Chapter 15
Models to Study Phosphorous Dynamics Under Changing Climate

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Contents

Abstract Phosphorus the macronutrient, a component of nucleic acid and helpful for grain developmental phases (reproductive growth) of crops. It is also component of energy carriers like ATP, ADP, NADPH and FADPH which provide energy for

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different physiological processes. Phosphorous plays an important role in the growth, development and yield of crops. However, P causes some environmental problems like eutrophication. The importance of the element necessitate its study through modeling and distribution under changing climate. Since P is present as organic and inorganic form but their fate is different in soils. The inorganic P accounts for 35–70 % while organic form of P accounts for 30–65 % of the total P but it is dominantly available as stabilized forms like diesters. The availability of this P depends upon mineralization processes by soil biota which has dependency upon soil moisture, temperature, physiochemical properties and soil pH. However, the transformation of organic p has strong influence on the availability of P in soil. Therefore, availability of P to crop is extremely complex and its needs to be evaluated using modeling approaches. The Phosphorus Use Efficiency (PUE) for crops might be increased by understanding P-dynamics which may be done by models. The understanding of P dynamics will help to optimized balance use of P. By monitoring P for longer period of time might increase P status of soil. The use of computer models will help to modify fertilizer application which can reduce use of P but will increase PUE. The effects of high temperature, elevated CO_2 and drought on the availability of phosphorous, PUE and its dynamics could be modeled using dynamics models like APSIM, AEP or by using regression modeling approaches.

Keywords Phosphorus • Soil biota • Phosphorus use efficiency • P-Dynamics • APSIM

Abbreviations

ATP	Adenosine Tri-Phosphate
ADP	Adenosine di-phosphate
NADP	Nicotinamide adenine dinucleotide phosphate
FADP	Falvin adenine dinucleotide phosphate
APSIM	Agricultural Production System Simulator
AEP	Agriculture Ecosystem model
PUE	Phosphorus Use Efficiency
IPCC	*Intergovernmental Panel on Climate Change*
NFDC	*National Fertilizer Development Centre*
IFPRI	*International Food Policy Research Institute*
DNA	Deoxyribonucleic acid
RNA	Ribonucleic acid
PAE	P Acquisition Efficiency

15.1 Introduction

Phosphorus the major macronutrient of plant is totally different from nitrogen as it does not come from air and have less solubility in water which leads to slow movement of P to downstream (Tiessen 2008). P is the 11th most abundant element in

