Research Findings

The Saga of the Agricultural Development of the Brazilian Cerrado

Scheid Lopes, A.[(1)], L.R. Guimarães Guilherme[(2)], and S.J. Ramos[(3)]

Introduction

The advancement of Brazilian agribusiness, which represented 23 percent of Brazil's GNP in 2006, has been a remarkable development in the evolution of the Brazilian economy over the past three decades (Lopes and Daher, 2008). A key factor regulating this agricultural progress has been the use of adequate nutrient management techniques ensuring that Brazil is very productive. This point is illustrated by the fact that during the period of 1992 to 2011, the area cultivated with grain crops in Brazil increased from 35.6 million hectares (ha) to 48.6 million hectares (40 percent rise), with a corresponding increase in grain production from 68.3 million tonnes to 160.1 million tonnes (230 percent), and a growth of fertilizer sales from 9.3 million tonnes to 28.3 million tonnes (300 percent). These figures represent geometric annual growth rates of 1.93 percent in cultivated area, 4.77 percent in grain production, and 5.55 percent in fertilizer sales.

One of the key factors in this development has been the expansion of agriculture and beef cattle production in the Cerrado, an area regarded as unfit for farming until the beginning of the 1960's (see Map 1). Norman Borlaug, Nobel Peace Prize Laureate and known as "The father of the Green Revolution", once said that "nobody thought these soils were ever going to be productive". The Cerrado, with more than 200 million ha plays an enormous role in agricultural production, and can nowadays be considered one of the world's great breadbaskets. As the second largest Brazilian biome, the region has a rich biodiversity, which can be used for the production of food, feed, fiber, and fuel, as well as timber, medicinal and ornamental plants.

This paper presents information about the Brazilian Cerrado considering both its potential as well as its limitations, while focusing on various practices, including nutrient management necessary to overcome soil fertility constraints and achieve successful agricultural production in the region.

Map 1. South America and distribution of the Cerrado region in Brazil (marked in green). *Source:* Adapted from Lopes and Guilherme, 1994. The Brazilian Cerrado is 2.04 million km², 23 percent of the total area of Brazil.

The Cerrado region in Brazil

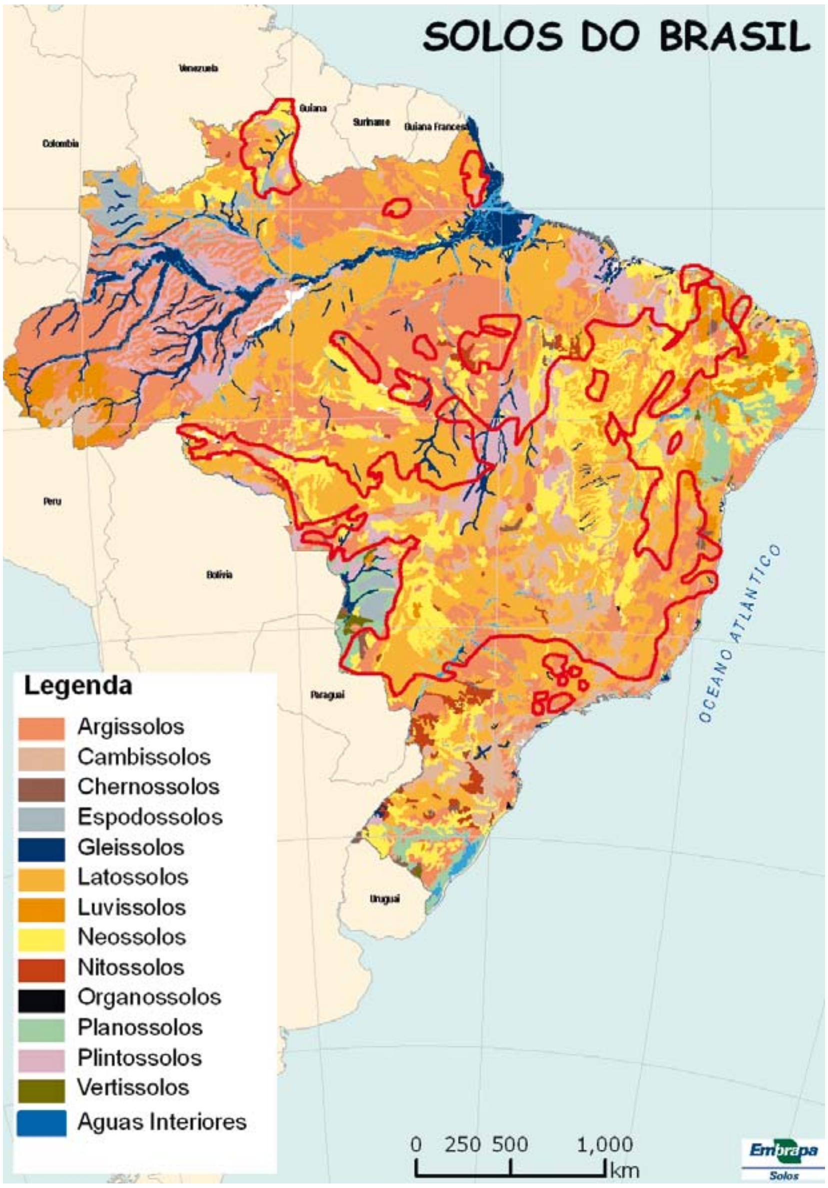
The area under Cerrado (savanna) vegetation in central Brazil occupies 2.04 million km^2 or 23 percent of the country (see Map 1). It is estimated that 50 percent of this area is adequate for agriculture whilst 66 percent could be incorporated into agriculture/livestock/forestry production. Annual rainfall ranges from 900 to 2,000 mm, usually in the 1,000-1,400 mm range, and the mean annual temperature is 22°C in the south of the region and 27°C in the north (Goedert, 1989). Most of the soils

