
Phosphorus in Forage Production

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Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.70202>

Abstract

The aim in developing this work was to summarize information about phosphorus (P) limitation and dynamic in tropical soils for forage grasses production. The major idea is direct information about limited factors affecting P availability, dynamic of P fractionation, P pools, P forms, P use efficiency, and the 4R's Nutrient Stewardship' for P-fertilizer in forage grasses. Organizing these sub-headings in a chapter can result in interesting of how P behaves under tropical soils, in order to take decision to manage P-fertilizer to accomplish forage grasses production with social, economic, and environmental benefits. As the most limiting nutrient in tropical soils, P-fertilizer in forage grasses can be more effective if the best management practices are followed. In order to avoid excess P-fertilizer application in soil or P-fertilizer response with low efficiency, it is important to understand the P dynamic and the factors associated with P adsorption in soil. Even with low amount of P requested to forages species, the P available in soil is quite low, and this knowledge is primordial to direct P-fertilizer. Tropical soils are quite limited in P content, due to the natural formation with parental material poor in P content and highly weathering condition. Thus, in order to improve phosphorus use efficiency, the 4R's must be followed to improve P use efficiency (PUE). It is not easy to improve PUE in highly weathering soil with high buffering capacity; however, all the combination of best management practices for P-fertilizer application can result in better use efficiency. Based on the scarcity of natural P-sources in the whole world, the use of alternative P-sources should be incentivized, and more researches about this issue are need for better understanding.

Keywords: soil fertility, P-use efficiency, *Brachiaria* spp., *Panicum maximum*, *Stylosanthes* spp.

1. Introduction

The essentiality of phosphorus (P) for plants, grazing animal, and human being is quite evident [1–3]. The matter is the amount of P reservoir lasting to sustain the growing population in earth. Phosphorus reservoir in the world is decreasing, and the consumption of P-fertilizer is increasing worldwide [4], which is a challenge for farmers cropping in tropical regions under highly weathering soil with high P-sorption capacity and low P availability [5].

Phosphorus is considered the major limited factor in forage grasses production followed by nitrogen in tropical climate. Phosphorus availability in tropical soils is quite low due to much factors associated with P pools. Even with the resistance of *Brachiaria* spp. in support of low amount of P content in soil [6], the P constraint can decrease the biomass production and persistence of this genus in grassland. *Brachiaria* spp. are widely cultivated in Brazil, and most part of tropical climate, which support the beef cattle production under low cost for farmers due to the capacity of forage regrowth and permanence in the field even in winter season [7]. The utilization of P-fertilizer is not widely practiced in extensive pastures, resulting in pasture degradation, which can be classified as stocking rate capacity <0.4, 0.4–0.8, and 0.8–1.5 AU ha⁻¹, respectively, highly degraded, moderated degraded, and soft degraded [8]. Brazil has millions of hectares with degraded pastures, resulting in small stocking rate and unsustainable production system.

Brazilian Cerrado is considered one of the last frontiers for agricultural land, and remaining degraded areas with low food production are no longer be allowed due to limitation of agricultural areas in the world and increasing demand for food in a growing population. The integrated crop-livestock system has been taken place of degraded pastures in Brazilian Cerrado, resulting in improvement of stocking rate due to better soil fertility for forages cultivated right after grain crops. In this case, forages are cultivated without expend in P-fertilizer because of residual P from grain crops cultivation is enough. In integrated crop-livestock system, there are possibilities to recover pasture degradation with grain crops and remain the pasture for more than 1 year in the same area; thus, the forage is introduced into a crop rotation system [9]. The benefits of forages grasses for soil physical and chemical properties are very considerable, as the improvement of soil organic matter (SOM), straws on soil surface, soil aggregate stability, including nutrient recycling and other improvement in soil properties [10, 11].

Despite the integration production systems, the most area cultivated with pastures under extensive livestock management are not well supplied with P-fertilizer. The potential to improve biomass production through P-fertilizer is quite evident due to P deficiency in highly weathering soil of tropical climate. The replacement of P extracted by grazing animals is not accomplished as it should be [12]. Phosphorus fertilizer in forages improves its capacity of tillering associated with faster and higher biomass production. The answer of forage depends on species cultivated; the most common species in tropical region are *Brachiaria* spp., *Panicum* spp., and *Stylosanthes* spp., which majority cultivars were developed by Brazilian Agricultural Research Corporation (Embrapa) through its forage breeding program [13].

Phosphorus fertilizer alone cannot recover a pasture degraded, because we must keep in mind that soil compaction, soil pH, and availability of other essential nutrients can affect the phosphorus use efficiency (PUE), and consequently, the P-fertilizer management need to

be well planned based on best management practice. The 4R's (right source, right rate, right place, and right time) nutrient stewardship is a very useful tool for fertilizer management [14], because it takes accounts of the social, environmental, and economic benefits that the fertilizer practice can promote. In order to improve PUE through the application of 4R's nutrient stewardship concepts, it is important to adjust in site-specific location.

In order to improve dry matter production, soil P content must be corrected and maintained for plant nutritional demands. The aim of this chapter is to summarize information about phosphorus (P) limitations, and that it is dynamic in tropical soil for forage grasses.

2. Dynamic of phosphorus in tropical soils

2.1. Phosphorus pool in soils

Most of tropical and subtropical regions have highly weathered soils, resulting in bases leaching and formation of Fe and Al oxides (the term includes oxides, hydroxides, and oxide-hydroxides). Iron and Al oxides contribute to increase positive charges in soil and consequently adsorption of anion, as the case of phosphate (H_2PO_4^- and HPO_4^-) [15]. Phosphorus is in soil under different forms, which were proposed different methods of fractionation usually divided into two pools, organic P (Po) and inorganic P (Pi).

