidentified compounds from their original forms and also effects of the reagents on pure compounds and mineral associations [19-21]. To overcome these problems, Hedley et al. [22] developed a sequential fractionation scheme to differentiate available and non available form. This method has more advantages; like, extraction of both Pi and Po forms, extraction of microbial P during the process. Despite the limitation of time requirement and complexity, this method is more reliable and been in use from last 30 years. Major fractions, which can be extracted by this method, are: Resin P, Bicarbonate P, Hydroxide P, Acid P and Residual P (further description given in Table 1).

3. PHOSPHORUS CYCLING OR DYNAMICS

Phosphorus, one of the essential macronutrient limiting plant growth and development, especially in subtropical and tropical region [10, 23]. Major pools of P are present in terrestrial ecosystems, which generally account 100-3000 kg ha^{-1}, so its cycle is also termed as sedimentary cycle [11, 12, 24]. Sparingly soluble calcium phosphate i.e apatite, in rocks and other deposits are the major source of P in terrestrial ecosystems [10, 25]. Primary minerals of P, present in stratum rock are apatite, hydroxyapatite, and oxyapatite and their chief characteristic is that, they are water insoluble. But, in spite of this fact, they are also the principal source of P and under suitable environment, they can be solubilized and become available for living organisms. Inorganic phosphate are also found, in soils having higher or lower soil pH and P is rapidly converted to sparingly soluble amorphous and crystalline compounds, i.e. Ca^{2+} and Mg^{2+} phosphates in neutral to alkaline soils; variscite (Al-P) and strengite (Fe-P) in acid soils [26], which belong to the slowly cycling P pool and are not directly available to biota [27]. Second major component of soil P is organic matter. The organic P pool, accounts for 15-80% of the total P pool [28-29] and can be greatly influenced by the quantity and quality of organic inputs and shifts in soil microbial community structure [30-32]. Organic P in soil is largely in the form of inositol phosphate, synthesized by microorganisms and plants and forms the most stable form of organic P (50% of the total organic P) in soil [33]. Soil P which occurs in equilibrium with the soil solution (bioavailable P) is referred as ‘Labile P’ and other P forms which are slowly available to plants are known as ‘non-labile’ [34].

Table 1. Forms of phosphorus extracted by Hedley et al. [22].

Sl. No	Form extracted	Form of P	Availability to plant
1.	Resin Pi	Adsorbed on surface of crystalline compounds	Soluble and easily available
2.	Bicarbonate - Pi	Adsorbed on surface of soil compounds	Available and remain in equilibrium with the soil solution
	Bicarbonate - Po	Labile Po inside the internal surfaces of soil aggregates	Available after mineralization and remain in equilibrium with the soil solution
3.	Hydroxide - Pi	Adsorbed on surfaces of secondary mineral (Al and Fe-P)	Low plant availability
	Hydroxide - Po	Extracts Po that is strongly held by chemisorption to Al and Fe components in the soil	Stable P involved with the long term transformation of soil P
4.	Acid - P	Associated with Ca and occluded within sesquioxides; acid extractable	Stable and low solubility
5.	Residual- P	Occluded and most recalcitrant P	Most stable, highly resistant and low bioavailability