[(1)]Agronomist, PhD; Emeritus Professor, Federal University of Lavras (UFLA), Brazil; Emeritus Researcher, National Council for Scientific and Technological Development (CNPq), Brazil. ascheidl@dcs.ufla.br
[(2)]Agronomist, PhD; Associate Professsor, UFLA; Research Fellow, CNPq. Corresponding author: guilherm@dcs.ufla.br
[(3)]Agronomist, PhD; Assistant Scientist, Vale Technological Institute - Mining. silvio.ramos@vale.com

in this area are highly weathered Oxisols (46 percent), Ultisols (15 percent), and Entisols (15 percent) (US Soil Taxonomy; see also Map 2), presenting serious limitations for crop production in terms of low natural soil fertility. These soils are acid and are low in available nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), molybdenum (Mo) and zinc (Zn). Additionally the soils are also highly saturated in aluminium (Al^{3+}) which makes them toxic to most crop plants. These soils also have high P fixation capacities (Table 1).

Besides these chemical constraints there are several other limitations to agricultural production in this region (Lopes and Guilherme, 1994):

- Typically a five to six month dry season (April to September).
- Dry spells of one to three weeks during the rainy season, locally known as "veranicos", which are generally associated with high evapotranspiration rates.
- Low soil water holding capacity, even in clayey soils.
- Limited rooting depth of many crops as a consequence of Al toxicity and/or Ca deficiency in sub-surface soil layers.



Map 2. Soil map of Brazil and the Cerrado region (marked in red). *Source:* Embrapa solos.

These points emphasize the need for appropriate management technologies to increase potential for increased agricultural production in Cerrado soils. Despite these problems, a breakthrough in agricultural development has occurred in the region during recent decades, mainly involving food crops, pasture and perennial crops.

Until the 1970s, economic activity in this areas was based on extensive cattle raising, rice cultivation, charcoal production and logging. However, over the past 30 years, agricultural activity has shown an exceptional development. Currently about 98.5 million ha are under agricultural production including 50 million ha under cultivated pastures, 30 million ha as native pasturelands, 15 million ha utilized for annual crops, and 3.5 million ha for perennial crops and forests. The Cerrado accounts for more than 55 percent of Brazilian soybean production, with higher yields than the national average. The region also plays a very important role in the production of other key crops and provides 76 percent of cotton, 31 percent of corn, 18 percent of rice, and 22 percent of beans, with regard to national production of these crops. Agricultural cultivation has been extended recently with an increasing contribution of crops such as sorghum, sunflower, barley, wheat, and rubber, as well as fruits and vegetables for the food processing industry. For livestock, the numbers in the Cerrado are also quite significant, with 42 percent of the 176 million national cattle herd, accounting for 55 percent of Brazilian meat production (Embrapa, 2012).

The agricultural potential of this region is so significant that Dr. Norman Borlaug referred to the Brazilian Cerrado as the last great agricultural frontier of the world (Borlaug and Dowswell, 1993). Estimates suggest that annually the area could produce 250 million tonnes of grains, 12 million tonnes of meat and 90 million tonnes of perennial crops (Macedo, 1995; Lopes and Guilherme, 1994).

Table 1. Chemical properties of 518 composite samples (0-15 cm) of top-soil under Cerrado vegetation in Brazil.

