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Impact of nutritional disorders of nitrogen and phosphorus in Poaceae and future prospects: a review

Impacto de desordens nutricionais de nitrogênio e de fósforo em poáceas e perspectivas futuras: uma revisão

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Abstract

Nitrogen (N) and phosphorus (P) deficiencies limit the productivity of crops the most, including of Poaceae, which have a C4 photosynthetic system and a high capacity for biomass accumulation in tropical regions, with a high requirement for these nutrients. The excess P and N (especially in the ammoniacal form) can cause nutritional disorders predominantly in very intensive cultivation systems. However, studies on the subject are scarce. The aim of this review is to address the occurrence and effects of deficiency of and excess N and P in Poaceae and its relationship with soil acidity. The main impacts of these nutritional disorders on the physiology and production of these plants were discussed. Possible alternatives to attenuate the nutritional imbalances of N and P in grasses are presented.

Additional keywords: soil acidity; nutritional stress; silicon in grasses; Poaceae.

Resumo

As deficiências de nitrogênio (N) e de fósforo (P) são as que mais limitam a produtividade dos cultivos incluindo as poáceas, que apresentam sistema fotossintético C4, alta capacidade de acúmulo de biomassa em regiões tropicais e alta exigência destes nutrientes. No entanto, o excesso de P e de N (especialmente na forma amoniacal) pode provocar desordens nutricionais, principalmente em sistemas de cultivo muito intensivos, mas os estudos sobre o tema são limitados. O objetivo dessa revisão é abordar a ocorrência e os efeitos da deficiência e do excesso de N e de P em poáceas, e sua relação com a acidez do solo. Foram discutidos os principais impactos dessas desordens nutricionais na fisiologia e na produção dessas plantas, e apresentadas possíveis alternativas para atenuar os desequilíbrios nutricionais de N e de P em poáceas, como a fertilização com silício.

Palavras-chave: acidez do solo; estresse nutricional; silício em gramíneas; Poaceae.

Introduction

Adequate mineral nutrition promotes the growth and production of cultivated plants (Marschner, 1995). However, if there is a deficiency of or excess nutrients in the plant, the metabolic functions become compromised, resulting in lower growth and visual symptoms characteristic of each nutrient (Malavolta et al., 1997; Prado, 2021). Symptoms may vary according to species. The nutritional deficiency that predominates in tropical regions occurs when nutritional requirements are not met.

The Poaceae family comprises species known as grasses. They are among the main species cultivated in tropical regions, such as corn (Mattos & Silveira, 2018), sugarcane (Soltangheisi et al., 2019) and forage plants (Rojas-Downing et al., 2017; Martins, 2021). However, low levels of N and P available in the soil limit biomass production (Touhami et al., 2022). Limiting levels of N are related to a low content of soil organic matter (SOM) and a high rate of N loss from nitrogen fertilizers by leaching or volatilization (Minato et al., 2020; Pereira et al., 2022).

Available P contents are low in tropical soils because of a parent material with a low P content. Also, this nutrient can have a high specific adsorption to the surface of colloids in the clay fraction (Lemos & Prado, 2017). However, aiming a high productivity in intensive production areas, often without adequate monitoring through soil and leaf analysis, high doses of conventional and organic fertilizers are used continuously, generating excessive accumulation of N and P in the soil (Lu & Tian, 2017; Omara et al., 2019). Such excess N and P causes a decrease in productivity and the environmental contamination of the water table or rivers, lowering the sustainability level of crops (Walton et al., 2020).

This review aims to explain the importance and the effects of nutritional disorders arising from deficiency and the relationship with soil acidity. It also aims to discuss the importance of excess nitrogen and phosphorus in the cultivation of some species of grasses such as rice, sugarcane, fodder, sorghum, and wheat. In addition, some perspectives regarding future research are addressed seeking to understand and mitigate these nutritional disorders.