3. Organic phosphorus

The availability of Po is directly related to soil carbon dynamic [16]. Soil organic matter mineralization contributes to 60–80% of the total P available in soil, and this speed of P release rate depends mostly on C/N ratio of straw, thus forage grasses with higher C/N ratio contribute to accumulate straw above and below ground, resulting in increasing SOM. Besides CO_2 sequestration, root decomposition is the majority route of carbon entrance in soil, which is 21.2% of soil carbon, especially in relation to grass that has higher root density associated with higher renew rate of root [17]; thus, forages can contribute to great increment of SOM in soil profile.

Phosphorus organic sources can increase the P content in solution through the mineralization of straws and consequently releasing P in soil solution. On the other hand, temporary immobilization of Pi can occur in soil through the incorporation of Pi in microbial biomass (source of energy), increased by addition of carbon source as forage grass straws with limited concentration of P to offer for microbial population growth. Therefore, to mineralize these straws is necessary initial immobilization of Pi for while related to decreasing of carbon source, resulting in decreasing C/P ration of straws to values close to microbial biomass C/P ratio [15]. Consequently, the Pi in solution tends to increase with the stabilization of C/P in straws and microbial biomass.

Organic P and carbon are quite related to structured soil components (granulometric fractions, mineralogy, aggregate), which are stored in macroaggregate compounds of microaggregates formed by fresh fraction occlude of SOM [16, 18]. However, Po content can decrease

faster in soils from tropical region than temperate regions due to higher rate of SOM mineralization, which are associated with higher temperature and rainfall [19, 20]. In tropical climate under forage grasses, 60% of Po in soil can be converted in P enzymatic against 36% in temperate climate [16].

The soil tillage and use as well as native vegetation can alter the P forms in the soil colloids, majority the organic forms, due to direct relation to soil biological activity. When a forestry is converted to a grassland and grain crops area, there are direct alteration in nutrient cycle. The transformation of Po into Pi is through the phosphatase enzyme. The phosphatase enzymes are excreted by plant roots and microorganisms in soil, as well as the deposition of straws on soil surface that increases the content of SOM [18, 19]. Organic P comprehended more than 50% of the total P in soil in agricultural systems [2], and its content depends on soil tillage and use. The hydrolase of Po and release of orthophosphate by enzymatic activity of phosphatase are affected by many factors, including the nature of Po, capacity of Po to interact with soil matrix, presence of microorganism that facilitated the mineralization, soil mineralogy, and physical–chemical soil properties [21].

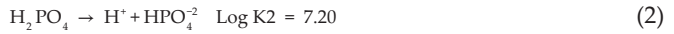
4. Inorganic phosphorus

Phosphorus cycle, differently from C, N and S cycle, involves equilibrium reaction among the organic and inorganic constituents of soil. Besides P be considered the macronutrient less required in quantity by forage grass and other plant species, it is the most limited nutrient by plant growth in tropical climate due to higher P-sorption with Al/Fe oxides colloids in highly weathered soils [22]. The magnitude of P-sorption is related to the type and quantity of adsorption sites on mineral surface. Thus, in soil with Pi deficiency and with great quantity of clay mineral and oxides, the adsorption of Pi is higher, resulting in high rates of P-fertilizer to supply plant requirement [19, 23], which is P-fertilizer the majority source of Pi in highly weathered soil.

Iron and aluminum oxides are considered the majority constituents of clay fractions in the most Brazilian soils cultivated with forages, example the order of Latosols (oxisol) that cover approximately 65% of national territorial, where 50% of this area belongs to Cerrado biome [24, 25], which are explored by livestock and grain crops and are considered the highest world celery [26]. The oxides are the most effective in P-adsorption [27]. Among the oxides, goethite are considered the most effective to bind orthophosphate, consequence of facility to bind in OH⁻ groups in mineral surface in the complex of adsorption in external sphere, beside the crystal morphology and higher surface area in relation to hematite [23].

Gibbsite is the other oxide related to Pi adsorption, however with lower effectivity in relation to goethite. In highly weathered soil, gibbsite has higher amount in clay fraction, and its total capacity of P-adsorption can be above the Fe-oxides [22]. On the other hand, in kaolitic soil, the lower amount of gibbsite can decrease the capacity of orthophosphate adsorption, due to its lower bind sites on mineral surface. In oxisol, the preview liming can decrease Al and Fe content due to precipitation, consequently decreased the adsorption sites. Conversely, excess of liming can increase the Pi associated with Ca (P-Ca), which decreases the Pi availability.

Therefore, the relative proportion of Pi compounds with Fe, Al, and Ca is dependent of soil pH, as well as type and quantity of mineral existent in clay fractions [23]. Thus, the pH also affects the chemical forms of Pi found in soil, following the dissociation of H_3PO_4 [28]:



The majority of soil cultivated in Brazil shows pH range of 3–6 units, the predominant Pi form is the $H_2PO_4^-$, this way, $H_2PO_4^-$ are considered more available to plants due to soil acidity [29]. The HPO_4^{2-} is less available in soil due to its higher capacity to bind with Fe and Al than $H_2PO_4^-$, thus increasing in soil pH above 7 decrease the availability of P in soil, besides the P-Ca precipitation. In pasture managed, P-fertilizer periodic and adequate stocking rates can increase the available Pi in soil (from 7 to 18 mg dm^{-3}) in 0–10 cm depth, consequently increasing in forage yield (from 3 to 7.4 Mg ha^{-1}) [20].

The soil class is the factor that has more impact on Pi forms, while the conditions of use and soil tillage control the content of total Po, as the Po in microbial biomass and activity of phosphatases, which means that there are mineralization/immobilization of P from organic compounds and solubilization/precipitation of inorganic phosphates [19, 20]. The actual knowledge about organic and inorganic P in soil restricts our capacity of developing management strategy to promote the use of more efficient P-fertilizer in crop production. However, in forage grass periodically managed, there is improvement in physical quality, by establishment of soil structure and chemical through different sources of Po, resulting in affect the biological activity and enzymatic response by bio-availability of P, occasioning in stimulation of specific mechanism of mobilization of labile P, returning the recalcitrant P back to the cycle [21].