Properties	Cerrado area	Properties	Cerrado area
	%		%
pH in water (<5.0)	50	Organic matter % <2.0	17
Ca $cmol_c/dm^3$ <1.5	96	Zn mg/dm^3 Mehlich 1 <1.0	95
Mg $cmol_c/dm^3$ <0.5	90	Cu mg/dm^3 Mehlich 1 <1.0	70
K $cmol_c/dm^3$ <0.15	85	Mn mg/dm^3 Mehlich 1 <5.0	37
Al $cmol_c/dm^3$ >1.0	15	N deficiency	32
Effective CEC $cmol_c/dm^3$ <4.0	97	$S\text{-}SO_4^{2-}$ deficiency	70
Al saturation of effective CEC >40%	79	B deficiency	60
P mg/dm^3 Mehlich 1 <2.0	92		

Source: Adapted from Lopes and Cox, 1977; and Malavolta and Kliemann, 1985.

Nutrient consumption in Brazilian agriculture and in the Cerrado region

NPK consumption has been rising steadily over the years, with a geometric annual growth rate of 4.9 percent from 1970 till 2011 (5.4, 3.82 and 5.86 percent for N, P_2O_5 and K_2O, respectively) (Fig. 1). The high demand for K relates to the crops grown in the area. Soybean – a highly demanding K crop – accounts for up to 35 percent of the Brazilian fertilizer market share, followed by corn and sugarcane, which also take up large amounts of K (Fig. 2). Over the past two decades, the use of more intense crop rotations, with the exponential rise of the no-till area in Brazil and the increased production of these high K extracting crops (e.g. soybean, corn and sugarcane), has significantly increased K removal from Brazilian soils. This is noteworthy because K plays a significant role in enhancing crop quality in Brazilian agribusiness, i.e. it improves the physical and chemical quality of sugarcane and the fiber quality of cotton. K also plays an important role in enhancing N fixation in soybean and increasing the quality of seeds.

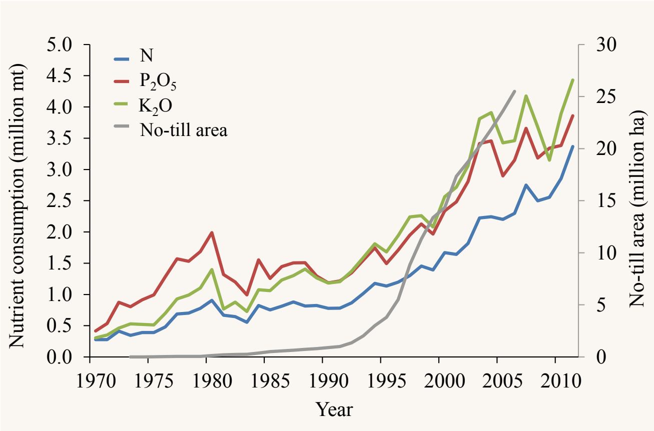


Fig. 1. Growth of N, P_2O_5 and K_2O consumption in Brazilian agriculture from 1970 to 2011, plotted together with the expansion of the no-till area in Brazil from 1973 to 2006.

One of the key factors leading to improved agricultural production and yield in the Cerrado region has been the increase in the efficient use of fertilizers, especially N, P and K. In 1970/71, at the beginning of the Cerrado agriculture expansion in Brazil, the average consumption of N, P_2O_5, and K_2O in Brazil was only 7.7, 11.5 and 8.5 kg ha^{-1}, respectively. The total cultivated area was 36 million ha and the production of 16 major crops (dry basis) was 52 million tonnes, with an average yield of 1.4 mt ha^{-1}. By contrast, in 2010/2011, the average consumption of N, P_2O_5, and K_2O was estimated to reach 39.9, 52.4, and 49.2 kg ha^{-1}, respectively, representing an increase of 5.2, 4.6, and 5.8 times the rate of consumption compared with 1970/71. The cultivated area reached

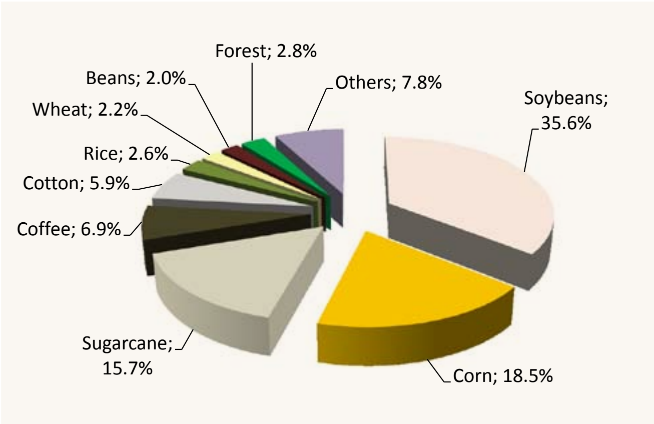


Fig. 2. Brazilian fertilizer market share by crop in 2011. *Source:* ANDA.