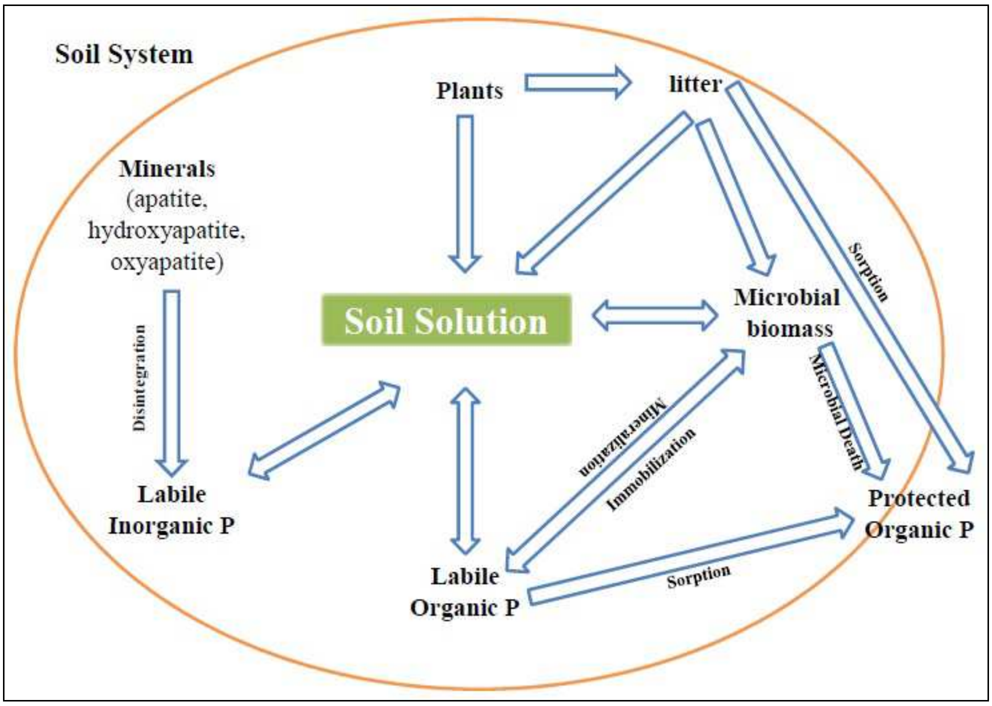

Figure 1. Phosphorus cycle in soil.

Phosphorus cycling or dynamics in soil can be defined as a series of processes influenced by the nature of the inorganic and organic solid phases present, the type and intensity of biological activity, the chemistry of the soil solution (pH, ionic strength, redox potential), and abiotic factors like texture and moisture content, [11, 34-35]. The natural P cycle starts with the disintegration (physical, chemical and microbial) of primary apatite P rocks and here, microbes play key role (oxidation and reduction of phosphorus compounds) so we can call them "forerunner of P cycle”. After weathering, P comes in soil solution and incorporates into the system as different secondary Pi and Po form, which are of limited availability [10]. These forms are inter-exchangeable via different chemical and biochemical (sorption-desorption, oxidation-reduction and mineralization-immobilization) processes [11, 34].

3.1. Phosphorus cycling in agriculture ecosystem

P cycling is continuous in nature and governed by the need of users while in crop field it is disturbed due to addition and removal in the form of fertilizers and crop produce, respectively. It is quite necessary to understand P dynamics in agricultural soil, for managing the P usage, its consumption by roots according to their potential and ultimately to increase P use-efficiency by plants. P cycling in soil is governed by some biotic and abiotic factors, including adsorption, dissolution and microbial activity, respectively [36]. Mineralization of Po and its cycling is the main factor on which availability of P to plant depends [37]. Effect of P fertilization on availability of soil P had been studied from last century. Now, it is established that soils not getting P fertilizer had low total P (TP) while fertilized soil had have high TP [38-40]. Application of P fertilizers increases the inorganic P content [41-42] while addition of organic sources increases organic P content [43]. There is more inorganic (63 to 92%) P than organic (5 to 25%) P in manure and application of manure produces positive effect on content of P fractions in soil [44]. Relevance of manures has considerable impacts because there is progressive turnover of P into other forms [45] and higher application of manures increases the amount of labile Po, moderately labile Po, moderately resistant Po, highly resistant Po, Al-P, Fe-P, O-P and Ca-P in soil [46]. Application of P fertilizers will surly give more yield but it may also have long term effect on the P fractions [47] and especially labile Po pool in soil [48].