4.1. Microbial activity in phosphorus dynamics

Phosphorus dynamics in soil are associated with environmental factors that control the microbial activity, which immobilize and release orthophosphate ions and the physical–chemical properties and soil mineralogy [30]. Mineral (Pi) and organic P (Po) forms are the majority pools in soil, since in oxisol, there is predominance of Pi bonded with high energy in inorganic fractions, and Po forms show stabilized forms, physically and chemically. According to the energy of binding, the Pi can be classified as labile and nonlabile. In this context, the labile fraction is shown by group of phosphate compounds capable to replace the soil solution, when orthophosphate Pi are uptake by plants and soil microorganisms [31].

Thus, the microorganisms show important rule in immobilization and availability of Po, especially in the function of enzymatic excretion that acts in this process. Phosphatases represent a wide group of enzyme that catalase the hydrolase ester and anhydrous of phosphoric acid, as well as showing positive and significant correlation with microbial biomass carbon (C-MBC)

and P_o of the soil microbial biomass (P-SMB) [32]. Phosphatases can be excreted by microorganisms or root of higher plants [33]. The intensity of excretion by roots and microorganism is determined by your orthophosphate demand that is affected by soil pH. Soil enzymatic activity and biochemical reactions can be a sensitive indicator of soil quality and stressed conditions in soil promoted by soil tillage [33].

The soil tillage and use can modify the activity of enzymes in soil and consequently the availability of P_i in soil. The pH increasing in soil due to liming broadcasting can stimulate the activity and diversity of microorganism population, resulting in increasing the enzymatic activity and consequently affect the nutrient cycle. Except the acid phosphatase, many enzymes have your enzymatic activity favored by pH increasing [33]. The transformations of P in soil are majority guide by microorganisms associated by a combination of factors including the plant species, type of soil, and environment [34]. The exudation of different plant species results in stimulation of different microbial species in rhizosphere via root exudation, which include sugars, aminoacids, organic acids, hormones, and vitamins [34].

In terrestrial ecosystems, the root exudation represents 40% of organic compounds [35]. The amount of enzyme exudates depends on difference in carbon metabolism among plant species under different growth stage [32]. Plant species and growth stage determine the effect of microbial activity and C-SMB, as well as the mineralization of the nutrients in dry matter composition. It is important to know that P_o associate with soil microorganism is a source of P labile for plant uptakes after mineralization.

Under conservationist system, the effects of plants on P availability (P-labile) differ among the species of crop rotation, thus with the increasing of root exudation and microbial activity in rhizosphere, there are higher levels of soluble carbon, which contribute to increase the microbial activity and biomass, resulting in increasing of utilization and solubilization of P_o and P_i [32].

The mineralization of P_o through soil microbial depends on carbon availability in soil. It has already observed lower amount of C-SMB in soil with low fertility and that the P_o mineralization is limited in soil with low amount of carbon [36]. Nevertheless, in soil with low P_i content was not observed inhibition of C-SMB growth, but P_i content in soil affects the amount of immobilization by microbial biomass [37].

Under restrictions of P_i content in soil, the activity of phosphatase increases, resulting in higher mineralization of P_o [38]. Besides the plant species and amount of available carbon, the quantity of immobilization and mineralization is dependent of microbial composition in soil [36]. The microorganism uses organic compounds phosphorylates as carbon source, resulting P_o mineralization. The procedure can increase P_i content by plants in locations where P is limited [36]. In conditions where P_i is supplied through P-fertilizer in enough amounts for plant and microorganism requirement, the P_o mineralization decrease due to phosphatase inhibition [38]. On the other hand, in conditions where P_i is not enough in soil, the activity of phosphatase increases. This fact is associated with the capacity of plant and soil microorganism having responded to alteration in environment for acquisition limited nutrient in soil, as the case of plants and microorganisms that increase phosphatase synthetize in constraint content of P_i in soil [39]. In the study accomplished by [38], decrease in microbial biomass in function

of Pi increment in soil was not observed; however, the reduction of 10% in mycorrhizae fungi was observed. These results were sustained by decreasing in carbon by microorganism under condition of enough Pi in soil, so the occurrence of mycorrhizae fungi decreases.

4.2. Phosphorus forms in soil

The total content of P in soil is distributed under different degrees of lability. Its lability, which are established through the linking energy with colloids, defined the labile forms, moderated labile, and no labile [40], define this distribution of P in soil. In each P form, the content of P is variable in function of soil type, tillage, cultivation, climate, and content of organic matter. The classification of P forms in soil according to lability is such arbitrary because depending on the P uptake rate by plants, the P forms are defined as labile or no-labile [41]. The division of P forms in soil is necessary to understand that there are pools of P in soil with higher or lower capacity to supply soil solution [42].

In soils under natural environments, the content of P in soil depends on primary material, which affects many physical–chemical soil properties due the difference in textural features, chemical composition, and mineralogy fractions of soil. In highly weathering soil and natural environment, the Po compile in important fraction of total P, most of labile P, which are converted in Pi through organic matter mineralization. However, under cropping system with P-fertilizer, there are accumulation of Pi and Po with different degrees of bonding energy, though the accumulation is more pronounced in Pi forms [43].

Changes in P forms distribution in soil can also be associated to system of soil tillage, P exported by harvesting, rates of P-fertilizer reposition, P-source applied, and ability of plants in using P reserves in less labile fractions [44]. In general, under tropical soils, there is predominance of Pi forms than Po [45–47]. Organic P shows great importance because its majority part is labile and moderate labile P fraction, which acts in supply soil solution with Pi when its concentration decreases through plant uptakes and microorganism immobilization [45, 48]. Phosphorus immobilized in microbial biomass constitutes a potential reserve of P able to supply forages in absence of P-fertilizer.

5. Phosphorus labile

In the Pi labile fraction, the P is bonding with less strength to soil colloids through monocoordinated linked, what allows desorption of nutrients to soil solution when Pi content decreases soil solution. The Po labile is the proportion of Po associated with the organic materials of easy mineralization. Thus, P labile is the amount in balance with soil solution and represents the group of compounds capable to supply soil solution content that is available for plant uptakes, which are dependent of weathering degree, soil mineralogy, granulometry, SOM, physical-chemical properties, biologic activity, and predominant vegetation [49]. In soil with low P-labile content, the majority strategy to increase P content is through P-fertilizer, by organic or inorganic forms.

