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CHAPTER 20

SOIL LIMITATIONS FOR CROP PRODUCTIVITY IN SOUTH AMERICA

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Abstract

The agricultural practices introduced by European colonisers have been practiced in South America for many years, resulting in depletion of the soil's natural fertility. The introduction of fertilisers and acidity amendments occurred in the mid-1960s and boosted production of many areas, but still with high soil erosion and low levels of organic matter. The widespread use of conservation systems, such as no-tillage, occurred latter and changed the relationship between soil indices and crop responses. Nowadays, South America represents 47% of the total global area under no-tillage, which covers an area around 56 million hectares. No-tillage reduces the annual rate of decomposition and increases the mean residence time of the soil organic matter. In some countries, the challenge of no-tillage adoption is getting closer to being overcome. The current challenge is working on a cropping system with diversified species and high residue input. The adoption of legume cover crops as a source of nitrogen (N) seems to be very important,

resulting in higher accumulation of soil organic matter compared to N fertilisation. The management of soil acidity was, and continues to be, one of the main factors limiting crop yields. The problems of diagnosis are mainly related to the sampled soil layer and the indicators used for decision making. Recent studies have demonstrated that neither the 0-10 cm nor the 0-20 cm soil layer is suitable for diagnosing soil acidity and the potential crop yield in no-tillage systems with chemical restrictions in the subsurface. In these areas, a stratified soil analysis is essential, covering at least one subsurface layer (10-20 cm). The incorporation of limestone may be the best and fastest way to eliminate problems related to soil acidity in the subsurface. Significant increases in crop yields have been observed when using agricultural gypsum based on the diagnostic soil layer of 20-40 cm. Doses between 2 and 3 Mg ha⁻¹ are sufficient to obtain 95% of the maximum crop yield. For phosphorus (P), there is no doubt that the biggest problem is restricted access: by farmers at the micro scale and by countries at the macro scale. Very often, when accessible, the inappropriate use of P fertilisers is common. The correct approach would be to raise the available P content above the critical level in the 0-20 cm soil layer, and then reapply the amount exported by crops in the row and at the time of sowing. Regarding potassium (K), although there is an assumption that the tropical soils found in South America have only minerals such as kaolinite and oxides, there are several studies that show that the mineralogy of these soils is not so uniform. It is common to observe situations where 2:1 clay minerals are present and crops do not respond to the addition of K fertiliser, or the available K content does not increase over time. The research on sulfur (S) has advanced and shown that in tropical soils there is a higher positive crop response to S addition than in subtropical soils, regardless of available soil S contents. The evaluation of the 20-40 cm soil layer can support decision making regarding S management. To enhance production of plants and to increase the soil organic matter content, it is necessary to encourage and promote the horizontal and vertical monitoring of soil fertility. Associated with this, it is necessary to establish research networks aimed at improving the establishment of critical levels of soil acidity and available nutrients in the soil to guide decision-making more assertively, thus maximising productivity and promoting more sustainable production.

Key words organic matter, no-tillage, nitrogen, phosphorus, potassium, sulfur.

Introduction

Agriculture in South America existed long before the arrival of Europeans. Local communities have used agriculture based on some conservation principles for millennia, such as direct sowing without soil plowing and maintaining a protective soil cover on the ground (Calegari et al. 2020). Although the production systems were not intensive or highly productive, they were sustainable and generated minimal environmental impact. However, after 1492, agriculture introduced by European colonisers was practiced, based on burning, fallow, monoculture, and intensive plowing. This model of agriculture rapidly depleted the soil's natural fertility and organic matter stocks (Tiecher et al. 2020). After the introduction of fertilisers and acidity amendments in the mid-1960s during the Green Revolution, previously unproductive areas were recovered and agricultural production boosted, but still with a high potential for soil loss through water erosion and with great difficulty in recovering the original levels of soil organic matter (SOM).