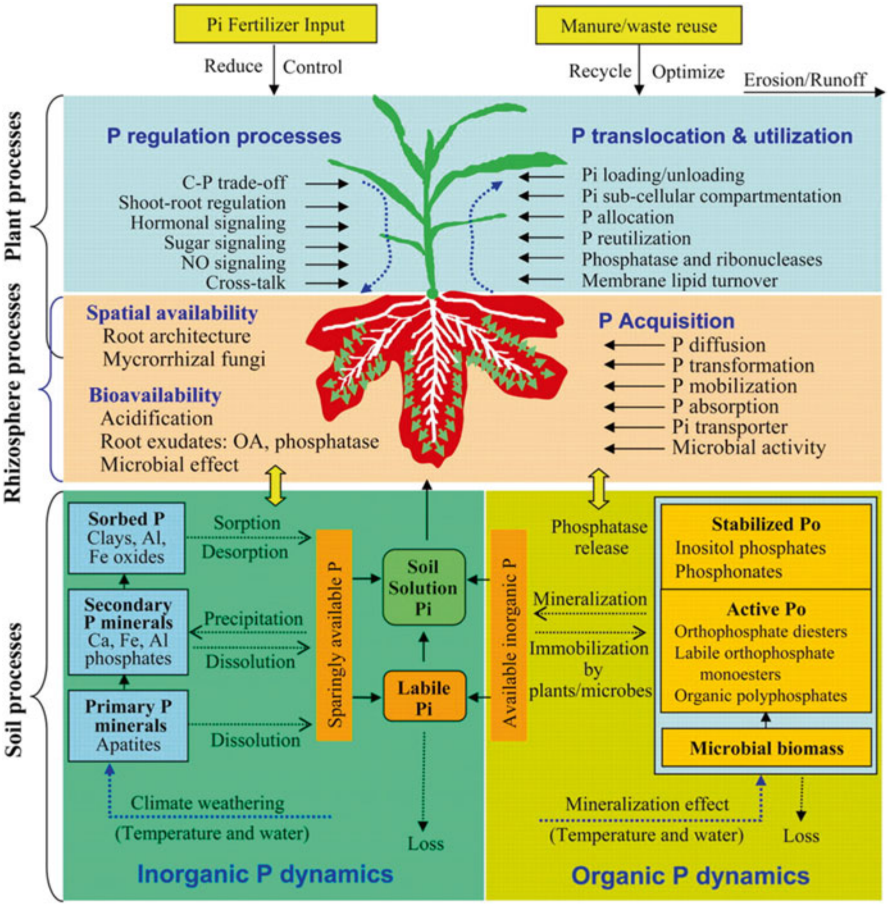

Fig. 15.1 P dynamics in the soil/rhizosphere-plant continuum (Source: Shen et al. 2011)

earth crust and its concentration reaches to 1200 mg P per kg. However, most of the soils contain 200–800 mg per kg while older soils have less compared to younger soils. The binding of P is maximum with Ca or Mg and its solubility in water becomes 0.5 mg P per liter. The decreased solubility than $Ca_3(PO_4)_2$ after weathering is due to Ca leaching which resulted to abundance of Fe and Al. Different physical and chemical reactions (mineralization, immobilizations, dissolution/precipitation and sorption/desorption) controls the availability of P to crops. P fixation is a misnomer as every chemical reaction to some extent is reversible however, since release of P is so negligible therefore, it is considered as non-significant. The organic phosphate esters and inorganic phosphates constitutes 99 % of naturally occurring P. Similarly high negative charge density due to four oxygen per P, $(PO_4)^{3-}$ resulted to its loving attraction to all positively charged ions. P is essential component of heredity material (DNA and RNA) and energy carriers like ATP. The phosphodieaster linkage maintains life on earth which is maintained by P. Since P is present as organic and inorganic form but their fate is different in soils (Turner et al. 2007). The inorganic P accounts for 35–70 % and dynamics of P in soil is further illustrated

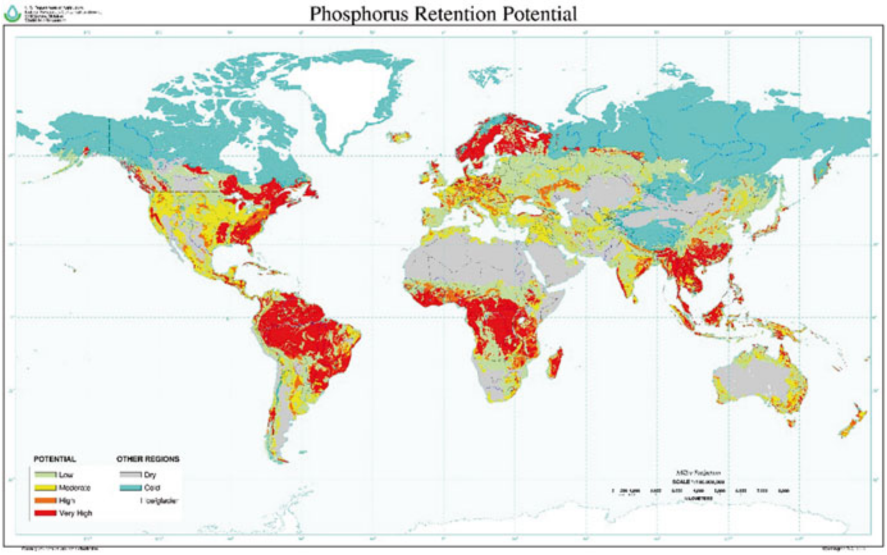

Fig. 15.2 The Phosphorus Retention Potential map (Source: USDA, NRCS 2012)

by Shen et al. (2011) (Fig. 15.1). However, organic form of P accounts for 30–65 % of the total P but it is dominantly available as stabilized forms like diesters (Condron et al. 2005). The availability of this P depends upon mineralization processes by soil biota which has dependency upon soil moisture, temperature, physiochemical properties and soil pH. However, the transformation of organic p has strong influence on the availability of P in soil (Turner et al. 2007). Therefore, availability of P to crop is extremely complex and it needs to be evaluated using modeling approaches since it is associated with P dynamics (s).