6. Phosphorus moderated labile

The moderated labile P forms are represented by P linked to chemical sorption to Fe and Al oxides and clay. These mineral are presented in soil and because its capacity in form complex with high energy, the sorption is slow and can occur in medium to long term. Inorganic P forms are physically protected in inner surface of soil aggregate and linked to Ca (parent material) and are considered P moderated labile [49], besides Po in the SOM stable.

7. Phosphorus no labile

Phosphorus no labile (recalcitrant) is the P linked with higher energy in soil and is strongly adsorbed or precipitate in insoluble compounds [20, 50]. The no-labile Po fractions are associated to humic compounds and physically protected inner of microaggregates. The no-labile P forms are represented to organic and inorganic recalcitrant compounds, which orthophosphate linked energy is through two coordinate links, this double link does not allow immediate desorption of P. In order to optimize P-fertilizer as growth factor for plants, the no-labile P must be quantified, understanding and controlled majority for highly weathering soil. The properties and mineral constituents of clay fractions are responsible by speed of transformation of labile-P through no labile-P [51].

8. Determination of P forms

In order to better understanding of P dynamic in soil, the knowledge of different P fractions in soil is prerequisite, which can be accomplished through sequential extraction by different extractors [52]. Thus, with the determination of P fractions, it is possible to have valuable information about P availability in soil. The relation of P forms in soil and its distribution is a relevant question, and the use of chemical fractionation technic that determine the quantity and distribution of P forms in soil is valuable in the understanding of P dynamic under different agroecosystems. There are many schemes of soil P fractionation, which were combined by [53] in the following classes: fractionation to Pi forms, fractionation to Po forms, fractionation to Pi and Po, and fractionation to Pi, Po, and P microbial.

Many authors have been using the fraction proposed by Hedley [44, 54–56]. Hedley's fractionation is widely used [57], majority in researches about P dynamic and cycling in soil associated with primary material, soil tillage, and use into diverse crop systems. Hedley's fractionation allows the determination of Pi and Po in soil based on chemical extractors with increasing capacity of P extraction; however, Hedley's fractionation only cannot explain the P forms in soil. Thus, the work of Cross and Schlesinger [49] correlated the P forms in soil with the Hedley's fractionation, resulting in separation of the labile P from the no-labile P forms, which shows the possibility of identifying the preferential forms that P are retained in soil.

Assume that the quantification of P forms in soil can be accomplished through labile P, which are composed by the sum of P extracted by anionic exchange resin and fractions of Po and Pi

extracted with NaHCO_3 . The moderated labile P fractions are composed by Pi and Po fractions linked with higher energy to Fe and Al, which correspond to P extracted with NaOH (0.1 and 0.5 mol L⁻¹). The no-labile P fractions are composed by fraction extracted with HCl (P fraction linked to Ca with constraint availability) plus residual P (Po and Pi fractions insoluble) [51].

Phosphorus forms and degrees of lability in soil change with the soil properties. In new soils and with lower degrees of weathering, Ca phosphates are the major supplier of P to life organisms. Conversely, in highly weathering soil, the bio-cycling of organic phosphates has great importance in maintenance of bioavailability, throughout it is not enough for maximal economic yield of commercial crops [31]. Phosphorus dynamic in natural ecosystems and managed are established majority by interactions of nutrients with the Pi and Po pools and with soil microorganism. Thus, researches about P dynamic and availability require separation and identification of different P fractions in soil. The technic of P fractionation aims to identify the preferential fractions, which P are linked in soil, and your occurrence and magnitude that the fractions have to supply plant P requirement. Thus, studying the P fractions is essential because of the great difference between many types of soil and crop systems, much more about the practices of liming and fertilizer application technics, which alter the P dynamic in soil [42].

8.1. Phosphorus use efficiency

The low availability of phosphorus (P) in Brazilian soils requires the application of this nutrient in grain, fiber, wood, horticulture systems, and forages, mainly via soluble inorganic fertilizers. However, the imminent depletion of phosphate rock reserves in the next century [58], and the use of P rates greater than the ability of the soil to retain can make it polluting in water, make the use of phosphate fertilizers to be minimized and used more efficiently. The low availability of P is one of the most restrictive factors for livestock, since the forage plants can be very demanding in P, due to a higher production of biomass, consequent to the greater extraction and export of this nutrient [12].

The nutritional adjustment in crops depends, beyond the technology level used, on the ability to uptake and P use by plants, characteristic that is related to morphophysiological parameters of genetic orientation specific of each cultivar, and expressed in function of environmental conditions in the cultivation area. Evaluating biomass production and agronomic efficiency as function of phosphorus supply in different genotypes of *Brachiaria brizantha*, [59] observed that the Arapoty variety and the B5 genotype showed greater efficiency in the use of P, because it produced more shoot biomass per unit of applied P, being able to indicate for breeding programs of this species, while the Capiporã variety and the B12 genotype were less efficient.

According to [60], efficient plants in phosphorus use have genes that confer adaptive mechanisms to contour low availability of nutrients in the environment, among them modifications in architecture and growth of the root, increase in phosphatase production, and change in the activity of several enzymes in glycolytic route. Nevertheless, in presence of appropriate nutritional P levels, these genes may not express themselves, resulting in a lower plant response to the environmental improvement. Thus, differences between genotype plants in relation to efficiency in the use of this nutrient can be assigned to the fact that the absorption of the phosphorus present in the soil solution occurs via root interception, so that plants of bigger root system present advantages in its capture [61].