Lots of work have been done in past to study the effect of organic and inorganic P application on yield of crop, solely or in different proportions, their effects on different P pools, soil modification like pH, tillage and application of microbial inoculants just to increase the P use efficiency. Agricultural practices can also contribute in the composition of soil P like, the content of organic P in soil heavily depends on cropping system and tillage depth than the fertilizer used [49]. According to McLauchlan [50], tillage and crop removal have the tendency to reduce organic C of soil and concentration of the organic P in soil is directly proportional to organic matter content of soil [48, 51]. However, no-tilled surface soils have higher amount of organic C and available P in comparison to conventionally tilled soil [52], due to non-incorporation of applied P fertilizers. But in heavy soils like clayey ones, competition is there between organic anions and PO_4-P for the same sorption sites so, the availability of P is enhanced [53]. Another important factor which plays a role in deciding the P cycling is rhizosphere, association between plant roots, soil and microbial activity; where different exudates such as mucilage, organic acids, phosphatases modify the soil environment. According to Marschner [54], roots can decrease the pH of rhizoshpere by 2-3 units and increase the P availability. Rhizosphere pH can also be changed by uptake of cation and anion like in case of nitrogen, where ammonium uptake causes acidification while nitrate causes alkalization. pH change in the rhizosphere is mainly affected by uptake ratios and nitrogen assimilation. Now in recent years rhizospheric P management became a novel approach and Jing et al. [55] reported that by using P plus ammonium, maize growth improved in a calcareous soil due to rhizosphere acidification. Similarly, faba bean (*Vicia faba*) can also acidify its rhizosphere [56]. Rhizospheric microorganisms like arbuscular mycorrhizal fungus (AMF), phosphorus solubilizing microorganisms (PSM) and plant growth promoting rhizobacteria (PGPR) are also known to increase P cycling [57] and it has been found that combined usage of AMF and PSM showed the positive response in P uptake [58].

These results with respect to the effect of different strategies on P cycling or improvement are not clear-cut and it can be supported with the findings of Jalali and Ranjbar [59] who suggested that different P pools, like Ca-P, Fe-P, Al-P and organic P, are highly active and their content depend on the actual properties of the soil. So management practices for increasing the organic C should be imparted in field to maintain availability of P. Many studies are there on the effects of pH modification on P availability, but a consistent plan to manage soil phosphorus for sustainable crop production and to minimize P loss from soils have not been fixed. Different forms of P are available in soil due to the inherent properties of soil, which are not available to plants and changing these characteristics of soil on long term basis may be difficult to achieve.

3.2. Phosphorus cycling in forest ecosystems

Soil nutrients are the key drivers of any ecosystems, however in forest ecosystems; they play an important role in development and maintenance of the ecosystem sustainability [60-61]. In forests, the nutrient cycle is maintained by itself, as there is development of thick forest floor due to addition of litter. Litter fall is in form of branches, leafs, bark and fruit, which contain an appropriate amount of nutrient and by their decomposition nutrient are returned back in soil [62-63]. But released nutrients may be immobilized or mineralized, depending on the site conditions [62-64]. Nutrient use efficiency in any forest depends on the amount of nutrients content in litter, root and woody biomass of trees [65]. In areas having permanent vegetation, like forests, Po fractions are present in higher proportions [29, 66]. According to Chen et al. [67], amount of dry matter produced per unit of P is scientifically inferior in temperate forests as compared to tropical ones. There is always difference in organic matter deposition and nutrient cycling, between forests and other ecosystem, because, both affect the mineralization and immobilization processes and show significant impact at ecosystem level.

First report on P dynamics in forest ecosystem was published by Fisher and Stone [68], they observed that under pine plantation mineralization of organic P was higher as compared to the adjacent abandoned fields and larch plantations. In New Zealand, several workers also reported that under recently established forest, there was increased mineralization of organic P but the level of microbial biomass P and enzyme activities responsible for organic P mineralization is lower [67, 69]. This may be attributed to lower inputs of organic matter and in addition due to decrease in soil pH [67]. Davis [69] also found that concentrations of total and organic P were lower under the *P. radiata* stand, which is attributed due to enhanced nutrient uptake and decompostion of organic matter by the pines. Chiu et al. [70] reported that concentration of bioaviliable inorganic P was greater in soils under Chinese hemlock (*Tsuga chinensis*) as compared to the dwarf bamboo (*Yushania niitakayamensis*) and in NMR analysis, they found that inorganic orthophosphate monoesters was the major forms of P extracted by trees. Decline in the content of orthophosphate monoesters under pine vegetation is mainly due to the utilization of these compounds by conifers through root-microbe symbiotic interactions [67, 71]. Plant root-microbial association is important activity in any terrestrial ecosystem, because it plays most vital role in alteration or decomposition of soil organic matter and release of associated nutrients. Roots are the secretors of various exudates in form of chemical compounds into the soil [67, 72], which become signals for microbes to initiate the transformation process of soil organic matter and associated nutrients [11]. There are many reports defining the ability of different bacterial species (*Pseudomonas, Bacillus, Rhizobium, Burkholderia, Achromobacter, Agrobacterium, Microccocus, Aerobacter*, etc.) to solubilize insoluble inorganic phosphate compounds [73]. Microorganism associations like mycorrhizae are known to modify root structure and their functions also [74-75] and mediating the availability of soil P to associated plants. There are ample reports suggesting that mycorrhizae releases low molecular organic acids such as citric, oxalic, maleic, and acetic acid, to solublise the organically bound P [76]. Chen et al. [67] also reported that mineralization of organic P was higher under pine forest due to the symbiotic association between pine roots and ecto-mycorrhizae. As ecto-mycorrhizae, releases organic acids and cause acidification of the rhizosphere zone, thus promoting the solubilisation of inorganic and organic P.