The crop productivity over the globe has strong relationship with soil fertility and most of world soils are limited in N and P hence leading to lower soil productivity. However, P deficiency is more often in old weather soils (Lynch and Brown 2011; USDA 2012) (Figs. 15.2 and 15.3). The limited availability of P might be due to several factors like its binding with Fe and Al, human activities (50 % of the agricultural soils in the world) erosion, acidification and mining of nutrients (Hartemink 2003). The developed countries have potential to increase the P status of soil however, in developing countries where P as fertilizer (World Bank 2004) use is limited might result to food security (Lynch 2007). Therefore, use of crops having high phosphorus use efficiency (PUE) and development of cropping systems with greater productivity might tackle the problem of food security (Lynch 2007). P-acquisition is the adoptive value of crop/plant to acquire P and it can be considered as trait called “Phene” (a phenotype is comprised of many distinct phenes). These “Phenes” determines the fitness of crop therefore; it needs to be considered in the domestication of crops. The “phene” which is important for P-acquisition is root hair length (Fig. 15.4). The phenes adaptability is interlinked with surrounding environments like in case of root hairs; length has strong synergism with root hair

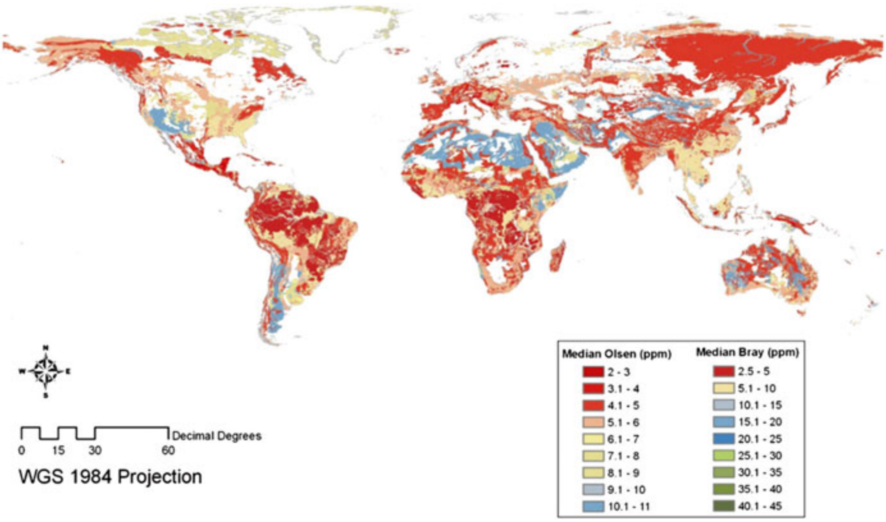

Fig. 15.3 Map of global soil Phosphorus availbility (Source: Lynch 2011)

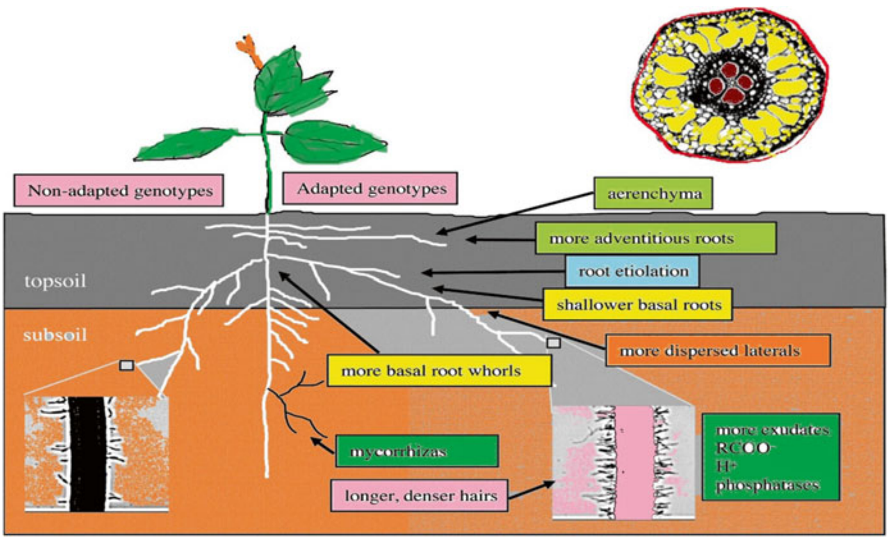

Fig. 15.4 Root phenes associated with genotypic differences in adaptation to low phosphorus (Source: Modified from Lynch 2007)

