REFEREED PAPER

REVIEW OF BRAZILIAN RESEARCH ON SUBSOIL ACIDITY

SUMNER ME

Regents' Professor of Environmental Soil Science Emeritus,
University of Georgia, Athens, GA 30602, USA
malcolm296@charter.net

Abstract

Perusal of past Proceedings of the South African Sugar Technologists' Association shows that very little transfer of information on soil acidity has taken place from the Brazilian literature, which is replete with many excellent contributions on the subject. This is despite the fact that the original impetus for the work in Brazil came from research conducted in KwaZulu-Natal in the 1960s and 1970s. This one-way transfer of technology has stemmed largely from the language barrier. To make amends, the research on this topic in Brazil conducted over the past 20 years will be reviewed with the aim of presenting a case for renewed work on subsoil acidity in the South African sugar industry. The Brazilian work shows that considerable yield responses to gypsum are possible as a result of the amelioration of subsoil acidity. The best yields were obtained when lime was used to address acidity in the topsoil and gypsum in the subsoil.

Keywords: sugarcane, aluminium, gypsum, lime, root growth, calcium/magnesium balance

Introduction

Research on the non-invasive amelioration of subsoil acidity stems from initial work, started in the early 1960s, in South Africa by Sumner (1970) and Reeve and Sumner (1972). These studies showed that the toxic Al^{3+} ion in acid subsoils could be neutralised by the surface application of gypsum. Being much more soluble than lime, the gypsum was able to move down into the subsoil where, as a result of the so-called 'self-liming effect', the Al was precipitated. Shortly thereafter, Gonzalez (1976) in North Carolina working on a red yellow Oxisol from the Cerrado of Brazil, where crop production up to that point had been difficult or impossible due to the strongly acidic nature of the soils, presumed that the crop responses to long-term annual applications of ordinary superphosphate (OSP) at 218 kg P/ha/yr, which contains approximately 50% gypsum, were due to the movement of Ca into the subsoil. Following up on this work, Ritchey *et al*. (1980) confirmed and extended the concept that gypsum was an effective non-invasive ameliorant for subsoil acidity in a leaching experiment. Field confirmation came from a maize (*Zea mays*) experiment on a dark red Oxisol from the 'Cerrado' in which ordinary and triple superphosphate (TSP) were compared at equivalent P rates (873 kg P/ha). The effect of the gypsum contained in the OSP (± 5 t) on Al saturation, exchangeable Ca+Mg and moisture content in the soil, which was sampled to depth five years after the initial P application, is illustrated in Figure 1. These results show that the gypsum contained in the OSP did in fact move into the subsoil where it reduced the Al saturation and permitted the entry of roots so that they could access water previously beyond their reach. Following the publication of these results, this subsoil amelioration strategy was rapidly applied to many other crops throughout Brazil and, in so doing, facilitated the opening up of the Cerrado to crop production which is now the breadbasket of Brazil.