The studies mentioned above provided background information about the studies conducted by the various researchers. Therefore, from the above studies, it has been concluded that, in forests there is dominance P_o (Table 2), its mineralization mainly depends on microbial aspects and availability or transportation from soil to plant is governed by mycorrhizae. However, it can also be assumed that in P scarcity, trees have to absorb from inside the deeper layers of soil to take more nutrients and in this case, there is more below ground development of roots which may hamper the aboveground canopy development. To overcome this, there is need to improve our knowledge regarding to the processes controlling P availability in surface and deep soil layers. There is also need to develop certain strategies which can enhance the mineralization of P_o, as it is the major P pool in forest ecosystem.

Table 2. Literature reports on soil P fractions (mg kg^{-1}) in surface soil (0-15 cm) under different vegetation types.

Sl. No	Study Area	Vegetation type	pH (H_2O)	SOC (g kg^{-1})	TP	Po	Pi	MBP	Reference
1.	Daqinggou National Nature Reserve, Inner Mongolia, China	Elm (*Ulmus macrocarpa*) savanna with dense grasses	7.3	8.9	149.0	94.8	54.3	4.78	[77]
		Grassland	6.5	3.6	107.0	70.7	36.3	2.89	
		Mongolian pine plantation	6.7	4.0	79.9	47.7	32.2	2.69	
		Chinese pine plantation	6.7	3.5	73.1	38.6	34.5	2.10	
		Poplar plantation	6.7	4.3	109.5	69.7	39.9	3.53	
2.	Qingyuan Experiment Station, Institute of Applied Ecology, China	Natural secondary forest	5.82	50.45	741	475	272	40.3	[78]
		Larch (*Larix olgensis*) plantation	5.55	34.70	1025	543	481	26.1	
3.	Rio Paja Forest plot, Panama Canal watershed, central Panama	Tropical rain forests	3.55	-	45	27	18	-	[79]
4.	Campo Chagres Forest plot, Panama Canal watershed, central Panama	Tropical rain forests	7.00	-	824	494	330	-	[79]
5.	Cave Stream forest, Craigieburn research area, central south island, New Zealand	Mixed stand of Ponderosa pine (*Pinus ponderosa*) and Corsican pine (*P. nigra*)	-	-	839	552	287	37.4	[76]

SOC: soil organic C; TP: total P; Po: organic P; Pi: inorganic P and MBP: microbial biomass P