In the last three decades, the widespread use of conservation systems such as no-till, especially when associated with the use of crop rotation, has slowed soil degradation, increased soil carbon (C) stocks, and maintained soil fertility with less dependence on external inputs. However, even with these improvements, technological advances in phytosanitary control, and genetic advances, in many cultivation areas it is possible to observe a stagnation in crop productivity. Much of this is due to the strong gradient of acidity and nutrient availability with depth due to the lack of soil disturbance associated with the addition of lime and fertilisers on the soil surface (Bellinaso et al. 2021). It is increasingly evident that horizontal monitoring of soil fertility alone is not enough to explain crop response, and it is increasingly necessary to understand the dynamics of soil acidity, nutrient availability, and SOM accumulation in areas under no-till. In this chapter, the main challenges of managing soil acidity, nutrients and organic matter in South America will be addressed.

Management of carbon and nitrogen in the soil

In the tropical and subtropical soils of South America, SOM accumulation is essential for more sustainable and resilient agricultural systems, as this governs many soil properties that strongly affect crop production and the quality of the wider environment (Lal 2004). The benefits of SOM are mainly related to water retention, improved soil structure, reduce Al activity, increased cation exchange capacity and

improved nutrient cycling. However, the intense solar radiation and high precipitation covering the majority of South America favour highly weathered soils and high SOM decomposition rates. At the same time, these climatic conditions also favour the cultivation of a wide diversity of crops over the year. To favour the accumulation of SOM in the agricultural soils of South America, management systems that decrease SOM decomposition and increase the input of plant residues to achieve a positive balance between the input and output of C are recommended.

Tillage systems

No-tillage (NT) is the basis of conservation agriculture and is considered an important tool for the sustainability of agricultural activities in tropical and subtropical regions (Lal et al. 2007). The area under NT has been growing steadily all over the world, but the highest rates of adoption have been achieved in South America. South America represents 47% of the total global area under NT, which covers an area around 56 million hectares (Derpsch & Friedrich 2009). In Argentina and Brazil, the countries with the greatest area under NT in South America, 70% of NT is permanent, which means that once started most farmers never till again.

Switching from conventional tillage (CT) to NT can result in the sequestration of an average of $0.48 \text{ Mg ha}^{-1} \text{ year}^{-1}$ of carbon in Brazilian subtropical regions (Bayer et al. 2006). In comparison to CT, the elimination of soil tillage leads to a marked reduction of the annual rate of SOM decomposition (0.040 year^{-1} in CT versus 0.025 year^{-1} in NT). This reduction is mainly associated with increases in soil macroaggregates, which physical protect SOM from microorganisms and their enzymes (Veloso et al. 2019). The less oxidative soil environment in NT increases the mean residence time of the SOM (the time between the photosynthesised C input in the soil until its microbial oxidation to CO_2) from 25 to 40 years. Thus, the permanence of the SOM is greater in NT compared to CT, which amplifies the benefits of the cycling of SOM.

Besides environmental conditions, the decomposition of SOM is strongly influenced by soil particle distribution and mineralogy. Bayer (1996) found higher decomposition rates and a greater impact of NT in reducing decomposition rates relative to CT in an Acrisol with 22% clay and predominantly kaolinite mineralogy than in a Oxisol with 68% clay (with predominance of oxides). The organo-mineral interaction is the main mechanism controlling the long-term stability of organic matter (Kogel-Knabner et al. 2008), and microorganisms have difficulty oxidising organic matter bound at the mineral surface (Sollins et al. 1996).

Influence of cover crops

In some countries of South America, such as Brazil, Argentina, Paraguay, and Uruguay, the challenge of converting CT into NT is getting closer to being overcome. The current challenge is identifying cropping systems that have diversification of species and high residue input, without making big changes to the farm budget. One alternative to keep the traditional main cash crops (soybean, maize, cotton, coffee, and wheat) cultivated in South America, is the adoption of cover crops between the growing seasons. In this way, we can combine the benefits of high value crops with species that aid the environment in the same agricultural system.