Soil acidity and nutrient availability

In the cultivation of crops, liming is fundamental to increase the availability of nutrients and consequently the absorption of these nutrients by plants. Liming is necessary when there is a high acidity in the soil together with a low availability of nutrients, which compromises the productivity of crops. Soil acidification is a natural process resulting from a base poverty of the parent material and/or weathering processes that lead to a loss of soil cations such as calcium, magnesium, and potassium. However, this acidification may accelerate while cultivating the soil, as soil bases are removed by the harvested product as well. Furthermore, the decomposition of SOM and the addition of nitrogen fertilizers also contribute to soil acidification (Natale et al., 2012).

The main direct effects of soil acidity are low base saturation and aluminum (Al^{3+}) toxicity. Base saturation is a percentage of soil surface charges at the solid phase that are occupied by basic cations (Ca^{2+}, Mg^{2+}, and K^+), which are plant nutrients. In acid soils, most charges are occupied by acid cations (H+ and Al^{3+}). Therefore, nutrients may be lost by leaching (Brady & Weil, 2013). Thus, before carrying out fertilizations, it is necessary to release the soil charges so that the added nutrients are retained and can be absorbed by the crop according to its demand.

Aluminum toxicity restricts the growth of plant roots, making them thick and short and impairing the absorption of water and nutrients. This leads to water stress and nutritional deficiencies such as phosphorus, nitrogen, potassium, calcium, and magnesium deficiency (Singh et al., 2017; Sousa Junior et al., 2022). In sugarcane, for example, aluminum toxicity reduces nutrient use efficiency (Borges et al., 2020). In oxidic soils, acidity increases phosphate adsorption to the solid fraction (Vinha et al., 2021) due to the protonation of OH groups into iron and aluminum hydroxides, generating positive charges that adsorb phosphate (Farias et al., 2009).

Fortunately, soil acidity can be corrected by applying correctives, commonly limestone. Lime solubilization in the soil releases calcium and magnesium carbonates and hydroxyls, which react with free H^+ in the soil solution. Thus, liming consumes soil acidity by raising the pH, favors the neutralization of Al^{3+} that precipitates in the form of hydroxide, provides calcium and magnesium, and increases the availability of phosphorus in the soil (Raij, 2011). In a corrected soil, there is better root development, favoring an efficient use of water and nutrients by plants. The efficiency of liming depends on an early application at sowing, uniform distribution, and incorporation of limestone into the soil (Carneiro et al., 2018).

In addition to limestone, a sustainable option that may be used to correct soil acidity is steel slag. Steel slags are byproducts generated in the process of obtaining raw iron from iron ores and from other products, such as steel and its derivatives. Such materials have been used in many crops with positive results, such as raising pH and decreasing potential soil acidity, increasing base saturation and P availability, and increasing the production of stalks in sugarcane (Prado & Fernandes 2000; 2001; Prado et al., 2002a; Brassioli et al., 2009; Fonseca et al., 2009; Silva & Prado, 2019).

Steel slag consists of calcium and magnesium silicates, which are strong bases similar to calcium carbonate, that is, limestone. However, it may contain micronutrients in its composition (Prado et al., 2002b), requiring attention to the levels of potentially toxic heavy metals that may exist in its composition (O'Connor et al., 2021). The similarity of limestone and steel slag is well known, and both provide increases in pH and in the availability of P, Ca and Mg, resulting in a lower potential acidity and a higher base saturation (Vidal and Prado, 2011; Guimarães et al., 2019). Because it favors the availability of nutrients such as Ca, root growth in plants is better (Prado & Natale, 2004a).

Silicates are also sources of silicon (Si), a beneficial element for crops (Pereira et al., 2007a). It can increase the availability of phosphate in the soil as silicate competes with phosphate for adsorption sites (Prado & Fernandes, 2001). In marandu grass (*Urochloa brizantha*), nitrogen fertilization associated with slag increases Si absorption and forage dry matter production (Fonseca et al., 2009). It is important to remember that correctives must be applied based on soil chemical analysis and on the characteristics of the corrective material regarding granulometry and ability to neutralize acidity. The excessive use of correctives may compromise the aggregation of soil particles (Prado, 2003) and reduce the availability of micronutrients (Pereira et al., 2007b) and of P itself, as it can induce the formation of insoluble calcium phosphate, especially if applied on the soil surface (Penn & Camberato, 2019).