3.3. Phosphorus cycling in grassland ecosystems

Grasslands, a biological community, characterized by mixed herbaceous (non-woody) vegetation cover, with high biodiversity due to high plant species diversity [80-81]. Plant diversity is a key element in grasslands because: increased forage production [82-83], stability against disturbances [84] and also improves nutrient cycling [82]. In grasslands, nutrient addition includes atmospheric inputs, fertilizers and animal feed while removal of nutrients through animal product, harvested forage and via off-site nutrient transport including leaching and surface runoffs [86-88]. Among the nutrients, P has a tremendous influence on species richness [89] after nitrogen. In grassland soils, total P content varies between 200 to 1100 ppm and concentration depends upon the age of soil [90]. According to Kemp et al. [87], in grasslands or pastures, most of the nutrients taken up by plants are returned to the soil in the form of litter and root residues (10-70%) or animal excreta (50-95%). In grazed pastures, cycling of P is secured in comparison to N, as it is less soluble and mobile, so surface runoff is a major loss pathway through which P is lost Whitehead [91]. According to Parfitt [92], from intensively fertilized plot receiving 38 kg P ha^{-1}, 4 kg P ha^{-1} yr^{-1} could be lost due to runoff. Timmons and Holt [93] reported that from an ungrazed, unfertilized, native prairie in Minnesota, P loss through runoff is 0.1 kg P ha^{-1} yr^{-1}. The plant mycorrhizal symbiosis absorbs P from the soil solution, which comes from hydrolysis of labile ortho-P or mineralization of Po [94]. Plant litter and animal excreta are the main source of P in grazed pasture. Whitehead [91] reported that only 100 to 250 g P kg^{-1} of P in the diet of animals is converted into live-weight gain or milk, while rest is recycled to soils in form of plant residues and animal excreta, so mineralization of organic compounds is the key process in grasslands with respect to the P dynamics. There are more chances of net P immobilization in tropical grasslands because P content in grasses is < 2.0 ppm [95].

Land use change is the key activity which can alter the rate of mineralization or cycling of P in grasslands. The most common land use change occurred in all over the world is the afforestation of grasslands with conifers and this enhances the rate of mineralization of organic matter and associated P and hence, P availability in topsoil is increased [67]. Till date, most of the work has been focused on changes in land use and its effect on P cycling. There is need to know, what changes can occur in soil microbial community due to the particular land use change [67, 96-97]. We can't ignore the changes in the structure and activity of soil microbial community, as they are the fore-runners or key drivers in the mineralization of P.

4. VARIABLES INFLUENCING P DYNAMICS IN TERRESTRIAL ECOSYSTEM

Phosphorus occurs in soils in various forms, organic and inorganic which can be further divided into labile and non-labile P [98]. Therefore, soil P can be considered in terms of ‘pools’ of varying availability to the plants. A major portion of soil P exists as insoluble and fixed forms including primary phosphate minerals, humus P, microbial biomass P, insoluble phosphate of Ca, Fe and Al and also P fixation by hydrous oxides and silicate minerals. This fraction is known as non-labile P and is the largest pool of soil P in terms of quantity [99]. Whereas, labile P is the readily available fraction that exhibits a high dissociation rate and is in rapid equilibrium with solution P [99-100]. Soil P moves among these pools and remains in continuous dynamic equilibrium. Phosphorus may also move among pools as shown by the conversion of organic P into inorganic P via mineralization by microbial and root-released phosphatases [101]. The factors which influence these equilibrium reactions are discussed in the following sections.

4.1. pH

In highly weathered soil solution, P concentration primarily depends upon the soil pH levels that indicate how certain minerals iron and, aluminum, interact with phosphorus in the soil, and it is the interaction that affects the phosphorus availability in soil [102]. The inorganic P compounds mainly couple with amorphous and crystalline forms of Al, Fe, depending upon the acidity of the soil [22]. Because surface adsorption of P increases with decreasing pH, these adsorption processes would often be expected to be more influential at low pH [103] resulting in a “positive” pH dependence (i.e. increased solution P level at higher pH), provided that adsorption is fully reversible within the time scale of interest. However, precipitation of solution P with Ca is expected in calcareous-alkaline soil with higher pH. A number of Ca-P minerals may form, such as amorphous calcium phosphate (ACP), octacalcium phosphate (OCP) and apatite (hydroxyapatite or fluorapatite). Precipitation/dissolution of these minerals will cause “negative” pH dependence (increased solution P level at lower pH) [104]. Murrmann and Peech, [105] performed back titrations for two soils and found decreasing P solubility with increasing pH until about pH 5.5 to 6, at which pH minimum solubility occurred.

At higher pH, P was more increasingly dissolved again. At very high pH, however, (>8-9) P solubility decreased due to Ca-P mineral precipitation.