The adoption of cropping systems, considering cash and cover crops, will directly impact the biomass input that drives SOM accumulation. In Southern Brazil, SOM accumulation rates strongly depend on the cropping system adopted and can vary between 0.11 and 0.68 Mg C ha⁻¹ yr⁻¹ (Bayer et al. 2009). The residue input from roots and shoots plays a key role in determining SOM accumulation and can be responsible for 80% of the differences in SOM stock in different cropping systems (Veloso et al. 2018). It is interesting to note that some researchers have found that the roots show greater conversion into SOM compared to the shoots and contribute more to SOM stocks (Tahir et al. 2015).

In addition to residue input, species diversification is another important point to consider when seeking to increase SOM accumulation. In cropping systems where maize is the main cash crop, the introduction of legume cover crops can further increase the potential for SOM accumulation. Legume cover crops add C and N from their own residues (roots and shoots) and increase biomass input from the subsequent crop. Veloso et al. (2018) found that legumes added between 82 and 115 kg N ha⁻¹ yr⁻¹ when one or two legume cover crops were added to the cropping system, which increased the maize biomass cultivated in the subsequent crop by 1 Mg ha⁻¹ yr⁻¹. Also, the greater lability of legumes may result in a greater conversion of residues into SOM. Compared to N fertilisation, the adoption of legumes more than doubled (0.22 vs 0.09 kg SOC) SOM accumulation: in other words, each kg of C input by the legume cover crops resulted in the accumulation of 0.22 kg of soil organic carbon, compared with only 0.09 kg soil organic carbon for N fertilisation (Veloso et al. 2018).

The most cultivated legume cover crops during the autumn/winter period of subtropical regions of South America, are white clover (*Trifolium repens*), common vetch (*Vicia sativa* L.), hairy vetch (*Vicia villosa* Roth), blue lupin (*Lupinus angustifolius* L.), corniculata (*Lotus corniculatus*), among others. The fodder turnip (*Raphanus sativus*), although not a legume, also plays an important role in biomass input, and helps recycle N from

deeper in the profile in the winter seasons. Regarding the legumes cover crops that can be cultivated during spring/summer seasons, some examples are: caupi (*Vigna unguiculata* (L.) Walp), crotalaria (*Crotalaria* sp.), feijão-guandu (*Cajanus cajans*), lablab (*Lablab purpureus* (L.) Sweet), and mucuna (*Mucuna pruriens*) (Bayer et al. 2019).

Management of soil acidity

Liming

Soil acidity was, and continues to be, the main factor limiting the crop productivity of tropical and subtropical agriculture in Brazil (Bellinaso et al. 2021; Pias et al. 2020), Argentina (Alvarez et al. 2020), Chile (Bonomelli & Artacho 2021), Uruguay (Beretta et al. 2017), Paraguay (Kawavata 2018), and Colombia (Caballero et al. 2019). Exceptions to this problem are places with low rainfall, in poorly weathered and poorly drained soils, or near the sea, where the acidity gives way to problems related to excess salts (Denardin et al. 2020). The use of soil acidity correctives has been a common practice since the beginnings of agriculture and is still used as a “key” input in highly weathered acidic soils in South America. Among the inputs used for agricultural production, lime is certainly the one that results in the greatest response in crop yields and with the greatest residual effect, therefore, with an excellent cost-benefit ratio.

Our understanding of the dynamics of soil acidity and its effects on soil chemical properties and plant response has greatly evolved from the 1960s to the late 20th century (Rheinheimer et al. 2018). Criteria were established to estimate the efficiency of correctives based on their chemical composition and particle size distribution, which were calibrated for cropping systems with intense tillage and soil mobilisation. However, these criteria may not be as efficient in conservation management systems, such as NT, in which lime is broadcast. In NT systems, which cover huge areas in Brazil, Argentina, Uruguay, and Paraguay, there is still great uncertainty regarding the best acidity diagnosis methods, lime rates, and the type and mode of application of lime.