The need to adequately correct soil acidity for an optimal crop development has been studied for many years in tropical regions (Cruz et al., 1994; Santos et al., 1996; Caires & Rosolem, 1998; Kaminski et al. al., 2000; Prado et al., 2002a) and other regions of the world (Alley & Zelazny, 1987; Sumner et al., 1991; Noble et al., 1995; Scott et al., 2000). Due to its indispensable character, liming continues to be studied by soil scientists aiming to establish liming recommendations according to crop, source, and innovative technologies for applying corrective materials, respecting different production environments (Prado & Natale, 2004b; Bambolim et al., 2015; Galindo et al., 2017; Fontoura et al., 2019; Silva & Prado, 2019). Therefore, correcting soil acidity is a basic premise for a sustainable agricultural production as it ensures availability of nutrients and efficiency of fertilization, including of nitrogen and phosphate. Consequently, liming is the best economic return practice in agriculture.

Impacts of N and P deficiency in Poaceae

Nitrogen (N) and phosphorus (P) are essential elements for various forms of life on Earth. In most soils in tropical regions, these nutrients limit crop production, requiring fertilizer applications to reach high levels of productivity and thus meet the growing demand for food in the world. N and P deficiency occur in 18 and 43% of soils in cultivated areas in the world, respectively (Du et al., 2020).

Nitrogen is required in large amounts by crops. It is absorbed mainly in the forms of nitrate (NO_3^-) and ammonium (NH_4^+). It acts in vital plant processes, such as the synthesis of chlorophyll, nucleic acids and proteins. It is a component of all enzymes, including PEPC and RuBisCO, essential for the fixation of CO_2 in photosynthesis (Prado, 2021). Equally important is phosphorus, an essential component of molecules of ATP, NADPH, nucleic acids, sugar phosphates, and phospholipids, all of which play roles in photosynthesis (Hammond et al., 2004; Prado, 2021).

In addition to the natural scarcity of N and P in tropical soils, phosphate and nitrate anions may have a low availability as a result of some processes. Nitrate is poorly retained by the soil solid phase, making it prone to leaching losses (Bowles et al., 2018), while phosphate can be strongly adsorbed into soil solid particles (Santos et al., 2008), especially in clayey and highly weathered soils (Penn & Camberato, 2019; Pavinato et al., 2020). Also, the method of P application affects the productivity of sugarcane, as it is a demanding crop responsive to phosphate fertilization (Sousa Júnior et al., 2017); in corn crops, with more localized methods of application, it decreases the adsorption of P into the soil and increases absorption and crop production (Lemos et al., 2022).

P and N deficiency limits the production of Poaceous crops, such as forage (Primavesi et al., 2004; Hou et al., 2020), sugarcane (Caione et al., 2015a), corn (González et al., 2016), and rice (Deus et al., 2020). Thus, plants grown in environments deficient in N or P have a low absorption efficiency of these and other nutrients, such as Ca, Mg, and S (Gondim et al., 2010). In trials with sorghum cultivation in nutrient solution, the individual omission of N and P reduced the production of dry matter of shoots and roots, and the deficiency of P impaired the absorption of N, K, Ca, S, Mg, and Mn in sorghum plants (Prado et al., 2007). In sugarcane, N and P deficiencies reduced plant growth by 91 and 57%, respectively, with a lower nutrient uptake, progressing to visual symptoms such as slow development (Vale et al., 2011). N and P have structural functions and transfer and storage of energy in the plant. Therefore, their deficiencies compromise the synthesis of proteins and nucleic acids (Carstensen et al, 2018), resulting in lower plant growth.