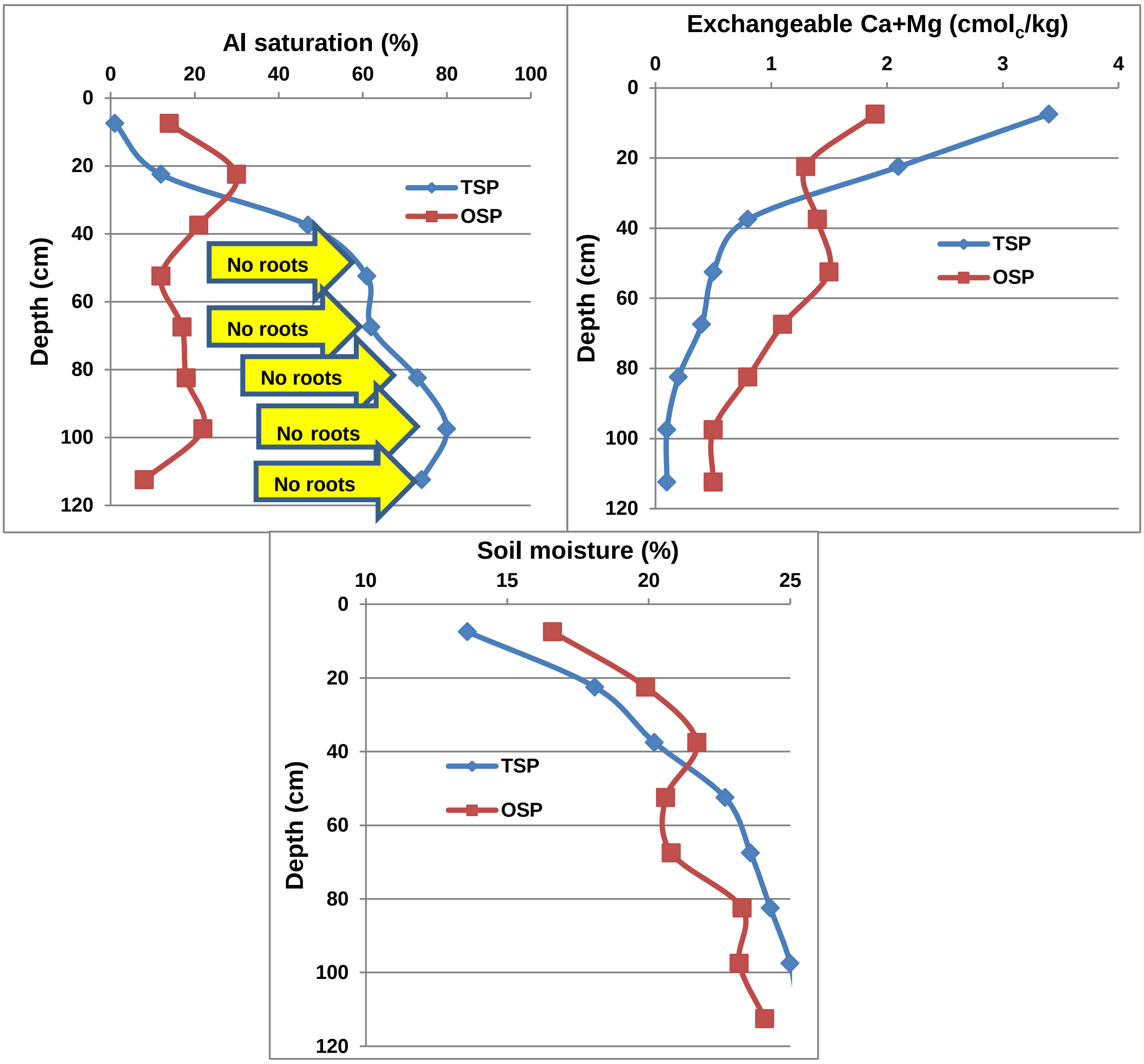

Figure 1. Effect of applications of ordinary superphosphate (OSP) and triple superphosphate (TSP) at rates of 873 kg P/ha on Al saturation, exchangeable Ca+Mg and soil moisture down the profile of a Brazilian Oxisol. Note the absence of roots in the subsoil in the TSP treatment which received no gypsum. No error terms were presented (Ritchey *et al*., 1980).

As this work started in South Africa, it is appropriate to complete the cycle by summarising a portion of Brazilian work, specifically on sugarcane (*Saccharum officinarum*), for potential application in the South African sugar industry. A survey shows that there has been little exchange of technology on this topic between Brazil and South Africa, presumably due largely to the language barrier.

Although the focus of this paper will be on sugarcane, results for other crops are available in the Brazilian literature from which valuable lessons can be learned. A recent publication by van Raij (2008) summarises all the Brazilian experience with gypsum in ameliorating subsoil acidity and is worthy of consultation. This paper will focus mainly on a discussion of the effects of gypsum on acid subsoil amelioration in sugarcane because lime, due its relative insolubility, has been shown to be less effective in moving down the profile to neutralise subsoil acidity (Reeve and Sumner, 1972; Sumner, 1994).

Sugarcane responses to gypsum and lime in Brazil

Initial work on phosphogypsum in Brazil (Vitti *et al*., 1984; Fernandez, 1985; Vitti *et al*., 1989) demonstrated sugarcane yield responses (8-14 t cane/ha) to low rates of phosphogypsum (139-650 kg/ha) as a result of responses to S.

The first sugarcane yield responses to the amelioration of subsoil acidity by application of phosphogypsum up to 2 t/ha were reported by Demattê (1986) (Table 1). Gypsum markedly reduced Al saturation in the subsoil which promoted better root and cane growth. Subsequently, Morelli *et al*. (1987) demonstrated the close relationship between exchangeable Ca and sugarcane root density with depth in a highly infertile sandy alic Oxisol after the application of up to 6 t phosphogypsum/ha (Figure 2). Such a relationship for maize roots had first been reported by Ritchey *et al.* (1981) down to 2 m depth. Similar results were obtained by Mazza *et al*. (1991). They also showed that phosphogypsum could be more effective than lime in promoting root growth, particularly at depth in the soil, whereas lime was better in the topsoil. Morelli *et al*. (1987) followed the decline in base saturation that occurred over five crops of sugarcane (Figure 3). Clearly the basic cations applied in the dolomitic lime and phosphogypsum treatments are being leached out of the soil over time, with some being taken up by the crop. Unfortunately, no data for exchangeable Al were presented, so it is not clear whether the soil was reacidified or whether the cation loss was due simply to reversal of the variable charge sites that were originally activated by the dolomitic lime and phosphogypsum treatments.

In Brazil, base saturation is expressed on the basis of the effective cation exchange capacity (sum of exchangeable Ca+Mg+K+Na+Al). Subsequent work by Morelli *et al*. (1992) answered this question by showing that exchangeable Al was not increased and pH even increased or stayed the same 27 months after application of dolomitic lime and phosphogypsum relative to the values at 18 months (Table 2). Consequently, the changes in soil chemistry (Al precipitation) brought about by the dolomitic lime and phosphogypsum appear to be somewhat permanent, lasting for as long as 15 years after amendment as, shown by Toma *et al.* (1999).

Table 1. Effect of phosphogypsum at 2 t/ha on base saturation and yield of sugarcane grown on a sandy dystrophic Oxisol in Brazil (Demattê, 1986).

Treatment	Depth (cm)	Base saturation** (%)	Cane yield* (t/ha)
Control	0-20	60	87
	20-40	25	
	40-60	15	
Gypsum (2 t/ha)	0-20	64	101
	20-40	45	
	40-60	23	