The problems of diagnosing soil acidity are mainly related to the sampled soil layer and the chemical indicators used for decision making. There is no doubt that for acid-sensitive species, the acidity of the entire volume of soil explored by the roots should be corrected. This would avoid problems related to toxicity with Al^{3+} and would also increase the availability of various nutrients. However, the correction of soil acidity for annual crops and cultivated pastures is generally restricted to the topsoil (up to 20-30 cm),

as this is where most of the roots develop and concentrate, and also due to the large increase in corrective and operational cost when seeking to correct deeper soil layers (below 30 cm). In systems with soil tillage, or before the beginning of the NT system, the diagnostic layer must be 20 cm deep. The incorporation of lime promotes the correction of acidity evenly in this layer (Miotto et al. 2019). In NT systems, the diagnostic layer can be more superficial (0-10 cm), since the soil re-acidification is more intense in the first centimeters of soil (Rheinheimer et al. 2018).

Various chemical indicators can be used to diagnose soil acidity. The most commonly used are pH in water or salt (active acidity), saturation by aluminum (Al), and saturation by alkaline and alkaline earth cations (sodium [Na], potassium [K], calcium [Ca], and magnesium [Mg]). As the soil pH influences the availability of all nutrients in the soil, and also Al toxicity, it is generally used as a key parameter to make liming decisions. But to define the lime dose, it is necessary to estimate the potential soil acidity (H+Al), because it buffers the active acidity. Despite this, decision-making and the dose of lime to be applied are often established based on saturation by cations (Ca, Mg, K). Although Ca and Mg are commonly called bases or basic cations, even in soil fertility books, this term is not adequate and should be abolished (Lambers and Barrow 2020), as bases react or remove acids (H⁺), which Ca and Mg do not. Of course, after liming, there is a simultaneous increase in soil pH and in the concentration of Ca and Mg, but the increase in the concentration of these nutrients is a consequence, and not the cause, of the decrease in soil acidity. Furthermore, we cannot assume that the relationship between Ca and Mg saturation and pH is linear and the same for all soils, as it varies widely depending on e.g., soil type and mineralogy.

The mode of lime application has been widely studied (Miotto et al. 2019; Rheinheimer et al. 2018; Bellinaso et al. 2021). Currently, there is great resistance on the part of technicians and farmers to incorporate lime in areas where NT is already established. In NT soils, generally, the pH of the superficial layer (0-5 cm) is corrected with superficial liming. Several studies have demonstrated the limitation of surface liming on the neutralisation of subsurface acidity since the action of limestone is restricted to some centimeters below the deposition point (Rheinheimer et al. 2018). Changes in soil chemical properties related to acidity due to surface liming are insignificant below 10 cm in depth (Bellinaso et al. 2021). Furthermore, the higher pH of this layer can reduce or inhibit the reaction of larger particles of lime, since without acidity, carbonate solubilisation does not occur. Moreover, the soil pH and organic matter may be high enough to not adequately supply copper (Cu), zinc (Zn), and manganese (Mn) (Moreira et

al. 2019), and at the same time, the root system suffers from Al toxicity a few centimeters below the soil surface (Miotto et al. 2019). Recent studies have demonstrated that neither the 0-10 cm soil layer nor the 0-20 cm soil layer is suitable for diagnosing soil acidity and the crop productive potential in NT systems with chemical restrictions in the subsurface (Bellinaso et al. 2021). In these areas, a stratified soil analysis is essential, covering at least one subsurface layer (10-20 cm). In the 10-20 cm layer, 20% of Al saturation is enough to reduce the maximum soybean yield by 20% (Bellinaso et al. 2021). In these situations, strategic tillage or occasional tillage with the incorporation of limestone may be the best and fastest way to eliminate problems related to soil acidity in the subsurface and ensure good root development and high crop yields.

Agricultural gypsum

After correcting the soil acidity with lime in the 0-20 cm layer, it is also possible to further reduce Al toxicity in the subsurface (below 20 cm) in NT areas using agricultural gypsum, which promotes high migration of Ca^{2+} , Mg^{2+} and K^{+} associated mainly with the sulfate anion (SO_4^{2-}) from the surface to deeper soil layers, as long as there is no mechanical impediment (soil compaction) (Alves et al. 2021). The increase of cations at depth promotes a reduction in the activity and toxicity of exchangeable Al^{3+} below 20 cm depth, enabling the deepening of the plant's root system and, consequently, improving the use of water and nutrients.