4.2. Nature and amount of clay

4.2.1. Hydrous oxides of Fe/Al

Fe/Al oxides and hydrous oxides are abundant in acid soils and high P retention in these soils is attributed to active Al and Fe associated with organic (mainly Al-humus complexes) and mineral fractions (ferrihydrite), which form in the course of soil development [100, 106]. These oxidized secondary minerals can bind P making it temporarily unavailable for plants and microbes through the formation of labile and non-labile P [107-108]. P ions bind to the Fe/Al oxide surface by interacting with OH- and/or OH^{2+} groups on the mineral surface in two steps, a mononuclear adsorption followed by a binuclear

4.2.2. Calcium carbonate

The solubility of P in Ca rich calcareous soil is mainly controlled by the solid phase dicalcium phosphate of chemisorption of P on calcite, with the formation of a surface complex of calcium carbonate bound P with a defined chemical composition [109]. Impure and/or, amorphous calcium carbonate with large specific surface area exhibits greater P adsorption and more rapid precipitation of Ca-P minerals. Calcareous soils with highly reactive calcium carbonate and high Ca-saturated clay content will exhibit very low solution P levels, since P can readily be precipitated or adsorbed [100]. The lower the Ca:P ratios of the Ca phosphates the higher their solubility in water. The equilibria of Ca phosphates from solution P to the highly insoluble hydroxyapaptite is shown below [110].

$H_2PO_4^- + Ca^{2+} \Leftrightarrow CaHPO_4 + H^+$

$3\ CaHPO_4 + Ca^{2+} \Leftrightarrow Ca_4H(PO_4)_3 + 2H^+$

$Ca_4H(PO_4)_3 + Ca^{2+} + H_2O \Leftrightarrow Ca_5(PO_4)_3OH + 2H^+$

From these equilibria it is clear that H^+ promotes solubility of Ca phosphates in the soil and Ca^{2+} has the reverse effect in calcareous soil. The hydroxyapaptite formed in this reaction has very low water solubility, thereby depleting the solution P concentration to the greatest extent.

4.2.3. Silicate minerals

Soils derived from volcanic ash (Andisol soil) are characterized by unique property of high phosphorus retention capacity, with main constraint for plant growth being usually the low solution P and its availability [106, 111]. Allophones (Si-Al-Fe-O-OH-OH_2) have a large surface negative charge which is partly or, entirely balanced by the complex aluminium cations. Phosphorus gets adsorbed by reacting with such aluminium cations [112]. In this way, some phosphate of the labile pool is continuously being transferred to non-labile P and thus becomes immobile.

4.3. Soil organic matter (SOM)

SOM is the major source of organic P pool and that, in highly weathered and high P-sorbing soils, the P maintained in organic pools may be better protected from loss via fixation than by P flowing through inorganic pools [113]. The organic P compounds are associated with rapidly to slowly decomposable organic molecules, such as nucleic acids, phospholipids, sugar phosphates, inositol phosphates, and recalcitrant humic substances [22]. Different organic anions produced from OM decomposition form stable complexes with Fe/Al, preventing the formation of non-labile P by reacting with phosphate anions. These complex ions exchange for P are adsorbed on Fe/Al oxides. Anions such as oxalate, citrate, tartrate and malate are found to be most effective in doing such [100]. In addition to that, SOM may be sorbed to soil particles at non-specific sorption sites, which would increase the surface negative charge of the particle. This would reduce the electrostatic attraction of P to the soil and keep more P in solution [114].

4.4. Microbial biomass

The soil microbial biomass plays a central role in soil phosphorus dynamics, especially in the dynamics of soil organic P [115]. The soil microbial biomass has two main roles in the dynamics of P in soil: i) the principal driver for the transformation of organically-bound phosphorus to plant-available phosphate (solution and labile P), and ii) the accumulator of a significant pool of P [116].

Additionally, microbes indirectly affect P availability by changing the soil pH and via organic molecules released during decomposition of organic materials (Fig. 2), which may block P sorption sites and complex Fe, Al and Mn [107,117]. Microbial biomass P responds rapidly to the addition of C substrate to the soil. In the short term, net mineralization will occur if the amount of soluble P in added residues is in excess of that taken up by the microbial biomass. However, residue P content is often insufficient to meet the requirements of the growing microbial biomass. Under such circumstances, the microbial biomass will take up P from the solution and labile pools in soil; leading to net immobilization of soil P, thereby depleting those pools of soil P [116]. In addition to that, the microbial biomass has a high capacity to acquire P from non-labile pools that are generally not considered to be plant-available, and will be more competitive than plants for solution and labile P [118-120].