*Mean of plant and four ratoons
**Three years after application

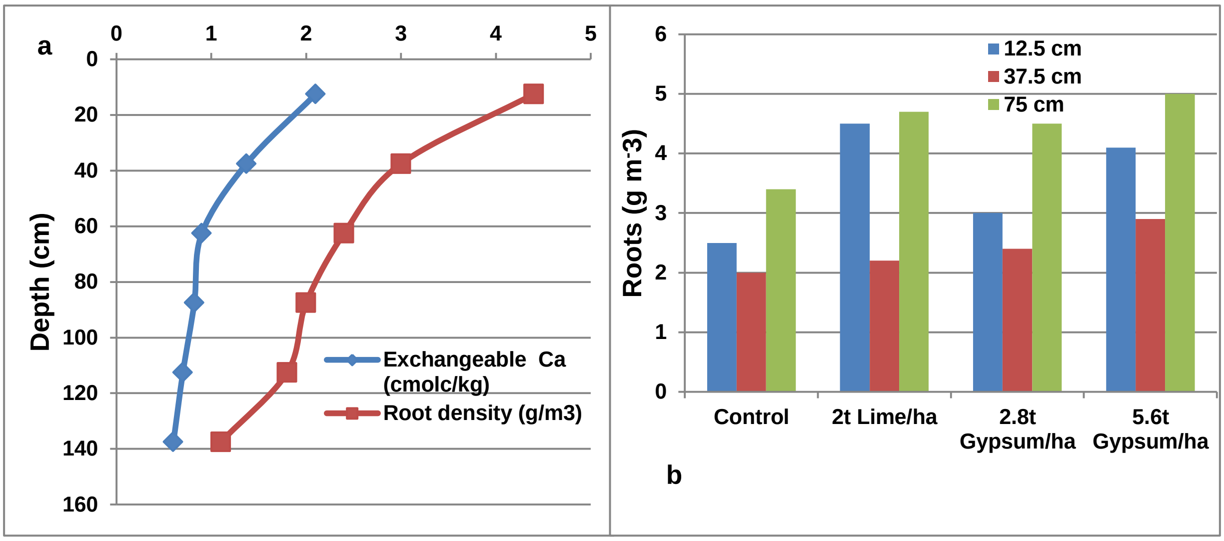

Figure 2. (a) Relationship between root density and exchangeable Ca and (b) effect of phosphogypsum and dolomitic lime on root density at three soil depths in a Brazilian Oxisol (Morelli *et al.*, 1987).

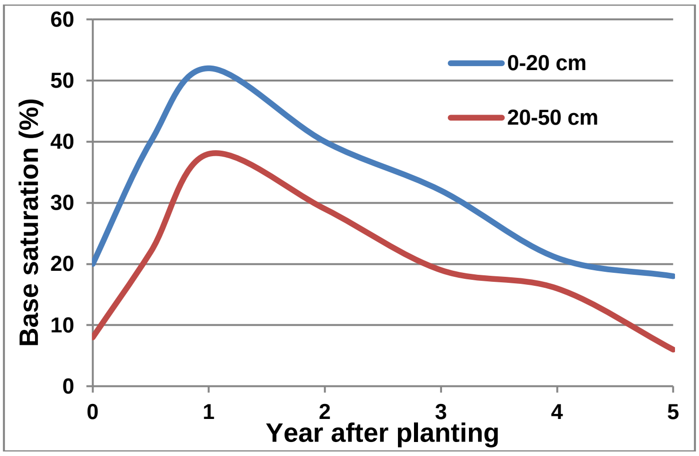

Figure 3. Change in base saturation of a light textured Brazilian Oxisol treated with lime and phosphogypsum over a plant and four ratoon crops of sugarcane (Morelli *et al.*, 1987).

Table 2. Effect of time after application of dolomitic lime (6 t/ha) and phosphogypsum (6 t/ha) on soil pH and exchangeable Al with depth in a Brazilian Oxisol under sugarcane (data from Morelli *et al.*, 1992)

Depth (cm)	pH $CaCl_2$		Exchangeable Al	
	After 18 months	After 27 months	After 18 months	After 27 months
			$cmol_c/dm^3$	
0-25	5.0	5.3	0.07	0.05
25-50	4.2	4.5	0.52	0.35
50-75	4.2	4.2	0.56	0.57
75-100	4.2	4.3	0.50	0.50
100-125	4.3	4.3	0.54	0.46

Vitti (1991), who studied combinations of phosphogypsum and dolomitic lime at different rates on sugarcane, showed that the cane yield response to gypsum was a little more marked than that to lime alone (Figure 4), but in combination the two ameliorants produced the highest yields. He was the first in Brazil to link reductions in exchangeable Al to the yield response obtained from phosphogypsum. From Figure 5, it can be seen that increasing the rate steadily decreased Al saturation down the profile. He also showed that phosphogypsum applications caused the transfer of exchangeable Mg and K from the upper to lower depths in the soil, as had been demonstrated previously by Reeve and Sumner (1972).

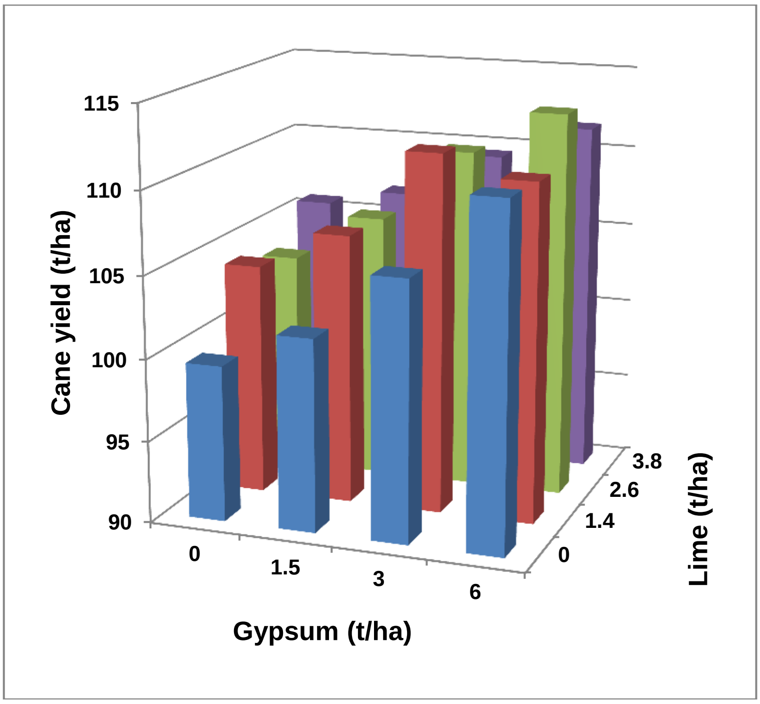

Figure 4. Effect of dolomitic lime and phosphogypsum on sugarcane yield on a Brazilian Oxisol averaged over a plant and two ratoon crops (data from Vitti, 1991).