As with any other agricultural inputs, the use of gypsum should not be indiscriminate, but based on a technical position. According to a meta-analysis of the effect of using agricultural gypsum for grain crops under NT in Latin America by Pias et al. (2020), the 20-40 cm depth should be used as the diagnostic soil layer for decision-making on whether to apply agricultural gypsum, with the type of crop, Al saturation, and water availability also considered. In the absence of a water deficit, soybean responds positively to gypsum in soils with Ca content lower than $0.5 \text{ cmol}_c \text{ dm}^{-3}$ and Al saturation greater than 40% in the 20-40 cm layer. In the presence of a water deficit, soybean responds when the Al saturation is greater than 10% and the Ca content is lower than $2.0 \text{ cmol}_c \text{ dm}^{-3}$. Corn and other winter cereals, on the other hand, have a high probability of productivity increase when the Al saturation is greater than 5% in the 20-40 cm layer, regardless of whether there is a water deficit or not.

When it is necessary to apply gypsum, doses between 2 and 3 Mg ha^{-1} are sufficient to obtain around 95% of the maximum crop yield (Pias et al. 2020). When the objective is to obtain maximum productivity, doses of up

to 6 Mg ha⁻¹ can be used and also guarantee a greater residual effect in the soil. However, care must be taken with the application of these high doses when the levels of exchangeable Mg in the surface layer are low (<1.0 cmol_c dm⁻³), especially in sandy soils, because the application of large amounts of Ca via gypsum can induce Mg deficiency (Alves et al. 2021). An efficient strategy to reduce the undesirable effects of gypsum is the prior application of dolomitic limestone.

Deficiency of sulfur (S) in agricultural soils has become more common in recent decades due to the use of concentrated fertilisers with no S in their composition, reduction in the atmospheric deposition of S, reductions in SOM, and increases in the productive potential of crops (Pias et al. 2019). Agricultural gypsum is an excellent source of S, containing on average 15-18% S. Therefore, even when Al saturation in the subsurface (20-40 cm) is low, increases in soybean productivity can occur due to a greater supply of S to the plants. In these cases, the soybean response is even observed at low doses of gypsum.

Management of main macronutrients

Phosphorus-related limitations in agro-environmental systems

In South America, the literature contains abundant data on phosphate reserves and their use in agricultural production (Pavinato et al. 2020), the dynamics of phosphorus (P) in the soil (Rheinheimer et al. 2019), plant mechanisms for mining P from the soil (Lynch et al. 2021), biological interactions and their impacts on the use of P from the soil, and even the dynamics and impacts of the transfer of this nutrient from the terrestrial system to the aquatic environment (Bender et al. 2018). Thus, in this section, we will only list the authors' opinions regarding the main problems related to P in agro-environmental systems.

There is no doubt that the biggest problem related to P nutrition is the restricted access to it, either for farmers at the micro scale, or for countries at the macro scale. Poor countries have weathered soils that are low in bioavailable P, and poor farmers are located on the more fragile soils with limited P availability. Even in rich countries that have very high yields, plants require increasing amounts of P, even depleting the soil's P reserves. Thus, the productivity of plants, and therefore of animal protein, is totally dependent on exogenous P. Therefore, there is a real "Phosphate Apartheid", either because of the situation of unequal P availability in the different biomes and, consequently, of the implemented agroecosystems, or because of the unequal location of P-rich mineral reserves. The two situations

usually occur concurrently and play unfavourably against poor countries and farmers. Those with financial resources have access to suitable soil and can purchase phosphate fertilisers; those who are outside the capitalist system cannot afford to buy phosphate, among the other means necessary for production. Thus, agricultural production is concentrated in a few rich countries and in a few developing countries, thanks to rich farmers and agricultural companies. Most farmers are poor, do not have access to fertilisers, including phosphates, and do not produce enough even to support their families.