Forage grasses have a high demand and a high ability to remove nutrients from the soil (Werner et al., 1996). Therefore, N and P deficiencies reduce growth and tillering. Conversely, adequate fertilization with these nutrients improves the morphogenetic and structural characteristics of forages (Farias et al., 2019; Ramos et al., 2009), as well as the production of forage mass in pre- and post-grazing (Zanine et al., 2020). In addition to the amount of forage, deficiencies of N and P affect forage quality. Animals that consume forage poor in N or P may present abnormalities such as poor formation of bones and teeth and low fertility (Malavolta et al., 1986). This occurs because the deficiency in nitrogenous compounds in the forage implies ruminal conditions that limit microbial activity, forage intake, digestibility, and animal performance (Lazzarini et al., 2009; Mwangi et al., 2019). Phosphorus is also essential for metabolism, transfer of energy and genetic information, and it is required by the rumen microbiota of animals (Karn, 2001).

In plants, there is a strong synergy between N and P in plants (Rietra et al., 2017). The lack of P slows down the process of energy transfer and storage in the plant (Malavolta, 1989) and impairs cell division, reducing the length and renewal of roots (Silva & Delatorre, 2009). The low supply of N reduces mass production and has a negative effect on the absorption of other macronutrients by forage plants (Fernandes et al., 2008; Fonseca et al., 2011). It also decreases tillering, thus explaining the low biomass production of leaves and low pasture height

(Martuscello et al., 2019). In maize (*Zea mays* L.), nitrogen limitation reduced shoot growth and photosynthetic capacity (Khamis et al., 1990) due to a decrease in chlorophyll content (Malavolta et al., 1997).

Plants respond to deficiencies using some survival strategies. Under N limitation, they can activate the expression of high-affinity NO_3^- transporters, with absorption at low concentrations and high efficiency in N remobilization (Lezhneva et al., 2014). Plants cultivated in a low-P environment undergo changes in root architecture, carbon metabolism, and membrane structure (Vance et al., 2003). In addition, they dissipate excess energy, protecting the photosynthetic apparatus (Stirbet & Govindjee, 2011), and activate the expression of genes that improve the efficiency of P use (Hammond et al., 2004).

Organic matter is the main N reservoir in the soil. It also provides P and other nutrients (Brady & Weil, 2013). There is also a significant contribution of N to the soil by atmospheric N_2 fixation carried out by free-living fixing bacteria associated with Poaceae (Keymer & Kent, 2014; Roley et al., 2018). However, even with these inputs, it is still necessary to complement the supply of N and P to sustain high-yield cultivated systems; this may be done either with chemical or organic fertilizers (Omara et al., 2019). This occurs because the extraction of nutrients from the soil does not occur constantly during the crop production cycle; on the contrary, the absorption curve has a sigmoid shape characterized by an initial phase of low growth and nutrient absorption by plants.

In order to allow an optimal productivity of crops in view of the high cost of chemical fertilizers, their use has been associated with organic residues in the cultivation of Poaceae, such as filter cake in sugarcane (Caione et al., 2015a; Caione et al., 2015b; Castillo et al., 2015) if enriched with microorganisms, it favors even the availability of P in the soil (González et al., 2016). Organic sources supply N and P to the soil and make soil P more available as organic acids compete with phosphate for the adsorption sites of soil colloids (Pavinato & Rosolem, 2008), allowing a greater P absorption and sugarcane productivity (Moda et al., 2015; Vasconcelos et al., 2017). Animal residues such as bovine manure or liquid pig manure are also used in the cultivation of grasses as a source of N and P, reducing production costs (Soares-Filho et al., 2018), especially in pasture fertilization (Drumond et al., 2006; Zanine & Ferreira, 2015).