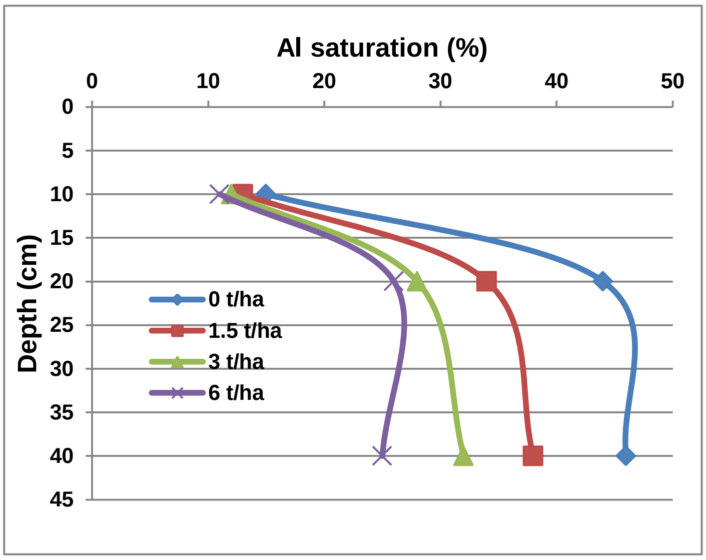

Figure 5. Effect of different rates of gypsum on Al saturation with depth in a Brazilian Oxisol (Vitti, 1991).

The first comprehensive study of varying rates (0, 2, 4, 6 t/ha) of phosphogypsum and dolomitic lime on the amelioration of Brazilian acid subsoils was published by Morelli *et al*. (1992). They demonstrated that dolomitic lime was effective in neutralising exchangeable Al in the upper 40 cm (Figure 6), and that a combination of lime and gypsum was even more effective in reducing exchangeable Al down the entire profile.