Regarding the absorption and use of P from the soil by plants, there are at least two major obstacles. Firstly, even in soils highly deficient in bioavailable P there is a considerable amount of total P (Rheinheimer et al. 2019). However, years and decades of research related to the dynamics of P in the soil, including all knowledge related to physicochemical and microbiological mechanisms, has not translated into technologies that are truly usable by farmers. Information is often too generic, such as: “mycorrhizae are essential”, “there are plants with a greater ability to absorb and use P”, and “there are solubilising bacteria”, etc. Some biological products have even appeared on the market that are more magical than phenomenological. The “Phosphorus Legacy” is quantifiable (Gatiboni & Condon 2021; Pavinato et al. 2020), but there are no technological means available to farmers to “mind” this stock of P via commercial crops. Even with advances in agroecology, and all the implications for land use and management, it is still not possible to offer viable and quantifiable alternatives for using this P stock.

The second obstacle, and obviously closely related to the first one, is the inappropriate use of phosphate fertilisers. Farmers who access and consume most of these fertilisers are the same ones who produce major commodities (soybeans, corn, wheat, cotton, coffee, orange juice, sugarcane), are the owners of huge areas of land, and are those that use any and all “modern” technology (total mechanisation of activities, GMO plants, and pesticides). The use of the NT system is representative of this type of farmer, especially in Brazil and Argentina. Phosphate fertilisers are just an input like any other and, for this type of farmer, the cost of P is very low compared to other production costs. The effectiveness of fertiliser application is prioritised for its agro-environmental efficiency, which can lead to overuse and eutrophication of surface water sources (Bender et al. 2018). But this overuse is currently only a major concern for scientists and urban populations, and not for fertiliser users. At the same time as overuse of P is a problem in some sectors, in other sectors problems arise from not correcting the severe lack of P in the soil profile when natural biomes

(Cerrado, Tropical Forests and Campos Sulinos – Pampa) are destroyed and the high toxicity of Al leads to limitations in deep root growth. This severely decreases the efficiency with which added phosphate is utilised. The scientifically correct approach would be to raise the available P content above the critical level in at least the 0-20 cm layer, and then reapPLY the P exported by crops in the row and at the time of sowing. Unfortunately, this proven approach is not adopted by all users of phosphate reserves.

Potassium

Due to its chemical properties, K is not part of the structure of any organic molecule, and therefore only exists in the soil in the following inorganic forms: (a) at low concentrations dissolved in the soil solution in the form of hydrated K^+ ions; (b) as part of primary minerals resistant to weathering (structural K); and (c) adsorbed to functional groups in surface complexes with varying degrees of energy. It is common in the literature to find the terms “exchangeable K” and “non-exchangeable K”, but this terminology has no relationship to the type of complex formed between the K^+ ion with the functional group, and only makes sense when properly associated with laboratory conditions used in the method (solution concentration, stirring time, soil:extractor ratio, number of extractions, among others) (Bourder et al. 2021). Plants absorb K from the soil solution, and as its content decreases, it triggers a rapid and stoichiometric release of the K retained with lower energy electrostatically adsorbed to functional groups, and more slowly of the K retained with greater energy in the interlayer of 2:1 clay minerals, or by hydrolysis of structural forms of the solid phase in soils with primary minerals containing K.

The total K content in soils varies greatly depending on the source material and weathering. More weathered soils derived from basalt can have a total K content of up to 3,000 mg kg^{-1} (Almeida et al. 2021), while younger soils derived from granite can have up to 30,000 mg kg^{-1} (Flores et al. 2021). Even with high total K contents, only a small fraction is available to plants and the bioavailable fraction is commonly estimated by routine soil analysis methods. These generally use cation exchange resin, ammonium chloride, ammonium acetate, or the Mehlich-1 solution as extractors. The K extracted with these methods is called “exchangeable K”, which accounts for the soluble K and part of the K adsorbed to soil functional groups with lower energy (Bourder et al. 2021). However, these methods may not show good correlation with plant uptake due to the contribution of non-exchangeable forms of K from the soil that are not accessed by these extractors. In fact, it is known that there is a considerable contribution of non-exchangeable K to

plant nutrition, which is attributed to the release of K from 2:1 clay minerals and the dissolution of K-containing minerals (feldspar and mica, for example) present in coarse soil fractions (silt and sand) (Moterle et al. 2019). However, the proper estimation of the contribution of these forms still represents a challenge, although the importance of the contribution of non-exchangeable forms of K to plant nutrition has been recognised for over 40 years in Brazil (Mielniczuk 1977; Mielniczuk & Selbach 1978) and Peru (Oelsligle et al. 1975).