density (Ma et al. 2001a) for P acquisition. Therefore, this type of interactions needs to be considered for phenes consideration in context with surrounding environment. The adaptation of crops under P limited conditions could be achieved by identification of phenes and understanding of physiological and ecological interactions. This could also be useful for breeding P-efficient crops having high PUE under

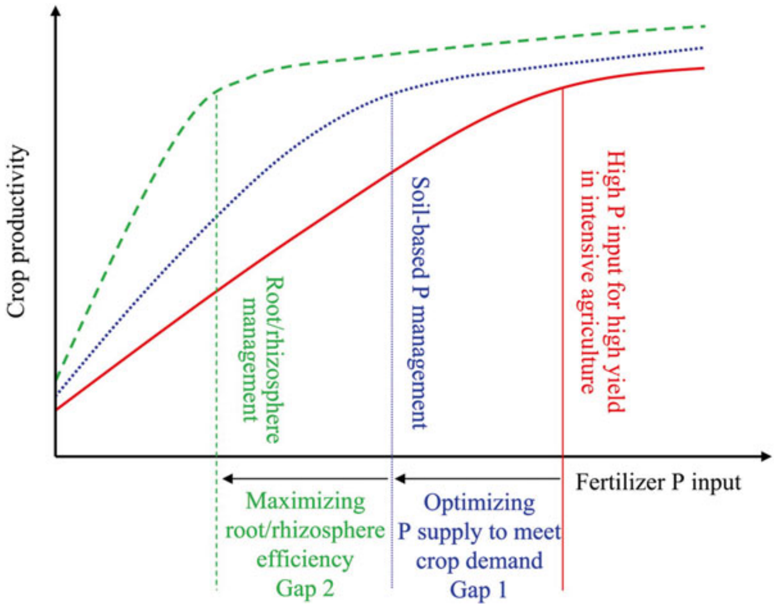

Fig. 15.5 Conceptual model of root/rhizosphere and soil-based nutrient managements for improving P-use efficiency and crop productivity in intensive agriculture (Source: Shen et al. 2011)

limited P. Since P is less mobile therefore, roots display features like mycorrhizal symbioses (Smith and Read 1997), root hair elongation and proliferation (Ma et al. 2001a, b), including rhizosphere modification through secretion of organic acids (Ryan et al. 2001), protons (Hinsinger 2001), and phosphatases (Hayes et al. 1999), and modification of root architecture to maximize P acquisition efficiency (Fig. 15.5, Lynch and Ho 2005).

The increase in R/S ratio (root to shoot) is another feature which plant adapts to compensate P-deficiency (Mollier and Pellerin 1999). Therefore, root growth might be considered to increase PUE (Manske et al. 2000, 2001). In general low P in soil is a constraint and crop adopt different strategies (P acquisition, Topsoil foraging P-solubilizing root exudates, Basal root gravitropism, and Lateral root branching, Reduced metabolic costs of soil exploration, Mycorrhizal symbioses, Phenological and morphological plasticity). The understanding of these strategies might lead to development of such crop genotypes which have high PUE under changing climate. The models might be used to study the role of root architecture in P-acquisition. The earlier results about this aspect using modeling approach indicated that root architecture have significant relationship with PAE (P acquisition efficiency). The change in root architecture resulted to change in PAE. The authors concluded that shallower root architecture might better explore P- rich upper soil layer which might increases the PAE (Yan et al. 2002).