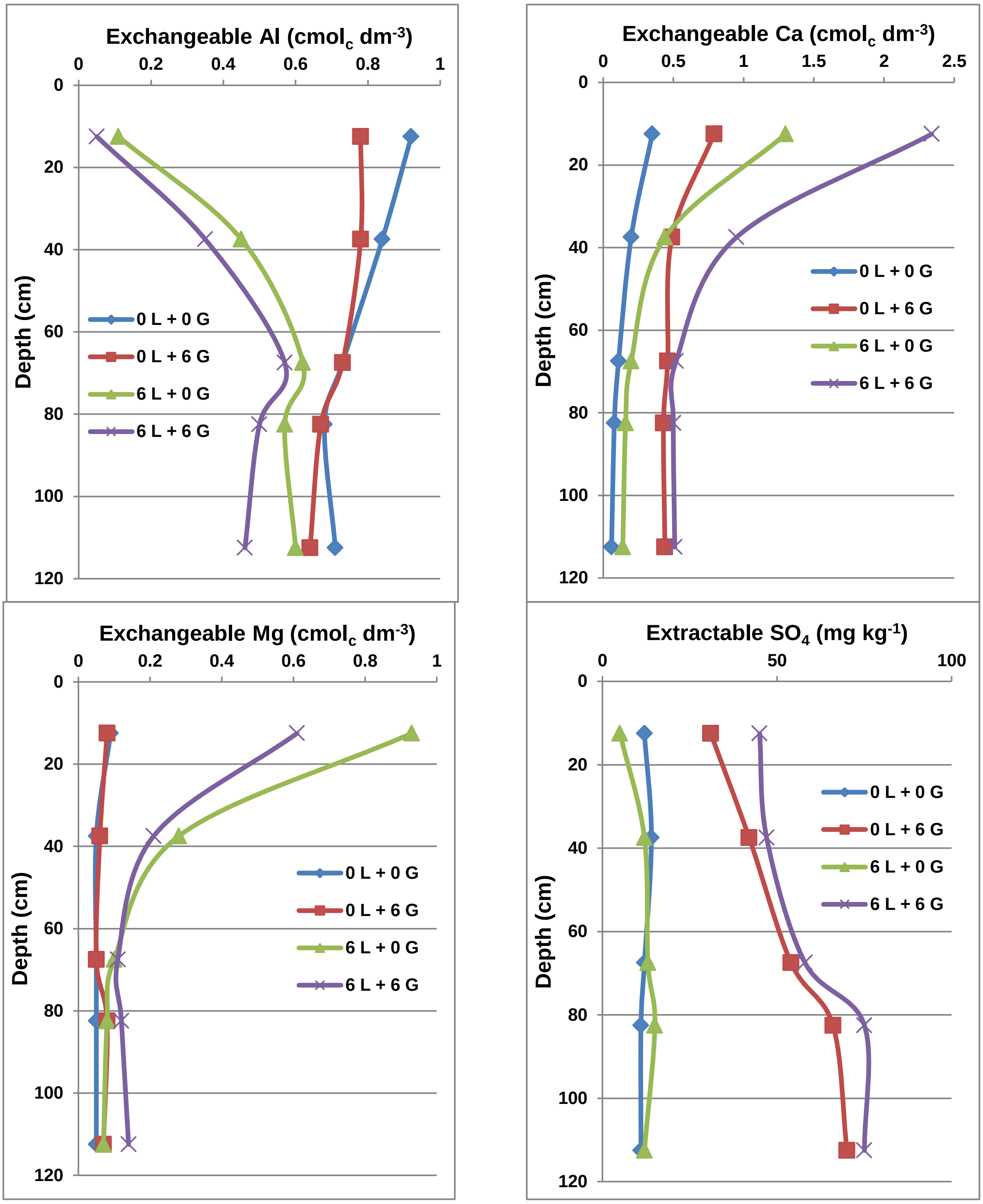

Figure 6. Comparison of the effects of broadcast and incorporated dolomitic lime (0 and 6 t/ha) and gypsum (0 and 6 t/ha) on soil chemical properties with depth in a dark yellow alic Oxisol of medium texture 27 months after application. No estimates of error were presented. (data from Morelli *et al*., 1992).

The phosphogypsum and dolomitic lime plus phosphogypsum treatments were the most effective in promoting the movement of Ca into the subsoil but, for exchangeable Mg, the dolomitic lime plus phosphogypsum combination resulted in the greatest transfer. Treatments including phosphogypsum increased SO_4 down the profile, with marked accumulations in the subsoil where the mineral surfaces have long been known to hold SO_4 in exchangeable form (Coleman and Thomas, 1967). Dolomitic lime alone and to some extent phosphogypsum alone increased soil pH in the upper 40 cm, and the combination of dolomitic lime and phosphogypsum effectively increased pH to depth in the profile (Figure 7). Yield responses to these treatments are presented in Figure 8. The effect of phosphogypsum was more pronounced than that of dolomitic lime at equivalent rates, but again the highest yields were obtained with combinations of the two, with 4 t dolomitic lime plus 2 t phosphogypsum/ha being the best. The benefits of applying both together were confirmed by Medina *et al.* (2000), Oliveira *et al.* (2005) and Lemes *et al.* (2009), while Lorenzetti *et al.* (1992) found that 2 t phosphogypsum/ha, or in combination with dolomitic lime, was as good as higher rates in increasing cane yield. They also showed that dolomitic lime promoted root growth more in the topsoil than did phosphogypsum, but the reverse was true in the subsoil (Figure 9).

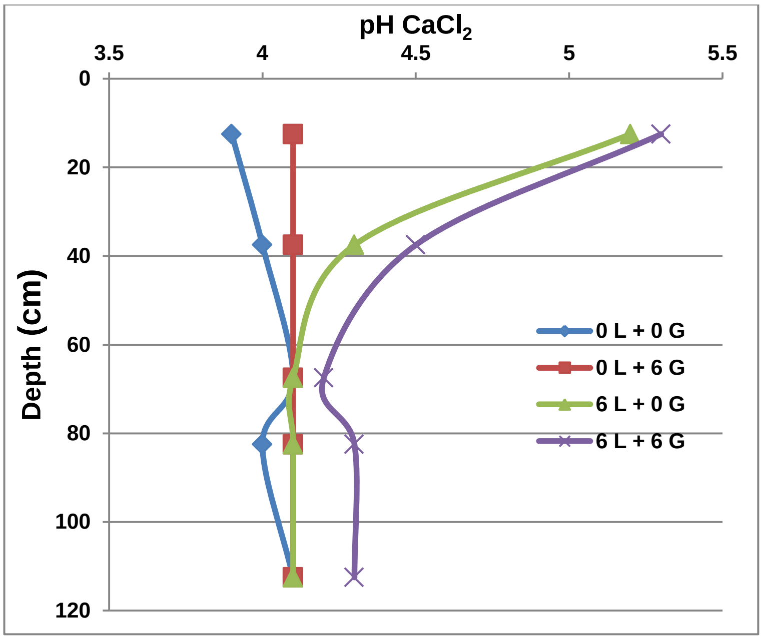

Figure 7. Comparison of the effects of broadcast and incorporated dolomitic lime (0 and 6 t/ha) and gypsum (0 and 6 t/ha) on soil pH down the profile of a dark yellow alic Oxisol of medium texture 27 months after application. No estimates of error were presented (data from Morelli *et al.*, 1992).

Subsequent work by Pernatti and Forti (1994) confirmed these findings on a range of Brazilian Oxisols (Figure 10). In the case of the Fazenda Augusta site, the soil was extremely acid, with high Al and low Ca saturations. Responses to dolomitic lime and phosphogypsum were substantial, with the highest yields resulting from a combination of the two. At the Fazenda Salthino and Pau D'Alho sites, yield responses on these less acid soils were more variable, but still the best yields were obtained with combinations of dolomitic lime and phosphogypsum. At the Fazenda Prata and Pouso Alegre sites where the soils, particularly the subsoils, were more acid, yield responses were more consistent, with the best yields being obtained at the highest rates of dolomitic lime and phosphogypsum. Braga *et al.* (2003)

showed that the response to phosphogypsum over three harvests was much better when the crop was irrigated, but was smaller than that obtained when filter press cake was applied. Demattê (2005) obtained 21 and 18 t cane/ha increases in yield to the application of 3 t phosphogypsum and dolomitic lime/ha, respectively, on an Oxisol with a higher cation exchange capacity.