In Southern Brazil, it is estimated that the non-exchangeable K contribution to the K nutrition of plants can range from 50 to 73% without K fertiliser addition, and from 1 to 18%, with K fertiliser addition (Steiner & Lana 2018). In Uruguay, the non-exchangeable K contribution to K nutrition can be up to 43% (Núñez & Morón 2017). In Argentinean soils, the initial exchangeable K and illite concentrations accounted for 90% of the variations in the K taken up by plants, demonstrating that mineralogy can help to better estimate soil capacity to supply K (Zubillaga & Conti 1996).

In highly weathered oxidic soils (Oxisols and Ultisols), with no or low 2:1 clay minerals, the supply of K to plants is primarily derived from the release of exchangeable K adsorbed to the surface functional groups of mineral clays and organic material. Under these conditions, the available K content in the soil estimated by routine methods (Mehlich-1, ammonium chloride, or cation exchange resin) represents almost the totality of the K absorbed by the plants. However, in soils with 2:1 clay minerals, the K dynamics are more complex, as these mineral structures can act both as a drain and a source of K (Flores et al. 2021).

Although traditional soil fertility assumes that the tropical soils found in South America have only secondary minerals, such as kaolinite and Fe- and Al-oxides, there are several scientific reports that show that the mineralogy of these soils is not so uniform (Almeida et al. 2021; Firmano et al. 2020; Schaefer et al. 2008), and this has greatly limited the understanding of South American soil chemistry. Although in many cases 2:1 clay minerals are present in much lower concentrations than oxides and kaolinite, they still have a marked influence on the chemical properties of the soil due to their high reactivity, and directly affect K dynamics (Britzke et al. 2012). When the K supplied via fertilisers is lower than that taken up by plants, K retained in the siloxane cavities of clay minerals such as mica may be released. When added K is greater than absorbed K, 2:1 clay minerals such as vermiculite can retain excess K in their interlayers (Moterle et al. 2019), which can decrease the availability of K for plants due to competition between the soil and the plant for the added K. In both cases, there may be changes in the

mineralogy of the clay fraction due to the entry or exit of K from the 2:1 clay mineral interlayers. For this reason, it is common to observe situations in soils with the presence of these clay minerals where crops do not respond to the addition of fertiliser, or the available K content does not increase even with large additions of K via fertilisers (Firmano et al. 2020). In these soils, adequate K fertilisation should focus on the repositioning of exported K to prevent temporary fixation, rather than being based on soil testing and raising the soil available K up to a critical content. Moreover, soil K management guidelines should consider both topsoil and subsoil nutrient status and variables related to soil K buffer capacity. The K supply capacity in the 0-20 cm layer has been estimated to average 48% in production systems in Argentine soils (Correndo et al. 2021), and about 60% for the 0-30 cm layer in soybean production systems in Brazil (Oliveira et al. 2021).

Sulfur

Sulfur (S) is a macronutrient nutrient absorbed in large amounts by crops. Historically, S deficiency is rarely described in the literature, and isolated cases where it has been detected are mainly sandy soils with low organic matter content (Pias et al. 2019). Because of this, S is the least studied macronutrient in the world and in South America. However, with the advance of agriculture in recent decades, the occurrence of S deficiency has become more common. There are several factors that have contributed to this, including the: (i) increased productive potential of crops, (ii) use of concentrated NPK fertilisers, (iii) reduction in the atmospheric deposition of S, (iv) reduction in the use of S-based agricultural pesticides, (v) reduction in SOM contents, and (vi) occurrence of chemical and/or physical barriers to the deepening of plant root systems.