4.5. Anaerobic condition

Under anaerobic conditions, reductive dissolution of ferric hydroxides carrying P is an important mechanism of P release into the solution [121]. Thus, redox status of a soil is important determinant of the potential role of a soil to retain P. Other mechanisms include dissolution of occluded P, which increases the mineralization of organic P in acid soils, and also increases the solubility of Ca-P in calcareous soils, and maximizes P diffusion [100]. Alternate drying/rewetting, freezing/thawing, and associated microbial activity tend to destroy organo-mineral complexes and kill microorganisms, often resulting in releases of dissolved phosphorus from the affected soils [42].

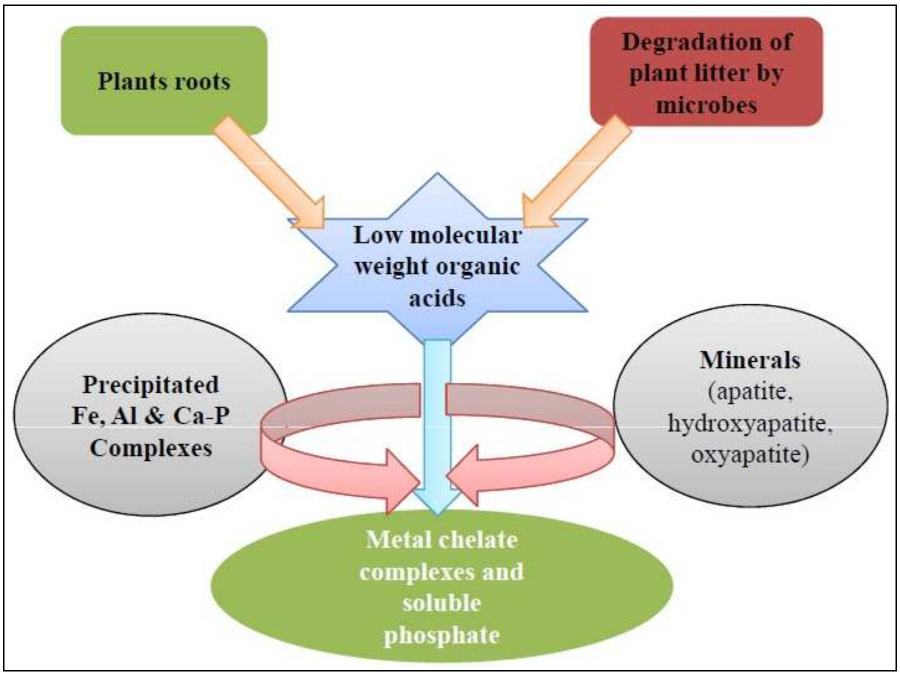

Figure 2. Release of P through the action of low molecular weight organic acids and other naturally occurring chelates.

4.6. Plants

Absorption of P by plant roots causes depletion in the solution P concentration, and labile P rapidly replenishes the solution P, but at a very slow rate depletion of labile P causes some non-labile P to become labile. However, the depletion rate of different P fractions in the root rhizosphere varies significantly among different plant species and different genotypes within a given species [22, 123-125]. Rhizospheric pH may be changed by imbalance uptake of cations and anions by plants, which can affect the P dynamics in the soil [126]. Organic anions secreted from plant roots (Fig. 2), increase the solution P by desorbing inorganic P (labile P) from a mineral surface and chelating or complexing cations, such as Al^{3+}, Fe^{3+},and Ca^{2+} ions that are bound to non-labile P [127]. Some enzymes secreted from plant roots, such as phosphatase, can catalyze hydrolysis of organic P. It has been suggested that higher phosphatase in the rhizosphere, compared to the bulk soil, can induce significant depletion of organic P in the rhizosphere [124, 128].