Some plants have different abilities to remove and absorb nutrients from the soil, mainly by processes occurring in the rhizosphere. For P, they use different mechanisms to access the less labile soil P forms and favor the cycling of P in the system as: increase in root/shoot ratio, root surface or increase in absorption rate per root unit [62]; increase in the number, shape, and thickness of the root hairs [63]; root phosphatases exudation [64] or organic compounds capable of complex metals phosphate associated [65]; by mycorrhizal association in which the fungal hyphae extend the root area [66] or with other microorganisms capable of favoring the cleavage or breaking of organic compounds with the consequent release of the phosphate anion [62, 67].

The detection and possible exploration and use of genotypic plant differences for P efficiency is one of the viable strategies to reduce the problem of P deficiency in tropical and subtropical regions, as a consequence of the naturally low P levels and the high capacity of fixation in soils. The development of plant genotypes adapted to the adverse conditions of soil fertility, notably to phosphorus deficiency, the introduction of selected material to certain environments are interesting aspects from the point of view of the efficiency in the P-fertilizer use and the sustainability of the productive system.

Together, the cycling of P by the plants is also important, because these have different degrees of adaptation to access the soil P. There are plant genotypes that take advantage of inorganic phosphorus (Pi) by their roots or associations with mycorrhizal and those that use organic phosphorus (Po) by specialized enzymatic mechanisms, for each type of phosphate esters, which are used as nutrient sources [68]. As these mechanisms vary with plant species, in order to optimize soil P use by plants in agricultural systems, it is essential to identify those with the greatest potential to absorb and cyclize soil P, especially those that can be used commercially.

The interaction between fungus and plant varies according to the genotype, since they have affinity for root systems with characteristics that favor mycorrhizal symbiosis, like higher exudation of lipids, carbohydrates, and carbon compounds. These studies shown that low doses of P increase mycorrhization and efficiency of mycorrhizal fungi in promoting dry matter increase; however, high doses of this nutrient affect negatively the mycorrhization [69]. Evidence suggests that this is caused by a reduced reliance of plants on arbuscular mycorrhizal fungi for phosphorus, which is concomitantly dependent on N availability such that a reduced N:P ratio can suppress arbuscular mycorrhizal fungi [70]. The efficient cultivars in phosphorus use can be related to higher levels of mycorrhizal interaction and consequent increase in nutrient absorption.

According to [71], for managing grazing systems for improved P-use, efficiency should be to avoid over-application of P ('P equilibrium fertilization' practices in which P input in manure and fertilizer does not exceed P output in products); use pastures that are productive at lower plant available P concentrations; legume-based pasture systems; and plant traits that address P-balance efficiency (more root foraging, favorable root architecture, high specific root length, long root hairs, root adaptation to P stress, and high root growth rates) [71].

For pastures that are productive at lower plant-available P concentrations; legume-based pasture system, the key legume species in these systems (e.g., subterranean clover (*Trifolium subterraneum* L.) and white clover (*Trifolium repens* L.) often have coarse roots and short root

hairs and have higher critical P requirements than the forage grasses with which they are grown. The pasture is fertilized to meet the higher P requirements of the legume, because legume N-fixation drives overall productivity. It will be necessary to find legumes with lower critical P requirements to improve the P-balance efficiency of these pasture systems. Temperate pastures differ from some mixed pastures grown on infertile acid soils of the tropics (e.g., *Stylosanthes capitata* Vogel, *Zornia latifolia* Sm.–*Brachiaria decumbens* Stapf., and *Andropogon gayanus* Kunth grasslands of Central America).

9. The 4R's nutrient stewardship' for P-fertilizer in forage grasses

The concept of best management practices (BMPs) for fertilizer application is universal used for grain crops, following the 4R's nutrient stewardship (right source, right rate, right place, and right time) [14] (**Figure 1**). All the BMPs that follow the 4R's nutrient stewardship must be associated with environmental, social, and economic benefits (**Figure 1**). Despite the chapter being focused on P-fertilizer, all fertilizers must follow these concepts in order to improve sustainable agriculture. First, this concept of 4R's nutrient stewardship was introduced by [14], which was followed and applied worldwide with great acceptance in many

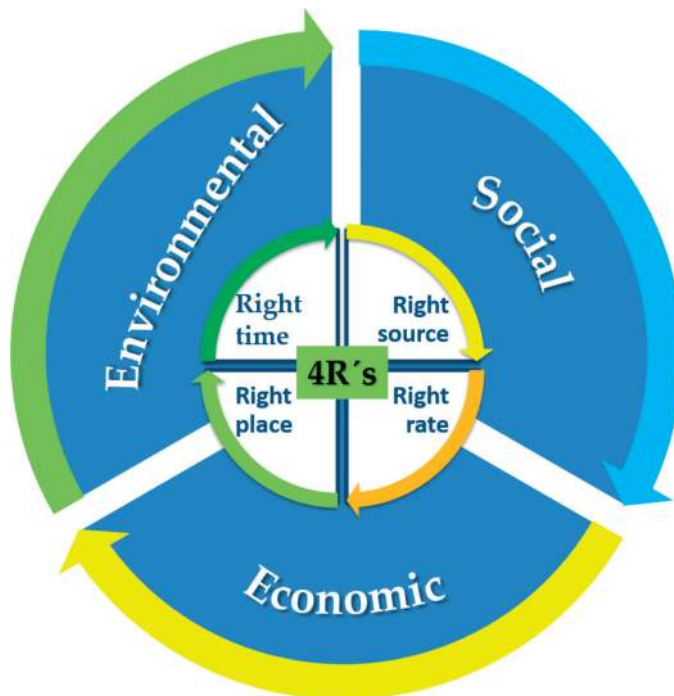


Figure 1. The 4R's nutrient stewardship for P-fertilizer on pastures. Adapted from Kochian [5] and elaborate by the authors.

crops. The application of 4R's in forages can be in advantage in BMPs in tropical region, due to many wrong practices applied in grassland related to nutrients management. The natural P-fertilizer sources are finite, which justify its use carefully to improve its efficiency. Forage grasses (*Brachiaria* spp.) are recognized to be very efficient in P use efficiency [5], nevertheless in tropical region, P availability in soil is very restricted.