The PUE for crops might be increased by understanding P-dynamics which is possible by using simulation modeling paradigm. The understanding of P dynamics will help to optimized balance use of P. By monitoring P for longer period of time might increase P status of soil by adopting suitable strategies. The use of computer models will help to modify fertilizer application which can reduce use of P but will increase PUE. This will save P by maintaining crop productivity (Fig. 15.4) (Shen et al. 2011). The models like Agriculture Ecosystem (AEP model) could be used to describe P dynamics on farm scale. Cassell et al. (1998) concluded in their work that simulation modeling could be used to understand complex P dynamics and to design management strategies which could achieve the goal of resource sustainability and climate protection.

Phosphorus export from agriculture is major cause of eutrophication (Cassell et al. 1998). P export pattern over time and space is dependent upon human activity, hydrology and physiochemical and biological processes those store and transform P. The ecosystem paradigm was suggested to study P dynamics (Cassell et al. 1998). The AEP model depicted P dynamics with good accuracy and describes P dynamics on farm scale driven by amount of P stored in agricultural soils and systems. Cassell et al. (1998) in their studies concluded that dynamic simulation modeling is valuable tool to study P dynamics for development of policies and management options to achieve climate sustainability. Models are of extreme importance in scientific systems (Frigg and Hartman 2006). A model is a schematic demonstration of the ideology of a system or a set of equations, which shows the performance of a system. Also, a model is "A demonstration of an object, structure or proposal in some form other than that of the individual itself". Models are used to describe and improve the behavior of a system in real and simple form and this simplicity results in the effectiveness of models as it presents the complete explanation of problem (Ahmed 2011; McCown et al. 1996; Murthy 2002). Building, testing, comparing and revising models needs a great deal of time of scientists and the introduction, application and interpretation of these imperative tools needs much general space (Frigg and Hartman 2006). Physiological sub models of complex crop growth includes basic physiological, biophysical and biochemical processes even at cellular or organ level, and it is difficult to conclude a large number of model parameters with which the modelers will have to deal (Mo and Beven 2004). The reaction which occurs within the plants and the interaction of plants with environment is represented in the agricultural models. The agricultural models are the clear picture of reality as it is very difficult and impossible to represent the complete system in arithmetical expressions due to incomplete status of present knowledge and complicacy of the system. In the agricultural sector, universal models do not exist as in the fields of engineering and physics. Complexity level is adopted according to the principle of the model and for different systems; different models can be used (Kumar and Chaeturvedi 2009).

15.2 Statistical and Mechanistic Models

Models are grouped in to different types according to their principle. These include

Statistical Models These models are used to describe the correlation between yield and climate parameters. Crop reaction to the fertilizers can be described by using the simple linear and quadratic models as the scientists used these models as in those researches where the goal is to achieve maximum yield (Willcutts et al. 1998).

Mechanistic Models Models which can describe the correlation between yield and climate parameters along with the function or action of these models. Similarly, "visualization modeling" and "mechanistic" or physiologically based modeling is to describe how a real plant functions using a virtual crop.

Deterministic Models Deterministic models have defined coefficients and predicts accurate yield.

Stochastic Models In these models a possibility factor is involved to every output. These models describe the yield at particular rate.

Dynamic Models Time is taken as variable in these models and both variables remain stable over a known time period.

Static Time is not taken as variable in these models and both variables remain stable over a known time period.

Simulation Models These models are the numerical expression of actual world system and the major objective of crop simulation model is to predict the agricultural yield as a purpose of climate, soil situation as well as crop management.

Descriptive Models These models describe the performance of a system in a simple way and comprises of one or more arithmetical equations.

Explanatory Models These models comprises of quantitative explanation of the functions and processes that causes the performance of the system (Murthy 2002). These models are used to predict the behavior of crop in an area where no crop has been grown earlier and helps in predicting about weather risks and selection of suitable varieties (Van keulen and Wolf 1986).

Process-Based Models These models are used to estimate the influence of fluctuating climate at local and international scales on crops (Rosenzweig and Parry 1994; IFPRI 2009) and the absence of these models for several minor crops confines the opportunity of this technique (Wolf and Van 2003).