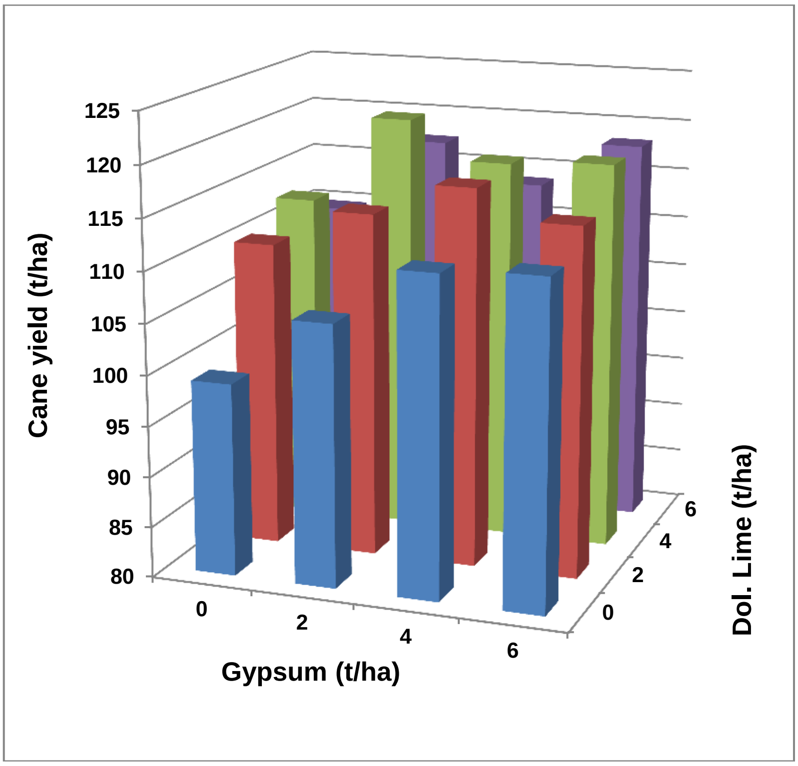

Figure 8. Effect of combinations of dolomitic lime and gypsum on mean yield of a plant and three ratoon crops of sugarcane grown on a dark yellow, alic Oxisol of medium texture. No estimates of error were presented (data from Morelli _et al_., 1992).

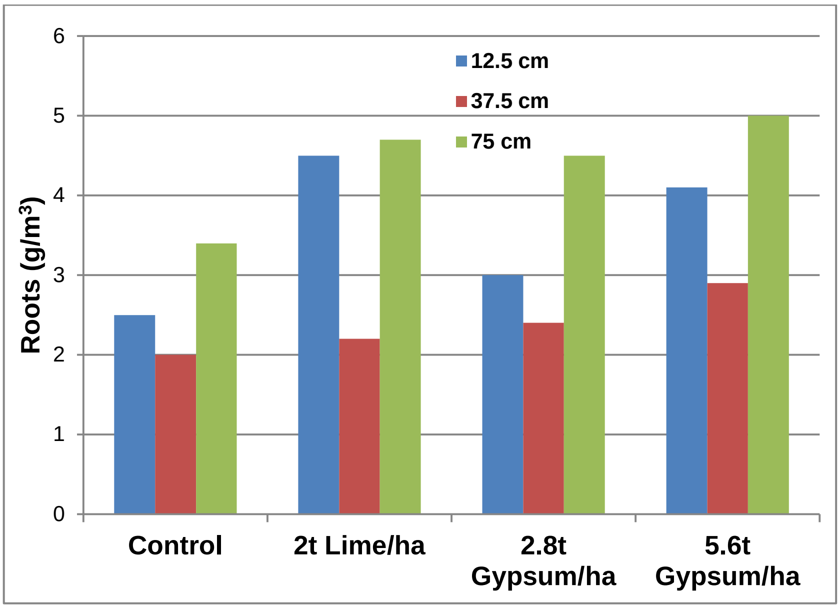

Figure 9. Effect of lime and phosphogypsum on root growth in a Brazilian Oxisol (Lorenzetti _et al._, 1992).