64 million ha in 2009/2010, with a total production of 258 million mt of 16 major crops and a yield of 4.0 mt ha^{-1}. These data represent a 1.8 fold increase in cultivated area, with a corresponding 2.9 fold increase in yield (from 1.4 to 4.0 mt ha^{-1}), leading to five times the total increase in production. The estimated area spared from this increase in yield – which has a lot to do with adequate use of nutrients – was 77 million ha of land, an area equivalent to half of the Amazon State in Brazil.

These data also reveal that K was the nutrient with the highest increase in use, especially over the two most recent cropping seasons (2010/11) in Brazil (Fig. 1). Indeed, when comparing the data for total nutrient consumption for 2011 with that of 1970, a 14.4 fold increase in K_2O consumption took place during this period, as compared with a 12.2 fold increase in N, and 9.3 fold increase in P_2O_5. This important growth in nutrient consumption has occurred mainly in the last two decades, starting with the expansion of the no-till area in Brazil and reaching 25.5 million ha in 2006, much of which took place in the Cerrado region (11.9 million ha under no-till in 2006).

That the largest relative increase in consumption was for K_2O, as compared with N and P_2O_5, is noteworthy. While contributing to an increase in production and yield of Brazilian agriculture, it has been shown that the adequate use of K in the Cerrado has many additional benefits, including reduction of water and thermal stresses, improved quality of agricultural products, increased protein synthesis, better fruit set, and higher N fixation in legumes.

Fertilization and soil management practices

Liming

Liming is an essential management practice for non-acid tolerant crops to correct low pH and Al toxicity (Table 2). The average rates of lime are 3 mt ha^{-1} (range 1 to 5), broadcast and incorporated into the soil profile as deep as possible to help increase rooting depth and, thus, tolerance to dry spells during the cropping (rainy) season. For established perennial crops, improved pastures and grain crops under no-till or minimum tillage, rates of lime are in general 25 percent of normal rates.

Since most of these low pH soils are also deficient in Ca and Mg, dolomitic lime or Mg lime are commonly recommended. The method generally used to evaluate lime needs in the region is that of an increase in base saturation, the rate of lime being determined by the following equation:

$$\textit{Rate of lime } (mt\ ha^{-1}) = T\ (V2 - V1)/100$$

where T = CEC at pH 7.0; V2 = base saturation adequate for a given crop and V1 = base saturation at pH 7.0 (Quaggio *et al.*, 1983).

Table 2. Economic balance of the liming effect on three crops in Brazil.

Lime rate in the first year	Production increase after liming: First year	Production increase after liming: Period under review
mt ha⁻¹	--------------------*kg ha⁻¹*--------------------	
Five years of corn		
3.0	422	7,877
6.0	600	11,619
9.0	1,250	13,777
Three years of soybean		
1.5	473	1,746
3.0	513	2,357
4.5	645	2,610
Four years of cotton		
1.5	32	1,072
3.0	245	2,609
6.0	442	4,092

Source: Raij and Quaggio, 1984.

For most crops, V2 values are 50 percent and the Ca:Mg ratio must be maintained between 1:1 and 10:1, with a minimum of 0.5 $cmol_c$ Mg/dm^3 (Sousa and Lobato, 2004). The residual effects of these lime rates can vary from three to five years. Lime should be broadcast and incorporated at least 60 to 90 days before planting or fertilization.

Amelioration of subsoil acidity

In most cases the beneficial reactions of lime occur only in the incorporation layer. Low levels of Ca and Al toxicity may still restrict rooting depth in sub-surface soil layers (Lopes, 1983; Goedert, 1987). Under these conditions the application of agricultural gypsum, a by-product of phosphoric acid production, has been shown to be an efficient management practice to increase rooting depth below the surface layer (Photo 1).

It is extremely important to evaluate acidity parameters (pH, Ca and Al levels) in the surface layer (0-20 cm), and to depths of 20 to 40 and 40 to 60 cm. For perennial crops, evaluations should also include the 60 to 80 cm depth. For areas with 0.3 $cmol_c$ Ca/dm^3 or less, and/or 0.5 $cmol_c$ Al/dm^3 or more, and/or more than 30 percent Al saturation of the effective CEC in these sub-surface layers, the use of agricultural gypsum at higher rates is recommended to enable the movement of Ca down these layers and/or to reduce Al toxicity throughout the soil profile (Lopes, 1983; Lopes, 1986). The simplest soil parameter to evaluate rates of gypsum under these conditions is the clay percentage.Two approaches are most commonly used:

- Rate of gypsum (kg ha^{-1}) = 300 + (20 x % clay), developed by Lopes and Guilherme (1994), to improve the 20 to 40 cm layer.

- Rate of gypsum (kg ha^{-1}) = 50 x % clay, developed by Sousa and Lobato (2004), to improve the 20 to 60 cm layer. For perennial crops, multiply the results by 1.5.