9.1. Right source

The most P-sources used in forage grasses are soluble P-sources (**Table 1**), and less is related to reactive natural phosphate (RNP), even with such researches showing the incorporation of RNP can result in approximated efficiency than soluble sources as triple phosphate [72]. Even with low solubility, maybe in sand soil, it is possible to improve the uptake of forage through the use of RNP in pasture because of minor adsorption site than in clay soil. Due to RNP be slow release P-source, the capacity of P-sorption may overcome the release, resulting in P deficiency for plants [50].

Even with the recommendation for RNP application be in soil with low pH (more acid), in some cases with $\text{pH}_{\text{CaCl}} = 6.0$ was possible to observe increasing of forage volume in 25% for *Panicum maximum* cv. Massai [73]. In the case of *Brachiaria decumbens*, application of RNF promoted 30% of dry matter production with RNF was applied [72]. Therefore, it is important to remember that acidity in rhizosphere is higher than surround soil [15], which can contribute to improve RNF solubility and plant uptake. The evidence of possible use of RNF in pasture as P-source is quite clean, but their use in pastures is not yet widely applied. Reactive natural phosphate can be an alternative to decrease the use of P-source more soluble used in pastures nowadays, which are in jeopardy due to limited P-source in the world (**Table 1**).

P-fertilizer source	Minimum guarantee*	
	Nutrient content and form	Nutrient solubility
Simple superphosphate	18% of P_2O_5 , 19% of Ca, 11% of S	Total content of P_2O_5 content soluble in ammonium neutral citrate plus water and minimum of 16% soluble in water. Total content of Ca and S.
Triple superphosphate	48% of P_2O_5 10% of Ca	Total content of P_2O_5 content soluble in ammonium neutral citrate plus water and minimum of 36% soluble in water. Total content of Ca.
Diammonium phosphate (DAP)	17% of N 45% of P_2O_5	Total content of N and P_2O_5 content soluble in ammonium neutral citrate plus water and minimum of 44% soluble in water.
Monoammonium phosphate	9% of N 48% of P_2O_5	Total content of P_2O_5 content soluble in ammonium neutral citrate plus water and minimum of 44% soluble in water.
Reactive natural phosphate	27% of P_2O_5 28% of Ca	Phosphorus determined as P_2O_5 total and minimum of 30% of the total soluble in citric acid at 2% in relation 1:100.

*Source: Adapted from Ministry of Agriculture, Livestock and Food Supply (MAPA) [75].

Table 1. Major P-sources used in forages, specification of the simple solid sources of P with minimum nutrient content guarantee by law.

Application of P-fertilizer sources with higher solubility can improve biomass production of pasture, however in soil highly weathering the precipitation of P-Fe and P-Al can result in no-labile P forms and consequent decrease of P-fertilizer use efficiency. Thus, application of P-source can be wisely decided to improve phosphorus use efficiency (PUE) and decrease P-sorption in soil.

The use of monoammonium phosphate (MAP) as P-sources in pasture can result in lower PUE in comparison to simple superphosphate. Monoammonium phosphate is more soluble and its use in pasture as P-source can result in faster P-sorption in highly weathering soils with higher buffering capacity. Then, most of P-fertilizer applied is going to be fixed in soil through time and PUE tends to decrease. The price of P-source normally determines its use for farmers, but the P-source must be decided directing to more efficient P-source that long lasting are going to obtain financial returns associated with absence of environmental negative impact. However, higher soluble P-sources tend to increase the dry matter production in short term, as the case of triple superphosphate in comparison to RNP in *B. decumbens* and *B. brizantha* [74].

9.2. Right rate

In order to define the P-fertilizer rate in pasture, it is necessary to know the plant requirement, because the genotypes show different demands for P acquisition. The genotypes *Panicum maximum* is very demanded for P, followed by *Brachiaria brizantha*, *Brachiaria ruziziensis*, *Brachiaria decumbens*, *Brachiaria humidicola*, and *Stylosanthes* spp. (Table 2). The degree of P-requirement for pastures species and soil P content determines the P-fertilizer rates to be applied. The difference in forage species in P-requirement is so evident that it is crucial to separate the species by the groups of P requirement (Table 2). In Table 2, the degree of P requirement for forages species which is very used in Cerrado region to direct P-fertilizer rates recommendations, which was developed by [76] are shown.

Forages species	Degree of P requirement
<i>Stylosanthes</i> spp.	Low
<i>Andropogon gayanus</i> cv. Planaltina	Low
<i>Brachiaria decumbens</i>	Low
<i>Brachiaria ruziziensis</i>	Low
<i>Brachiaria humidicola</i>	Low
<i>Paspalum atratum</i> cv. Pojuca	Low
<i>Brachiaria brizantha</i> cv. Marandu, Xaraés, Piatã, Ypiporã	Medium
<i>Panicum maximum</i> cv. Massai	Medium
<i>Panicum maximum</i> cv. Mombaça, Tanzânia, Aruana, Tobiãtã	High

Source: Adapted from Martha et al. [76].

Table 2. Degrees of P requirement for some forages species.

The quantification of Pi availability in soil is the first step to define the right rate of P-fertilizer. As reported previously, tropical region is composed by poor soil with constraints in P availability for plant growth. In the most Brazilian soils, the absence of P-fertilizer avoids plant normal development and economic yield.

The amount of P-fertilizer is very dependable of soil clay content, thus in sand, soil P-fertilizer rate must be lower than clayed soil due to less buffering capacity. In order to recommend P-fertilizer rates, the P extractor plays an important role in this definition. If the extractor is Mehlich-1, the clay content in soil must be determined to interpret the P content availability in association with degree of P requirement by forage species (**Tables 2 and 3**). With the increase in clay content, the amount of available P decreases, result of higher buffering capacity of P, than the amount of P-fertilizer is higher in clay soil than in sandy soil. When P-resin is used, the extractor has no significant dependence to clay content [51], thus quantification of clay is not necessary to define the P level.

The amount of P-fertilizer to achieve inadequate P content can be easily determined by the following formula: P-fertilizer rate (kg ha^{-1}) = [(P expected content–P available in soil) \times P buffering capacity] [76].