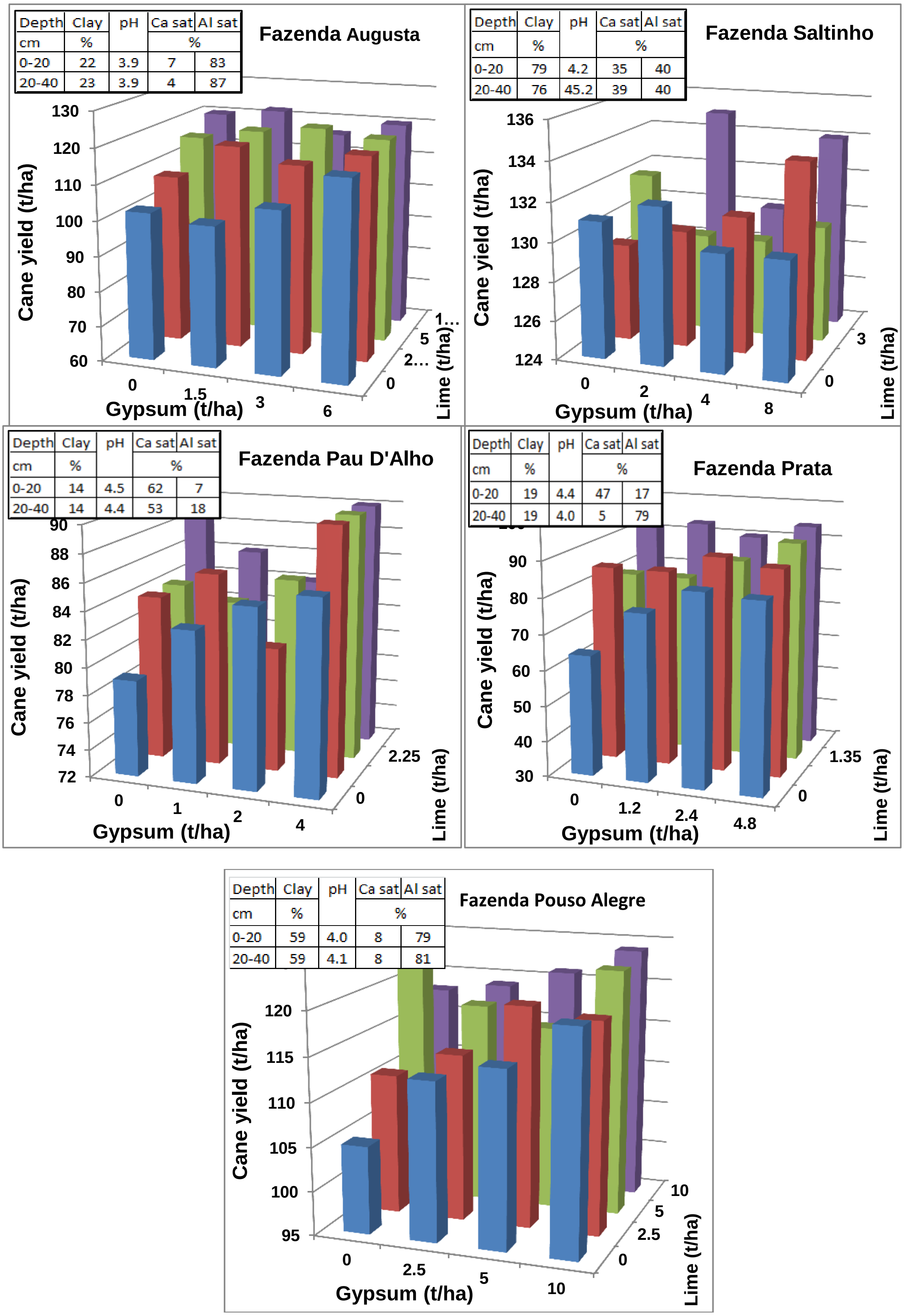

Figure 10. Examples of sugarcane responses to phosphogypsum and lime on Brazilian Oxisols. Original soil data before planting are presented in the table at the top of each figure. No estimates of error were presented (data from Pernatti and Forti, 1994).

da Rocha (2007) obtained a significant quadratic yield response to mined gypsum of differing particle sizes up to 6 t/ha on a dystrophic yellow Oxisol in Pernambuco State. Sucrose content was also increased by the gypsum treatment. Gypsum particle size played no role in the responses obtained. In a separate adjacent experiment, dolomitic lime (4.55 t/ha) and gypsum (4.66 t/ha) combinations resulted in increases in root growth in the 40-80 cm soil depth (Figure 11). However, the combination of lime and gypsum did not increase root growth over gypsum alone. The gypsum treatment increased subsoil Ca and decreased subsoil Al.

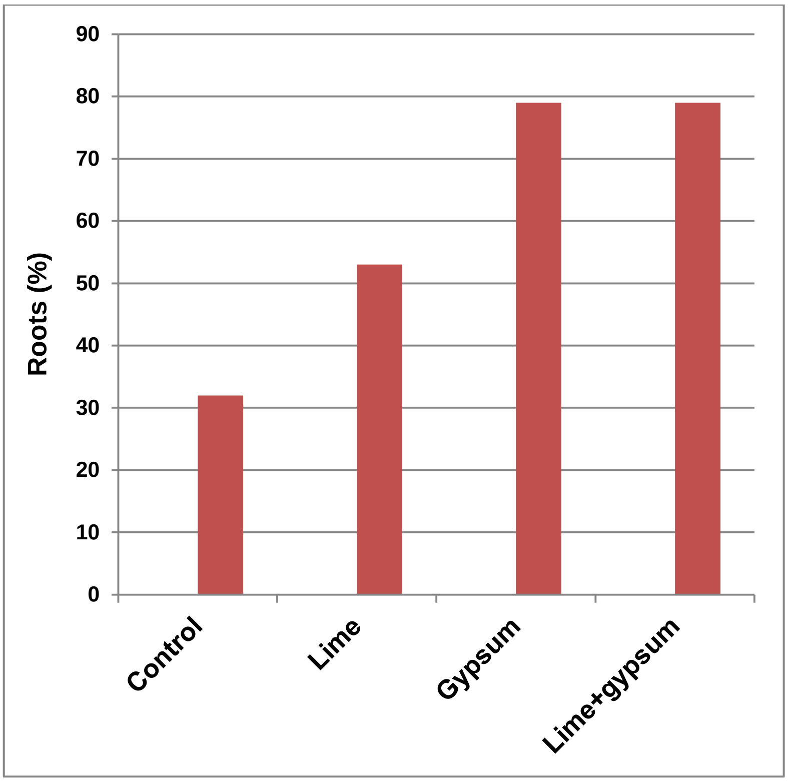

Figure 11. Effect of dolomitic lime (4.55 t/ha) and mined gypsum (4.66 t/ha) on root growth in a yellow Oxisol in Brazil (data from da Rocha, 2007).

Recently, Demattê (2011), after reworking the data of Morelli *et al*. (1992), showed that the greatest responses to lime and gypsum together over two ratoon crops of sugarcane were obtained when the exchangeable Ca/Mg ratio was maintained within a narrow range between 2.5 and 4. Because of the problems of scale in plotting such data, here they have been transformed by plotting the Mg/Ca rather than the Ca/Mg ratio to give a better representation of the situation (Figure 12). A boundary line (Walworth *et al*., 1986) was drawn to encompass the data, from which it becomes apparent that the optimal Mg/Ca ratio lies between 0.18 and 0.39, corresponding to Ca/Mg ratios of 2.6 and 5.5. This boundary line represents the limit of the values that are actually possible. When the Mg/Ca ratio is below 0.18, a zone is reached where Mg becomes limiting; whereas, when it is above 0.39, Ca insufficiency becomes manifest. These results indicate the importance of making balanced applications of both in order to achieve the best possible yields.