Generic Models These models calculate possibly achievable than the real yield. In developing countries where there is a great difference between the expected and the real yield, it is difficult to explain the calculated climatic variations in the real crop yield. These models forecast progressive influence of changing climate on the crop yield than the real possible in fields in regions with great yield differences (Tubiello and Fischer 2007). Future fitness of land for different crops can be compared by using this technique (Stockle et al. 2001). A model can predict the possibilities of production levels in a certain soil type based on rainfall (Kiniry and Bockholt 1998). In short there is a key role of models in the modern science. The role and significance of models in the scientific practice with increasing attention is recognized by the philosophers (Frigg and Hartman 2006).

Phosphorous (P) is the most important yield boosting nutrient for the crops (Schjorring and Nielsen 1987). According to (NFDC 2011), P deficiency in Pakistani soils reaches up to 93 %. These soils have pH >7(alkaline), hence majority of these are Calcareous in nature ($CaCO_3$ > 3.0 %). A large amount of P fertilizers are precipitated or adsorbed and a very small fraction of it added to soil solution and used by plants (Ahmed et al. 2003). High alkalinity in Pakistani soils decreases the P accessibility to the plants. So the sufficient amount of P fertilizers should be applied to sustain certain level of P in the soil (NFDC 2011). Organic and Inorganic P are two main sources of P (Fig. 15.6; Shen et al. 2011).