9.3. Right place

First of all, it is quite important to define the moment of P-fertilizer in forages; (1) forage implementation and consequently P-fertilizer correction for establishment, and (2) forage maintenance that is recommended to remain the adequate P level in soil. The implementation of forage can be conducted under no-till and tillage system, which change completely the P-fertilizer placement. Usually, in tillage soil the P-fertilizer in broadcasting and incorporate with arrow disc into 20 cm depth. This procedure is essential to improve the forage root

Interpretation of P content in soil (mg dm^{-3})—Method of Mehlich-1			P buffering capacity		
Clay content (%)	Degree of P requirement			Mehlich-1 ($\text{kg P}_2\text{O}_5 \text{ ha}^{-1}$)/(mg dm^{-3} of P)	Resin
	Low	Medium	High		
≤ 15	>9.0	>11.0	>14.0	5	6
16–35	>7.0	>9.0	>12.0	9	9
36–60	>4.0	>5.0	>6.0	30	14
>60	>2.0	>2.5	>3.0	70	19

Interpretation of P content in soil (mg dm^{-3})—Method of anionic exchange resin extractor (P-resin)		
Degree of P requirement		
Low	Medium	High
>7.0	>9.0	>12.0

Source: Adapted from Martha et al. [76].

Table 3. Phosphorus content in soil interpretation through critical levels of adequate P content in 0–20 cm depth by Mehlich-1 and resin methods, based on soil P adequate content and plant requirement for pasture establishment.

acquisition for P, which should be consider due to slow mobility of P in soil that is almost all by diffusion [2]. However, in soil with high P-sorption to incorporate P-fertilizer in soil can decrease its availability.

In integrated crop-livestock system, the no-till system P-fertilizer tends to be applied deeper in soil (10–20 cm) in the grain crop production instead of application directly for forage; however, in integrated crop-livestock system, the content of P in soil usually are above 5 mg dm^{-3} , which is considered enough for *Brachiaria* spp. requirements. It happened because soybean or corn has higher P requirement than forages, thus the residual P-fertilizer in soil is enough for forage growth.

The maintainance of P content through time under stablished pasture is usually proceeded broadcasting P-sources on soil surface without deep incorporation, this procedure has shown quite efficient to remain forage in adequate growth for decades.

9.4. Right time

The right time of nutrient application is related to the nutrient uptake pattern; in case of P, forage demand higher amount of P in establishment and vegetative growth. Then, correction of P content in soil before sowing is decisive to obtain faster initial growth, and remaining P content in soil will maintain the biomass production. Pasture implementation and maintenance are the two moments for P-fertilizer application. During maintenance, it is quite fundamental to remain the P content above the critical limit for each forage species nutritional demand (**Table 3**).

Phosphorus fertilizer to correct the P levels in soil is usually done in forage implementation and its content are maintained through vegetative growth. The recommendation to improve PUE is the application of P-source after soil acidity correction, especially in highly weathering soil.

Rain after broadcasting P-fertilizer in forages can cause surface runoff and soil erosion, which must be taken into consideration to decide the right time to apply P-fertilizer. Phosphorus has low mobility in soil, results in high concentration in soil surface [15], when P-fertilizer are broadcasting on soil surface in forage grasses.

10. Soil nutrient interactions with phosphorus

Principal component analyses (PCA) were performed to illustrate the relationship between P available in soil with some chemical and physical soil properties (**Figure 2**). Most of the variables were attributed to two principal components (PCs). The most PCs loadings were significant based on selection criterion defined by [77]. The two first PCs combined explained 53.35% of the whole variability in database. The first PC was positively correlated to base saturation (BS), exchangeable Ca + Mg, Ca saturation, exchangeable Ca, exchangeable Mg, Mg saturation, $\text{pH}_{-\text{CaCl}}$, $\text{pH}_{-\text{H}_2\text{O}}$, exchangeable K, S, $\text{P}_{-\text{Mehlich}}$, Ca/Mg, clay, organic matter, $\text{P}_{-\text{resin}}$ and negatively correlated to H + Al saturation, exchangeable H + Al, sand, Fe, Al, Al saturation (**Figure 2**). The second PC was positively correlated to exchangeable K, sand, exchangeable Mn, K saturation, exchangeable Fe, and negatively correlate to clay, Ca/K (**Figure 2**).

The structures obtained by PC-1 and PC-2 are supported by some rules relative to interaction between nutrients in soil, but other structures should be studied carefully for a better understanding (**Figure 2**). The opposite direction between $P_{-Mehlich}$ and P_{-resin} with exchangeable Al is clean evidence of the antagonism between these elements in soil, as exposed before, the soluble Al in soil can precipitate P (P-Al), which results in less P available in soil for plant uptake, consequently, lower exchangeable Al in soil to increase P availability.

Phosphorus-Ca, P-Fe, and P-Al are forms of P precipitation, and its solubility is associated with soil pH. The soil acidity correction is a practice to improve PUE, resulting in more P available due to Al precipitation before P-fertilizer application in 0–20 cm depth when liming is incorporate. Liming application is quite useful in soil with high amount of Al and with pH below 4.7 units. The increasing in soil pH above 4.7 can decrease soluble Al in zero (**Figure 3**). Nevertheless, for a better PUE, it is important to have no limitation in other nutrients availability in soil, as the case of N, S, K, and other essential nutrients. The soil compaction in clayed soil with animal trampling is a problem that can decrease the PUE due to impossibility of root P acquisition. As observed in **Figure 3**, exchangeable Ca + Mg were in opposite direction in first PC with Al, Al saturation, and exchangeable H + Al, which is possible to infer that the increasing in exchangeable Ca + Mg in soil are associated with liming, and consequently, its application tends to decrease soil acidity above pH = 4.7 units and Al saturation are totally precipitated in