Increase in yields from gypsum use in these soils is mainly a consequence of greater rooting depth and more efficient use of sub-soil water and nutrients. Agronomic responses from gypsum use have been reported as: 72, 59, 14, 30, and 80 percent for corn, wheat, soybean, coffee and lucerne, respectively. Significant responses have also been obtained for mango, orange and sugarcane (Sousa, Lobato and Rein, 1995). The recommended rates of gypsum are generally surface broadcast at 60 to 90 days after liming. Residual effects last from 5 to 15 years.

Photo 1. Cotton root development in depth without (left) and with (right) application of 3 mt gypsum ha^{-1}. Each square is 15 cm by 15 cm. Photo courtesy of D.M.G. Sousa. *Source:* Sousa and Rein, 2009.

Build-up of phosphate fertilization

These soils are extremely low in available P so building up phosphate fertility has been a crucial step in achieving adequate and economic yields over a short period of time. Average available soil P content is 0.4 mg/dm^3, and soil P fixation capacity is extremely high. There is a well-defined relationship between clay percentage, since most of these soils have low activity clay minerals, and application rate of P needed to build levels of soil P. In general, high clay content is related to high P fixation capacity. Consequently, fine-textured soils, such as clay loam soils, have a greater P fixing capacity than sandy coarse-textured soils. Clays of the 1:1 type (kaolinite) have a greater P fixing capacity than the 2:1 type clays (montmorillonite, illite, vermiculite). Soils formed under high rainfall and high temperatures, like Cerrado soils, contain large amounts of kaolinitic clays and therefore have a much greater P fixing capacity than soils containing the 2:1 type clay. High temperatures and high rainfall also increase the amount of Fe and Al oxides in the soil, which contribute greatly to the fixation of P added to the Cerrado soil.

Table 3. Recommended application rate for total build-up of P fertilization for the Cerrado region based upon clay percentage.

Clay	Extractable soil P level					
	Upland systems			Irrigated systems		
	Very Low	Low	Medium	Very Low	Low	Medium
%	--------	------	*kg P_2O_5 ha^{-1}**	------	------	--------
≤15	60	30	15	90	45	20
16-35	100	50	25	150	75	40
36-60	200	100	50	300	150	75
>60	280	140	70	420	210	105

*For acidulated phosphates: P_2O_5 soluble in neutral ammonium citrate plus water. For thermal phosphates and basic slags: P_2O_5 soluble in 2% citric acid (1:100 ratio). For reactive natural phosphates: total P_2O_5.

Source: Adapted from Sousa and Lobato, 2004.

According to Lopes (1983), for each one percent of clay, 3 to 5 kg of soluble P_2O_5 is required, generally broadcast in the first year and incorporated by disking before planting, followed by small maintenance crop fertilization to achieve the desired yield goal within three years of incorporation. More detailed recommendations for build-up P fertilization, based upon clay content, level of soil available P, under rainfed or irrigation are presented in Table 3. Higher doses are required for soils containing very low levels of soil P, as well as for soils containing higher amounts of clay. If a soil has an adequate P content, then the build-up P fertilization is not recommended.

Another common approach to gradually building up P status in these soils is to apply a little excess P_2O_5 at planting (30-40 kg ha^{-1} above normal maintenance crop fertilization). This rate should be applied for five to six years. After P soil levels reach medium to high levels, then only maintenance fertilization is used. For grain crops, sugarcane and coffee, soluble P fertilizers (i.e. single superphosphate, triple superphosphate, thermophosphate or highly reactive rock phosphates) have been confirmed as the most efficient sources for use following liming. Due to the low reactivity of most Brazilian rock phosphates, these products are usually only recommended for direct application when opening new areas with pastures of acid tolerant species (Smyth and Sanchez, 1982; Goedert and Lobato, 1984; Goedert and Lopes, 1988). Since liming reduces the agronomic effectiveness of low reactivity rock phosphates even more, lime in these cases is recommended at 25 percent of normal rates (Lopes and Guidolin, 1989).

Table 4. Recommendation of build-up K fertilization for the Cerrado region.

Extractable soil K	Interpretation	Total build-up	Gradual build-up
mg/dm³		-------------------*kg K_2O ha⁻¹* ------------------	
CEC at pH 7.0 less than 4.0 $cmol_c/dm^3$			
≤15	Low	50	70
16-30	Medium	25	60
31-40	Adequate[1]	0	0
>40	High[2]	0	0
CEC at pH 7.0 more than or equal to 4.0 $cmol_c/dm^3$			
≤25	Low	100	80
26-50	Medium	50	60
51-80	Adequate[1]	0	0
>80	High[2]	0	0

[1]For soils with adequate level of extractable K, rates of K_2O are recommended according to expected yield.
[2]For soils with high level of extractable K, rates of K_2O of 50 percent of the maintenance fertilization or expected/estimated K extraction are recommended in the last production.
Source: Adapted from Sousa and Lobato, 2004.