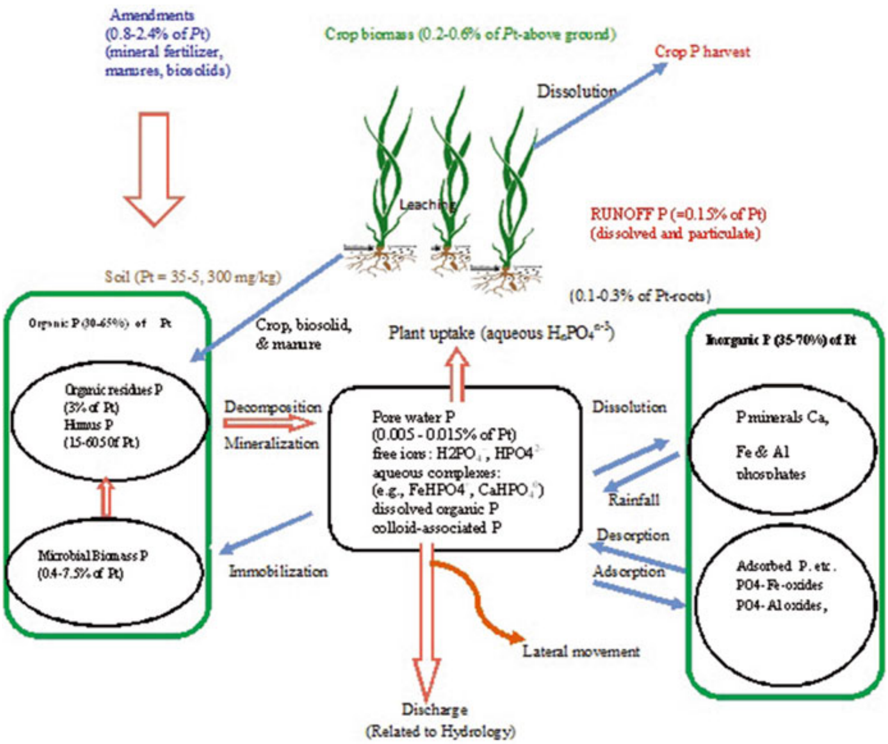

Fig. 15.6 P cycling in crop-soil systems

15.3 Sources of Phosphorus

Organic sources of P includes beef manure, dairy manure, dairy compost, vermi-compost, bone meal, compost having 1, 1, 1, 2, 11–22 and 0.05–2 % of P contents respectively while in poultry manure its concentration is 17 lb/ton (Zublena et al. 1993). Inorganic sources of P include super phosphate, concentrated super phosphate, mono ammonium phosphate, di ammonium phosphate and rock phosphate which contain 21, 45, 49, 47 and 34 % of P contents. Ortho phosphate is better than Poly phosphate (Rehm et al. 2011). Phosphorus plays an important role in plants metabolism, cellular energy transfer, respiration and photosynthesis. It is also the main element of genetic nucleic acid, chromosomes, phosphoproteins and phospholipids. Plant leaf area was reduced to 80 % due to phosphorous deficiency and it also affects the light saturated photosynthesis per unit of leaf area. Similarly, chlorophyll in the leaves of nutrient stressed plants was lowered. Meanwhile highest yield increase was recorded up to 22 % in wheat by the addition of 90 kg P_2O_5 per hectare (Khan et al. 2007). Similarly, sufficient application of P is essential at early stage of crop. P shortage at early crop stage effects the crop growth and it was reported that after this even the amplified application of P cannot recovers crop growth (Bertrand et al. 2003). Agronomically a plant showing good response to the P will be more valuable particularly from the present monetary and ecological point of view. Differences in uptake and use of P resulted in different yield responses of plants (Schjorring and Nielsen 1987). Physiological factors including root morphology (Romer et al. 1988) and Mycorrhizae (Smith and Gianinazzi-Pearson 1988) greatly affect the P uptake efficiency of the plants. Low solubility of P compounds in soil results in the low uptake of P by the plants. Excessive application of P results in leaching of P through macro pores water movement or through transportation in runoff and erosion (Sharpley et al. 2003). Review of modeling of P in current study will enhance our understanding of P availability, application requirement and efficient utilization by each sown crops for monetary as well as environmental points of view.

15.4 Phosphorous Modeling in Soil-Plant Atmosphere

Exact prediction of fertilizer application is becoming more difficult due to growing financial and ecological concerns related to its consumption. The accurate fertilizer rates for the crops can better be predicted by the modified quadratic plateau model than the quadratic plateau model (Bock and Sikora 1990). The correlation of accessible P fertilizer with wheat production can be described better using quadratic and linear plateau models than the quadratic plateau model (Zamune et al. 2005). A significant increase of dry matter production was observed by using linear response and plateau model (Swami and Singh 2008). Spatial variability of soil test P, specific characteristics of soil and production of winter wheat on dry landscapes of central huge plains determines that there are variations of winter wheat production and soil characteristics across landscape. The variables show extreme auto correlation and it helps the Kringing model in exact forecasting of soil characteristics and wheat production (Ortega et al. 1997). The effect of P on individual leaf growth rate and reduced assimilate accessibility for leaf growth in low P situation were testified. The P shortage resulted decline in plants leaf area, grain production and 32 % increase in Phyllochron. Leaf area expansion decreased and photosynthesis per unit leaf area even at higher radiations decreased up to 57 %. It was concluded that the gentle P deficiency at leaf appearance and tillering stage results in 80 % decrease in plant leaf area. The simulation model fails to describe the results due to severe P shortage as well as due to some other effects like direct effects of P on leaf expansion which cannot be explained by model (Rodriguez et al. 1998). The amount of P uptake by wheat plants and its effects on production of different varieties in rain fed as well as irrigated areas having acidic and calcareous soils was determined in an experiment which concludes that production increased significantly in acidic and calcareous soil after the application of P fertilizers. High P in acidic and low P concentration in calcareous soils results in high wheat production (Manske et al. 2001). Integrated effects of N, P, K along with organic matter and water greatly enhance the production which increased with increasing P dosage and 35.6 kg per hectare application of P gives maximum production by using water fertilizer yield model (Duan et al. 2004). P requirement of wheat to get 95 % relative yield by using adsorption isotherm in Freundlich model observed by addition of different amount of P solutions concludes that the highest wheat grain and straw yield was observed by adding 0.15 mg P L^{-1} and 0.50 mg P L^{-1} respectively. Highest P concentration in wheat grain and straw was 0.41 % and 0.16 % respectively. So it is concluded that to get 95 % relative yield 0.2 mg P L^{-1} exterior soil solution and interior P requirement is 0.27 %. The adsorption isotherm in the Freundlich model calculates the P requirement of wheat efficiently (Rehman et al. 2005). It is essential to assess the point to which the nutrient availability decreases the crop yield and the PARJIB model predicts the response of nutrient application to get maximum yield in better way (Reid 2002).

15.4.1 Modeling Phosphorous Availability Under Changing Climate

There will be a major change in production of food due to changing global climate (Rosenzweig and Parry 1994). Nutrient deficits greatly reduce soil productivity. Plants need accessible mineral nutrients in the soil for vigorous development. Shortage of accessible P in soil is a severe problem. P problem is challenging for farmers having small land holdings because of their low accessibility to inputs. The major factors responsible for the shortage of P are: Natural process: High temperature, precipitation, percolation and chemical disintegration are responsible for the nutrient loss. P deficiency is noticed in sandy loam and granite derivative soils.