A recent strategy to mitigate nutritional deficiency in plants could be the use of Si. It is a sustainable alternative without posing risks to the environment (Teixeira et al., 2020). Many studies have indicated that Si provides resilience to plants under stressful conditions (Ma, 2004; Verma et al., 2020; Souri et al., 2021), including those under nutritional imbalance (Ali et al., 2020; Silva and Prado, 2021). The application of Si improves the production of the forages *Megathyrsus maximus* and *Urochloa brizantha* grown in a medium deficient in K, Ca, or Mg by improving the use efficiency of these nutrients (Buchelt et al., 2020). This also occurs for N, P, and Ca in these species (Araújo et al., 2022). Si can be beneficial even in non-stressed plants.

In other grasses such as rice, the use of Si improved the production of N-deficient plants by modifying the C:Si stoichiometry (Deus et al., 2020). This change is certainly because of the lower energy cost of Si incorporation in relation to the synthesis of carbon compounds (Klotzbücher et al., 2017; Hao et al., 2020). Si also improved N uptake in deficient maize plants (Silva et al., 2021) and increased P accumulation and use efficiency in sorghum grown in P-deficient medium (Silva & Prado, 2021), improving the production of dry matter of plants.

Occurrence and effects of excess N and P on Poaceae

Fertilization with N and P has allowed transforming low fertility soils into highly productive areas (Singh, 2018; Pavinato et al., 2020). On the other hand, such a need placed Brazil among the five countries in the world that consume fertilizers the most. Brazil accounts for 3 and 11% of the global consumption of nitrogen and phosphate fertilizers, respectively (Lu & Tian, 2017). Part of this demand is because, in tropical soils, it is necessary to apply fertilizer doses that can exceed the amount of P fixation (Gichangi et al., 2009; Brenner et al., 2018) and the high requirement of N to provide a high yield of Poaceae (Galindo et al., 2018; Ronsani et al., 2018).

Global analyses indicate that the rate of fertilizer application to supply N and P to the soil has been increasing since the 1960s. In Brazil, fertilizers are found in regions of intensive production, in soils cultivated with agricultural crops or pasture (MacDonald et al., 2011; Lu & Tian, 2017; Li et al., 2019). In corn crops, for example, the applied amount of P increased by 105% in the last 20 years in Brazil in search of a higher productivity (Pavinato et al., 2020). Similarly, in intensive pastures, high doses of fertilizers are also required (Primavesi et al., 2005), especially those that provide N, which is a nutrient that determines productivity (Omara et al., 2019). However, nutrient input often exceeds crop demand (Reid et al., 2019).

The continuous application of high doses of nitrogen and phosphate fertilizers leads to accumulation of N and P in the soil and excessive absorption by plants. The excessive absorption of a nutrient increases its leaf content, causing a decrease in the production of dry matter either due to the toxicity of the element or by competitive inhibition of absorption, transport or assimilation of other nutrients

(Malavolta et al., 1986). The level at which N becomes excessively depends on the species and even the variety (Goyal & Huffaker, 1984). Among its effects are a lower synthesis of phenolic compounds (Elhanafi et al., 2019), reduction of transpiration and photosynthesis (Sperling et al., 2019), and the carbon:nitrogen ratio of plants (C:N) (Santi et al., 2019). al., 2003). Excess absorption of P increases its content in plant shoots, causing toxicity (Malhotra et al., 2018) and metabolic imbalances that affect biomass production (Malavolta et al., 1997).

The excessive application of N decreases the physiological and internal N use efficiency, reduces grain yield (Wang et al., 2011), and increases cadmium (Cd) content in wheat grains (Li et al., 2011) and in Tanzania grass (Leite & Monteiro, 2019). In sugarcane, high doses of N increased tillering but reduced stem diameter, with a consequent decrease in production (Vale et al., 2013). The excess N predisposes the plants to a greater attack by pests (Scriber, 1984), such as fall armyworms in corn due to the high concentration of easily assimilable free amino acids in leaf tissues (Sampaio et al., 2007); it even reduces alkaloid production (Rasmussen et al., 2007).