Build-up of potash fertilization

Building-up levels of K is also recommended for soils with low or medium extractable K. Rates are also estimated according to CEC at pH 7.0 (Table 4). Soils with CEC at pH 7.0 of less than 4.0 $cmol_c/dm^3$ present a high potential for leaching losses (Mclean and Watson, 1985). Under these conditions rates above 40 kg ha^{-1} K_2O must be split in band applications or applied broadcast. Rates to total build-up of K fertilization for broadcast application can also be calculated to achieve 3 to 5 percent K saturation of CEC at pH 7.0 (Lopes and Guidolin, 1989).

Role of K in the growth of soybean crop

Potassium is one of the major nutrients considered essential for crop growth and yield development, even though it is not an integral component of any cellular organelle or structural part of the plant. It is the most abundant cation in plants and is associated or involved with many of the physiological processes supporting plant growth and development. Water relations, photosynthesis, assimilate transport and enzyme activation are all affected by K (Pettigrew, 2008). Furthermore, Mengel (1980) also demonstrated that the transport of amino acids is enhanced by higher K levels, especially the transport of amino acids to developing seeds.

With regard to the demand of K_2O for agricultural crops in Brazil, soybean cultivation is ranked first, due to its high cultivated area (about 25 million ha in 2012) (IBGE, 2012).

According to Sacramento and Rosolem (1998), K plays a particularly important role in the mineral nutrition of soybean since K is one of the macronutrients taken up and translocated within the crop in highest amounts. One of the more obvious visual symptoms of insufficient levels of plant K is a reduction in plant growth (Pettigrew and Meredith, 1997). This reduction in biomass occurs because soybean plants growing under K deficiency often have a marked decrease in leaf area and size (Lana *et al.*, 2002).

To achieve or maintain maximum yields, supplemental K_2O fertilization is often required, particularly in Cerrado soils. Many researchers have reported soybean yield increases in response to K_2O fertilization. Lana *et al.* (2002) found that increased soybean yield under high K fertility was due to increasing production of both total and main stem pods per plant and more seeds per pod. The positive yield response to K can also be attributed to increases in most of the yield components, e.g. the number of pods per plant (Lana *et al.*, 2002), the weight of individual seeds (Serafim *et al.*, 2012), and increased number of nodules and N fixation in some soybean cultivars (Novo *et al.*, 1999). K thus not only promotes the production of carbohydrates in the leaves but also enhances their transport to the root system for use as an energy source for nodule formation, thereby stimulating N_2 fixation (Armstrong, 1998). Moreover, in Cerrado soils, where water is a major limiting factor for successful soybean production, K may temper water stress due to its role in cell turgor control and metabolic activity.

K can play a role in quality development of many crops (Usherwood, 1985). In soybean, Tanaka *et al.* (1995) found K fertilization increases seed oil content. Soybean seeds also contain isoflavones, a group of phytochemicals thought to provide human health benefits. Yin and Vyn (2004) reported that K fertilization increased the isoflavone concentration of the seeds.

Build-up of micronutrient fertilization

The concept of building-up fertility of Cerrado soils also includes micronutrients. Micronutrient fertilizers can be broadcast to those soils with naturally low micronutrient availability (Zn, Cu, B, Mn, and Mo). When these micronutrients are at a low level, a broadcast application is recommended of: 2, 2, 6, 0.4 and 6 kg ha^{-1} of B, Cu, Mn, Mo and Zn, respectively. These rates can be split into three band applications, annually. At medium level, 25 percent of these rates are recommended on band applications. At a high level of available micronutrients, application is not recommended.

Organic matter management

The great majority of Cerrado soils contain low activity clays, medium organic matter content and very low CEC, more than 70 percent of which is due to the organic fraction. Under management systems that include monocropping, conventional tillage and use of lime and fertilizers, organic matter depletion occurs quickly and can reach unsustainable levels after a few years of cultivation. Under these conditions it is extremely important to make use of a combination of more sustainable agricultural practices to avoid rapid declines in organic matter content.

Practices such as crop rotation including improved pastures, green manure, minimum or no-tillage, cover crops, mulching in the case of small farms, manure and adequate crop residues are all important management tools. The rapid increase in no-till in the region in recent years is certainly a key factor for future sustainable agricultural development.

Maintenance fertilization

Following the build-up program, adequate and balanced maintenance programs are essential to maintain soil fertility and optimum crop production potential. Maintenance fertilization for primary micronutrients is generally based on expected yield, soil and plant analysis.