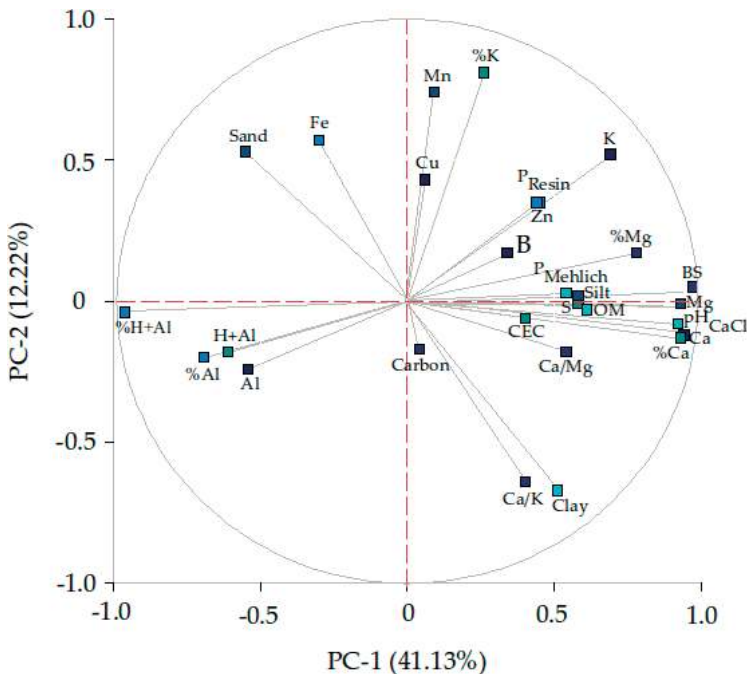


Figure 2. Monoplot of principal component analysis (PCA) for some physical and chemical soil properties under pastures in Cerrado West region of Bahia State, Brazil. PC—principal component; PC-1—the first principal component; PC-2—the second principal component; exchangeable Ca, Mg, K, Fe, Mn, Al and Zn.

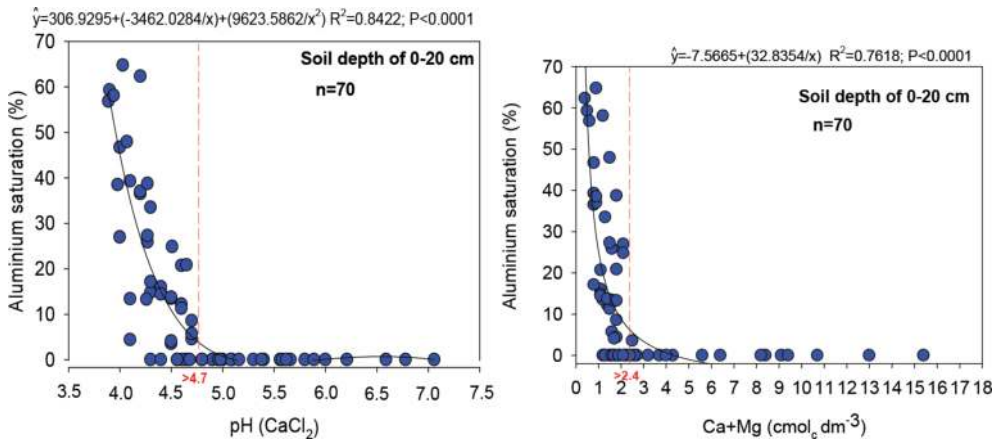


Figure 3. Relation between soil pH and Al saturation from soil samples collected in oxisol from 0 to 20 cm depth. Source: Authors, data not published previously.

hydroxides (Figure 2). Conversely, the decreasing in Al soluble results in less site to fix orthophosphate in soil and tends to increase its availability; however, it is quite important to mention that overrate of liming can result in Ca-P precipitation and decrease P availability as well.

For Phosphorus labile and P no-labile, it is quite important to observe that over time, 1 year after P-fertilizer, 79–95% is turned into no-labile P [51]. Thus, the P-fertilizer must be well observed in order to avoid decreasing in PUE. Soil organic matter is a way to improve P availability from P no-labile fractions. Thus, increasing SOM can be in alternative to improve PUE in tropical soils. The importance of using P-resin extractor instead of Mehlich-1 in soil with historic of P-fertilizer applied with reactive natural phosphate (RNP) is because the effect in acid extractor as Mehlich-1 in solubilize the P linked to Ca in RNP, resulting in overestimation of P content in soil [51].

It is not easy to improve PUE in soil with high P-sorption capacity. Most of Brazilian soils are located in region with very high P buffering capacity, resulting in low P availability [5]. The ability of forages as *Brachiaria* spp. to yield well with lower extractable soil P content is primarily associated with morphological traits such as long fine roots and long root hairs that enable foraging for available P and its uptake from soil solution. Together, these traits confer a large root hair cylinder volume (RHCV) which is strongly correlated with P uptake [78]. Physiological root traits, such as exudation of carboxylates (low-molecular-weight organic anions) and phosphatases into the rhizosphere, can potentially enable plants to these sources of soil P [71].

11. Concluding remarks

Tropical soils are quite limited in P content, due to the natural formation with parent material poor in P content and weathering. Thus, in order to improve phosphorus use efficiency, 4R's must be followed and adjust in site-specific conditions. Improving PUE in highly weathering

soil with high buffering capacity is a challenge; however, all the combination of best management practices for P-fertilizer application can result in better use efficiency. Based on the scarcity of natural P sources in the whole world, the use of alternative P-sources should be incentivized, and more researches about this issue are needed for better understanding in forages.

The propose to direct the knowledge in P dynamic with the best management practices can be a useful tool to improve P-fertilizer efficiency in forages in tropical soil highly weathered. The recognition and potential examination and use of genotypic forages plants with higher P use efficiency is a sustainable approach to aim the problem in tropical soil with higher P-sorption capacity. The development of plant genotypes adapted to the adverse conditions of soil fertility, notably to phosphorus deficiency, the introduction of selected material to certain environments are interesting aspects from the point of view of the efficiency in the P-fertilizer use and the sustainability of the productive system.

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