The increased uptake by the root and translocation of P to shoots leads to excess P accumulating in older leaves, causing P toxicity (Aung et al., 2006), which compromises photosynthetic performance, as observed for the grass Arundo donax (Cocozza et al., 2020). Excess P uptake leads to increased N uptake (Rietra et al., 2017), which stimulates plant senescence (Chiou et al., 2006) and compromises their C:N and C:P homeostasis (Elser & Hamilton, 2007). In rice, excess P increased susceptibility to diseases (Campos-Soriano et al., 2020).

Studies on excess N have focused on ammonia toxicity (NH_4^+). They indicate that the use of Si may attenuate its toxic effects in several cultivated species (Silva Junior 2019; Campos et al., 2020; Leal et al., 2021; Viciedo et al., 2020). Si seems to promote mechanisms to attenuate the excess of P, such as the modulation of P uptake, by regulating the gene expression of transporters (Hu et al., 2021). However, the effects of excess P and N in grasses are not yet clear. Further tests are necessary on the use of Si attenuating the damage caused in these plants, especially when cultivated in soils. In this sense, an unprecedented study began indicating that Si can attenuate toxicity in a forage cultivated in Typic Quartzipsamment (Entisol), a fact observed visually. However, it is important to advance in research to understand the physiological and nutritional aspects involved in this process (Melo et al., 2023).

Final considerations and future perspectives

The direct and indirect effects of deficiency of and toxicity by N and P in Poaceae highlights the need to carry out fertilizations adapting the doses of nutrients to the demand of crops and promote a greater use efficiency of nutrients by plants. For this, some actions are necessary.

It is necessary to update fertilization recommendation tables and the appropriate levels of nutrients for crops by carrying out comprehensive research on different cultivation systems and technological levels that are currently used so that fertilization efficiency can increase. In these studies, it is essential that the updated nutritional standards be accurate, that is, it is necessary to verify whether the resulting diagnoses are really true before publication in technical bulletins recommending nitrogen and phosphate fertilization for crops. For example, if the diagnosis of N or P deficiency is true, the application of these nutrient in the soil causes an increase in production; thus, the diagnosis was assertive. It is also necessary to investigate the synergy of N and P in plants of the Poaceae group because it would allow using optimized doses and avoiding surpluses. Thus, the scientific basis for N and P fertilization can be updated, ensuring an economic return for this activity with a rational fertilization and less occurrence of nutritional imbalances.

It is also advisable to use more sustainable sources such as organomineral fertilizers and recommend non-symbiotic N fixation, especially in pastures. In addition, it is necessary to improve the area of microbiology to optimize and explore the benefits of the symbiosis of microorganisms with plants, which may contribute to a lower dependence on nitrogenous and phosphate fertilizers. Advances in genetic improvement are also important, with a focus on selecting new cultivars of grasses that present high efficiency in absorbing and using N and P so that production can be achieved more efficiently.

Recent research has indicated that the use of beneficial elements such as silicon can improve nutritional efficiency in forage grasses, rice, corn, and sorghum grown in nutrient solution (Buchelt et al., 2020; Deus et al., 2020; Silva et al., 2021; Silva & Prado, 2021). However, there is a lack of studies on Poaceae crops planted in soil, especially in field conditions, using fluid sources of Si in irrigated systems. This could be important to evaluate its potential as a mitigator of N and P deficiency and verify whether it is possible to reduce the doses of these nutrients without loss of productivity.

Excess N and P has been scarcely investigated (Silva Junior et al., 2019; Sharma et al., 2007). Studies on the mitigation of N toxicity by Si are restricted to non-poaceous species such as passion fruit (Silva Junior et al., 2019), cotton (Leal et al., 2021), among others. Therefore, information on Poaceae is incipient (Hu et al., 2018; Cocozza et al., 2020). The results of Hu et al. (2018) for rice crops indicate that Si can also attenuate excess P, regulating its uptake by the plant. Therefore, it is possible that the use of Si in irrigated or dryland systems be a viable alternative to increase production in soils with very high levels of P. However, studies are lacking to prove this hypothesis.

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