Final remarks

During the last 50 years, the Cerrado region has changed from an area once considered marginal for agricultural production to that of high agricultural productivity; an example of an agricultural revolution. A great investment in research in several agronomic areas over this period has enabled the development of a number of management strategies that has allowed the Cerrado to become one of the most productive regions in Brazil in terms of grain, beef cattle, and agro-energy production, as well as reforestation. In addition, in order to become an example of "green agriculture", a series of more sustainable management technologies have been introduced to this region in recent years including:

- Increasing use of crop rotation and cover crops (e.g. Photo 2).
- No till and/or minimum tillage: in 1990 Brazilian farmers used no-till farming for 2.6 percent of their grain crops; today it is over 50 percent.
- Integration of crop-livestock production and/or crop-livestock-forest production (e.g. Photo 3): eucalyptus is one of the species most used in commercial systems, but over 100 useful species have been identified for agroforestry systems in the Cerrado (Schorr, 2001).

Photo 2. Brachiaria as a cover crop in maize field.
Source: Courtesy of R. Trecenti.

Photo 3. Crop-livestock-forest production system.
Source: Courtesy of R. Trecenti.

We believe that harmonious coexistence of agribusiness with the rational use of natural resources in this region – aiming at a more sustainable production process – requires not only increasing research efforts on various agronomic issues but also actions to remove several logistical problems. Among the numerous factors that limit a more robust growth of agricultural production in this region, two are worth mentioning: inadequate physical infrastructure and transport. Transport and logistical issues affect not only the final price of the agricultural output, but also the supply of competitively priced inputs to agriculture which, in the case of the Cerrado region, is strategic, since sustainable production is highly dependent on an adequate supply of lime and fertilizers, among other agronomic inputs.

References

Armstrong, D.I. 1998. Better Crops with Plant Food 82(3).

Borlaug, N.E., and C.R. Dowswell. 1998. Fertilizer: to Nourish Infertile Soil that Feeds a Fertile Population that Crowds a Fragile World. Keynote address at the 61st Annual Conference, International Fertilizer Industry Association (IFA), May 24-27, 1993, New Orleans, Louisiana, USA. 18 p.

Embrapa. 2012. Embrapa Cerrados – Apresentação. From http://www.cpac.embrapa.br/unidade/apresentacao/

Goedert, W.J. 1987. Management of Acid Tropical Soils in Savannas of South America. p. 109-127. *In:* IBSRAM (International Board for Soil Research and Management). Management of Acid Tropical Soils for Sustainable Agriculture: Proceedings of an IBSRAM inaugural workshop. Bangkok, Thailand.

Goedert, W.J., and E. Lobato. 1984. Avaliação agronômica de fosfatos em solos de cerrado. R. bras. Ci. Solo, Campinas, SP, 8:97-102.

Goedert, W.J. 1989. Região dos cerrados: potencial agrícola e política para o seu desenvolvimento. Pesq. agropec. bras., Brasília, DF, Brasil, 24(1):1-17.

Goedert, W.J., and A.S. Lopes. 1988. Eficiência agronômica de fertilizantes fosfatados para culturas anuais, perenes, pastagens e reflorestamento. p. 24-29. *In:* Seminário sobre recuperação de fósforo. São Paulo, SP, IBRAFOS.

IBGE. Levantamento sistemático da produção agrícola. Pesquisa mensal de previsão e acompanhamento das safras agrícolas no ano civil. Agosto 2012. Available at http://www.ibge.gov.br/home/estatistica/indicadores/agropecuaria/lspa/lspa_201208.pdf

Lana, R.M.Q, O.T. Hamawaki, L.M.L. Lima, and L.A. Zanão jr. 2002. Resposta da soja a doses e modos de aplicação de potássio em solo de cerrado. Bioscience Journal 18:17-23.

Lopes, A.S. 1983. Solos sob "cerrado": características, propriedades e manejo. Associação Brasileira para a Pesquisa da Potassa e do Fosfato, Piracicaba, SP. 162 p.

Lopes, A.S. 1986. Calagem e gesso agrícola. Encontro técnico sobre gesso agrícola. Fosfértil/Petrofértil, Belo Horizonte, MG. 58 p. (mimeo).

Lopes, A.S., and F.R. Cox. 1977. A survey of the soils under cerrado vegetation in Brazil. Soil Science Society of America Journal 41:742-747.

Lopes, A.S., and E. Daher. 2008. Agronegócio e recursos naturais no cerrado: desafios para uma coexistência harmônica. *In:* Faleiro, F. G.; Farias Neto, A. L. de (ed.). Savanas: desafios e estratégias para o equilíbrio entre sociedade, agronegócio e recursos naturais. Planaltina, DF: Embrapa Cerrados, 2008. cap. 5, p. 173-209.