Management of soil P bioavailability is one of the main challenges for many regions of the world. The main processes and/or factors controlling soil P bioavailability are P interactions with Al, Fe, and Ca hydrous oxides, amorphous, and crystalline complexes, along with organic P mineralization [129]. The rate and extent to which these processes occur are greatly influenced by agricultural management practices including rate of P fertilization, nature of fertilizer, and method of fertilizer addition, tillage, and drainage etc. The phosphatic fertilizer in current use scenario requires a greater input that cannot be afforded by the small to marginal farmers of the developing nations. Therefore, improved methods of phosphate application like application in granular form or, as bands in close proximity to the roots and fertigation, as well as liming acid soils, can definitely increase soluble P in soil and provide enough time to crops for its uptake and, reduce the influence of these factors on P availability in soil. Thus, these management practices can reduce the rate of expensive superphosphates application and maintain better soil health and sustainable production in terrestrial ecosystem.

5. LONG-TERM ECOSYSTEM MANAGEMENT

Primary productivity of any ecosystem depends on nutrients; like in terrestrial ecosystems, nitrogen (N) and phosphorus (P) are the most common limiting elements, both individually and in combination, while in aquatic ecosystem, P become most problematic as it causes eutrophication. In agriculture ecosystem, strategic P addition is important and it should be based on quantity of P available in soil, how much is going to be fixed and upto what extent crop can take. Combination of strategic P application and germplasm with high uptake capacity will provide agricultural sustainability, better P status in soil and increased P use efficiency. In forest ecosystem, litter produced is the major source of P, during the decomposition of woody debris by microbes, P is released in the soil. But in grassland ecosystems, long term accumulation of animal excreta is the major source of P and represents serious environmental concern. Quite well-organized nutrient recycling can be promoted in grazing land systems by using efficiently organized strategies like regular shifting of animal feed, supplying sufficient fertilizers and maintaining suitable population of animals can potentially improve P use efficiency by plants and restrict environmental pollution. In both, forest and grassland ecosystems, P cycling depends on the decomposition of organic matter and it can be restricted due to immobilization by plants and animal production. It can be assumed that to overcome the reduction there is release of P from organic pool or from weathering of rocks. To maintain the P cycling, intermixing of grassland and forest can be done. It will also lead to greater productivity of grasses and subsequently improved SOM and structural integrity. There is need of long term comparative studies on strategic P inputs, improved methods for P application and P efficient germplasms in agricultural ecosystems, controlled grazing practices and impact of intermixing of grassland and forest ecosystems on soil health and P cycling, as it will provide better solutions for P management.

6. FURTHER RESEARCH

In future, studies will be focused on mechanisms to increase the P use efficiency and associated processes under different ecosystems:

- Rate of P release from root and leaf litter inputs and its efficient utilization;
- Changes occurring in soil microbial community under different ecosystems using nucleic acid based techniques, including production of low molecular weight organic acids and their transport processes;
- Relationship between plant root and VAM associations;
- Understanding the effects of subsurface placements of P resources under different ecosystems

to arrest the P export and eutrophication;

- Development of mathematical models simulating temporal changes in residual soil and organic P;
- Practices to control export of P at their source, as it is most beneficial and effective.

7. CONCLUSION

Increased human activity influences the nutrient cycles in ecosystems as agriculture and forestry removes nutrients from these ecosystems and also increases the transport of P to aquatic ecosystems. There is a considerable association between the type of land use and export of P, as it has been proved that the alteration of forest into agriculture ecosystems quadruples phosphorus export. The key factors for controlling P export are geology, land use, SOM, pH and microbial aspects and by using these, it is easy to predict the P export and cycling within any ecosystems. However, heavy use of P fertilizers accelerated the problem of eutrophication, so there is need of efficient practices to increase the use of accumulated surface P, estimating P bioavailability in soil and improved methods of runoff control to control P export into aquatic ecosystems. There is need of information with respect to the effects of conservation on P cycling in long term basis. There are models available which simulates the changes in P availability in short times, using first order kinetics, but does not for long term changes. Therefore, use of these models is limited in order to estimate the loss of P and research should be directed towards the development of model, to recognize well-organized soil and management practices that may increase P use efficiency and reduces the export of P into water bodies.

AUTHORS’ CONTRIBUTION

All authors contributed equally for the success of this review article. The final manuscript has been read and approved by both authors.

TRANSPARENCY DECLARATION

The authors declare that there is no conflict of interests regarding the publication of this paper.

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