There is still no consensus in Brazil regarding the critical levels of soil S and the diagnostic layer that should be used. Thus, differing criteria are used by official agencies for S recommendations in different regions. In the states of Rio Grande do Sul and Santa Catarina, the critical content of available S varies from 5-10 mg dm⁻³ in the topsoil (0-10 cm) depending on whether the crop has a high or low demand for S (CQFS-RS/SC 2016). In São Paulo State, the critical levels are the same, but the diagnostic layer is 0-20 cm (Raij et al. 1997). In the state of Paraná, the application of S is recommended when the available S content in the 0-20 and/or 20-40 cm layer are below the critical levels of 3 and 9 mg dm⁻³, respectively (Pauletti & Motta 2017).

The content of S available in the soil, as discussed above, is dependent on several factors and has a large temporal variability. This makes it difficult

to accurately determine fertiliser requirements. For this reason, studies evaluating isolated cases have not found a good relationship between the S content available in the soil and the grain yield of crops (Osório Filho et al. 2007). On the other hand, a joint analysis carried out in a recent systematic review for Brazil, found that the available S content was the main factor influencing crop response to S fertilisation in soil under NT (Pias et al. 2019). In this study, no crop responded positively to the addition of S when the soil available S was greater than 7.5 mg dm^{-3} in the 0-20 cm layer. However, in soils with available S content lower than 7.5 mg dm^{-3} , there was a positive response in 50% of crops. It was also shown that 63% of the crop response to S (positive or no response) could be explained by available S content in the soil in the 0-20 cm layer, climatic zone, crop species, and productivity expectation.

Sulfur deficiency is more common in highly weathered tropical soils, which naturally tend to have low organic matter content (high mineralisation rate), especially when poorly managed, thus resulting in soils with low fertility. Studies with S in tropical NT soils (Cerrado region) found a positive response in 48% of crops, while in subtropical soils (Southern Brazil) the responses occurred in only 18% of crops. However, if we consider only soils deficient in S, in a tropical environment there was a response in 92% of crops, while in a subtropical environment only 22% of crops responded to S. Thus, it should be considered that in subtropical environments, even in soils deficient in S, the probability of a positive response by applying S is lower. Considering only grain crops in NT system in Brazil, Pias et al. (2019) determined critical levels of available S of 7.5 mg dm^{-3} for the surface layer (0-20 cm, 48 crops) and 8.5 mg dm^{-3} for the subsurface layer (20-40 cm, 34 crops). The evaluation of S contents in the 20-40 cm layer can support decision making regarding S management, as soils usually accumulate higher S contents in these layers.

Conclusions

One of the biggest challenges and limitations of crop productivity in South America is to increase the quantity of organic residues added by plant biomass to the soil and to reduce its rate of decomposition. There is no doubt that we should have plants growing and photosynthesising for as long as biologically possible during the year. In many places in South America, this means plants growing 365 days a year. Even so, unfortunately there are still vast agricultural areas that remain fallow for several months during the year, without the use of cover crops, and often without using conservation systems such as NT. The combined use of NT and cover crops should be

mandatory, as it brings benefits both inside and outside the farm. For the farmer, this means less dependence on N fertilisers, greater recycling of nutrients such as P, K, and S, greater cation exchange capacity, less soil and nutrient loss, greater soil water retention and, consequently, greater productivity. Outside the farm, it benefits society due to greater CO₂ sequestration and climate regulation, greater regulation of the hydrological cycle, and greater food production.

However, to maximise plant growth and biomass production, it is necessary to provide conditions so that plants can have adequate development. Undoubtedly, the major limitations for this are soil acidity and low nutrient availability, especially P. Although not relevant in some specific areas in South America, soil acidity in the surface and subsurface remains one of the main obstacles in tropical agriculture. While the need for sulfate and phosphate fertilisation can be predicted by properly evaluating the levels of S and P available in the soil, thus increasing the efficiency of fertiliser use, there is still a very large limitation to using this approach for K. To enhance production of plants and plant biomass, and consequently to increase the organic matter content of the soil and the sequestration of C from the atmosphere, it is necessary to encourage and promote the monitoring of soil fertility, not only horizontally, but also vertically. Associated with this, it is necessary to establish research networks aimed at improving the establishment of critical levels of soil acidity and nutrient availability to guide decision-making more assertively, thus maximising productivity and promoting more sustainable production.

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