Lopes, A.S., and J.A. Guidolin. 1989. Interpretação de análise de solos: conceitos e aplicações. ANDA, São Paulo, SP, Boletim Técnico N° 2, 3a. edição. 64 p.

Lopes, A.S., and L.R.G. Guilherme. 1994. Solos sob cerrado: manejo da fertilidade para produção agropecuária. ANDA, São Paulo, SP, Boletim Técnico N° 5, 2a edição. 62 p.

Macedo, J. 1995. Prospectives for the rational use of the Brazilian Cerrados for food production. Planaltina, EMBRAPA- CPAC. 19 p.

Malavolta, E., and H.J. Kliemann. 1985. Desordens nutricionais no cerrado. Piracicaba: Potafos, 1985. 136 p.

Mclean, E.D., and M.E. Watson. 1985. Soil Measurement of Plant Available Potassium. *In:* Munson, R.D., ed. Potassium in Agriculture. Madison, American Society of Agronomy, p. 277-308.

Mengel, K. 1980. Effect on Potassium on the Assimilate Conduction to Storage Tissue. Berichte der Deutschen Botanischen Gesellschaft 93:353-362.

Novo, M.C.S.S., R.T. Tanaka, H.A.A. Mascarenhas, N. Bortoletto, P.B. Gallo, J.C.N.N.A. Pereira, and A.A.T. Vargas. 1999. Nitrogênio e potássio na fixação simbiótica de n2 por soja cultivada no inverno. Scientia Agricola, 56:143-156.

Oliveira Neto, S.N., A.B. Vale, A.P. Nacif, M.B. Vilar, and J.B. Assis. Sistema agrossilvipastoril - integração lavoura, pecuária e floresta. 1ª. ed. Viçosa, MG: Sociedade de Investigações Florestais - SIF, 2010. 189 p.

Pettigrew, W.T. 2008. Potassium Influences on Yield and Quality Production for Maize, Wheat, Soybean and Cotton. Physiologia Plantarum 133:670-681.

Pettigrew, W.T., and W.R. Meredith jr. 1997. Dry Matter Production, Nutrient Uptake, and Growth of Cotton as Affected by Potassium Fertilization. Journal of Plant Nutrition 20:531-548.

Quaggio, J.A. 1983. Critérios para calagem em solos do estado de São Paulo. Unpublished manuscript M.S. thesis. ‚Escola Superior de Agricultura "Luis de Queiroz," Piracicaba, SP, 76 p.

Sacramento, L.V.S., and C.A. Rosolem. 1998. Eficiência de absorção e utilização de potássio por plantas de soja em solução nutritiva. Bragantia 57(2):355-365.

Serafim, M.E., F.B. Ono, W.M. Zeviani, J.O. Novelino, and J.V. Silva. 2012. Umidade do solo e doses de potássio na cultura da soja. Revista Ciência Agronômica 43:222-227.

Schorr, M. 2001. Sistemas agroflorestais para o Brasil. Instituto Anima. 64 p.

Sousa, D.M.G. de, and E. Lobato. 2004. Cerrado. Correção do solo e adubação. Planaltina, DF, Embrapa Cerrados. 2nd edition, 416 p.

Sousa, D.M.G. de, and T.A. Rein. 2009. Manejo da fertilidade do solo para culturas anuais: experiências no cerrado. Informações Agronômicas, Nº 126, Junho 2009. IPNI, Piracicaba, SP, p. 1-7.

Sousa, D.M.G. de, E. Lobato, and T.A. Rein. 1995. Uso de gesso agrícola nos solos dos cerrados. p. 20. Planaltina, DF, EMBRAPA-CPAC, Circular Técnica N° 32.

Smyth, T.J., and P.A. Sanchez. 1982. Phosphate Rock Dissolution and Availability in Cerrado Soils as Affected by Phosphorus, Sorption Capacity. Soil Sci. Soc. Am. J., Madison, Wisconsin, USA, 46:339-34.

Tanaka, R.T., H.A.A. Mascarenhas, M.A.B. Reginato-D'Arce, and P.B. Gallo. 1995. Concentração e produtividade de óleo e proteína de soja em função da adubação potássica e calagam. Pesquisa Agropecuaria Brasileira 30:463-469.

Usherwood, N.R. 1985. The Role of Potassium in Crop Quality. *In:* Munson, R.D. (ed.) Potassium in Agriculture. ASA, CSSA and SSSA, Madison, WI, p. 489-513, 1985.

Yin, X., and T.J. Vyn. 2004. Critical Leaf Potassium Concentrations for Yield and Seed Qualtiy of Conservation-Till Soybean. Soil Science Society of America Journal 68:1626-1634.

The paper "The Saga of the Agricultural Development of the Brazilian Cerrado" also appears on the IPI website at:

Regional Activities/Latin America