15.4.2 Human Action

Deficiency of P in the soil is caused due to farm managing techniques, extension of agriculture and further human accomplishments. Reaping of crops, burning of crop remains and the soil destruction directed to the phosphorous loss from the soil. P shortage inhibits growth, cause dark blue green or purple coloration and distresses the root growth (Anonymous 2012). Organic and inorganic phosphorous is produced from plants and bacterial action. These forms of P develop a series of instantly accessible to slowly accessible P which is bonded in an established compound to form a balance between each other. Roots of trees and mycorrhizae cause disintegration which results in phosphorous deficiency (Dijkstra et al. 2003). In an experiment fire showed adverse effects on P accessibility during first year and reduction in available P after 5 years.

15.4.3 Effects of High Temperature

Extremely high incineration temperature reduces the half of P availability to the plants (Thygesen et al. 2011). If the constant rise in temperature cross the specific limit it will also cause decline in crop yield with decreasing soil moisture (Monteith 1981). Effects of P on oat were observed under different temperature to determine P uptake. Soil fertilized with mono and di ammonium phosphate showed high P uptake at 5° C than in 16 and 27° C (Beaton and Read 1965). P concentration in entire plant, leaf, trunk, and roots was highest at 27° C. Increase in P concentration results in maximum phosphorous uptake in leaves and stem. At the temperature of 21° C and 27° C there was maximum P in panicle. There was poor growth at sub optimal temperature which restricts plant growth due to low P contents (Ercoli et al. 1995).

15.4.4 Effects of Elevated CO_2

The global warming and climate change due to increased CO_2 had resulted to the efforts which can reduce the discharge of worldwide CO_2 radiations by intergovernmental panel on climate change (IPCC 2007; Raupach et al. 2007). Supplementary intensification of CO_2 will effect the plant growth considerably, by encouraging the process of photosynthesis directly (Drake et al. 1997) and secondarily by encouraging global warming IPCC (2007). Increasing CO_2 and temperature results in more biomass production and restrictive nutrient accessibility to the plants. Ectoenzymes enhance rhizodeposition due to high atmospheric CO_2 (Lagomarsino et al. 2008) so the demand of P for microbes and plants is also increased (Dijkstra et al. 2003). Sweet gum woodland was treated with high CO_2 to observe the effects of high CO_2 on P availability but no impacts were found on the amount of phosphorous after 2 years of its supplementation. Plantation of popular under higher rate of CO_2 does not deplete P from soil but enhances P in the root zone (Khan et al. 2008). Excessive CO_2 cause 8.6 % decline in P accessibility after the fertilization of soil with P during first year but it shows 69 % rise in above ground trunk development (Webber 1990).

15.4.5 Effects of Drought

Availability of P to the plants decreased in the drought. Even a very slight phosphorous scarceness confines the accessibility of phosphorous to the shoots (Turner 1985). Decrease in the mineralization rate of soil is caused by the water stress which results in the reduction of P contents and also causes P accumulation (Sardans and Penuelas 2004). Due to limited presence/supply of water the nutrient availability is also restricted. Decrease in moisture up to 22 % results in 40 % decrease in P uptake by the plants. So the direct impact of low moisture results in the non-availability of P to the plants which will effects the plant growth and consequently there will be a severe effect on the environment (Sardans and Penuelas 2004).

15.5 Conclusion

The present review of P dynamics concluded that it plays an important role in the growth development and all the metabolic processes of the plants thus leaves great impact on the yield of all agronomic crops. Variations in the climatic conditions would result in the limited availability of P to the plants so there is an extreme need of modeling P dynamics under the changing climatic conditions to get optimum yield. The dynamic models like STELLA, APSIM, DSSAT and AEP might be used to understand the P dynamics on farm scale. Since P dynamics was largely driven by short term events like seasons and bio-physiochemical changes therefore, simulation models might be used to understand P dynamics for managerial decisions and policy making. Such decisions and policy making might promote long term environmental, economic and resource sustainability for future generations.

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