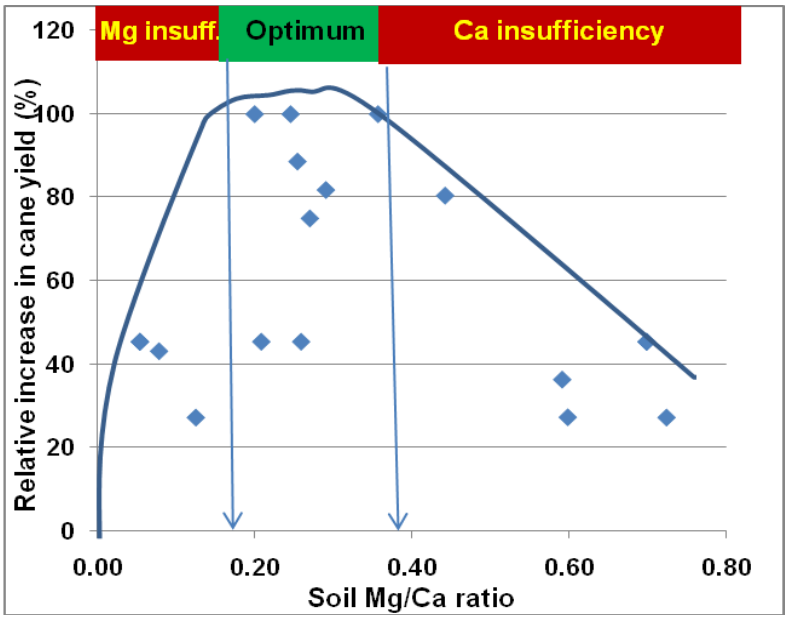

Figure 12. Effect of exchangeable Mg/Ca ratio for various combinations of dolomitic lime and phosphogypsum at different rates on the relative increase in cane yield over the control in two experiments (plotted from the data of Lorenzetti *et al*., 1992 and Demattê, 2011).

Discussion and Conclusions

Highly weathered, infertile soils with acid subsoils are a feature of sugarcane producing areas throughout the world, including South Africa. Because these soils usually occur under high rainfall regimes, they are less susceptible to the ravages of drought and are therefore potentially highly productive. The Brazilian experience with subsoil acidity in sugarcane closely mirrors that reported for many other crops such as maize, soybean (*Glycine max*), lucerne (*Medicago sativa*), cotton (*Gossypium hirsutum*), sorghum (*Sorghum bicolor*) vegetables, small grains, pastures and coffee (*Coffea arabica*), among others (Shainberg *et al*., 1989; Sumner, 1993; van Raij, 2008). This body of work has clearly demonstrated that highly infertile, acid soils can be converted into highly productive soils that can compete with the best in the world, as a result of ameliorating the entire profile by the judicious use of lime and gypsum. In implementing this technology, it is essential to ensure that the fertility status of the topsoil meets all the requirements for the highest potential yields by applying a balanced fertiliser and lime regime. Thereafter, application of gypsum to address the remaining subsoil acidity has its maximum benefit. It is absolutely essential to incorporate and thoroughly mix the requisite amount of lime (dolomitic if necessary) with as much soil near the surface as possible prior to planting, to create the best possible environment for root growth and nutrient uptake by the crop. The gypsum application can be made with the lime or after planting, although the former is preferable to allow the maximum amount of time for the gypsum to move down into the subsoil. On lighter textured soils, care must be taken to ensure that any losses of Mg and K by leaching ahead of the gypsum front are replaced to maintain productivity. It is important to maintain the balance between Ca and Mg when applying these amendments. Thus, after 40 years of work on two continents, the story of subsoil amelioration using gypsum has come full circle. The great success that has been achieved in Brazil using this strategy augurs well for its introduction into the sugar industries in southern Africa.

REFERENCES

Braga AMC, Oliveira PFM, Dopares RAB and Korndorfer GH (2003). Gesso e torte de filtro na produção de cana-de-açúcar cultivada sob diferentes regimese irrigação. p 35 In: *XXIX Cong Bras Ciên Solo*, Ribeirão Preto, São Paulo, Brazil.

Coleman NT and Thomas GW (1967). The basic chemistry of soil acidity. pp 1-42 In: Pearson RW and Adams F (Eds.) *Soil acidity and Liming*. American Society of Agronomy, Madison, WI, USA.

da Rocha AT (2007). Gesso mineral na melhoria do ambiente radicular da cana-de-açúcar e implicações na produtividade agrícola e industrial. DSc Thesis, Federal Rural University of Pernambuco, Recife, Brazil.

Demattê SLI (1986). Solos arenosos de baixa fertilidade. Estratégia de manejo. In: *Seminario Agroindustrial*, Piracicaba, São Paulo, Brazil. Mimeo unpublished.

Demattê SLI (2005). Recuperação e manutenção da fertilidade dos solos: Cultura da cana-de-açúcar. *Encarte Inform Agron* 111: 1-24.

Demattê SLI (2011). Ação do gesso e do calcário na relação calcio:magnésio do solo e na produtividade da cana-de-açúcar. *Inform Agron* 136: 11-16.

Fernandez FA (1985). Efeitos do gesso como fonte de calicio e de enxofre na cultura da cana-de-açúcar. MS Thesis, University of São Paulo, Piracicaba, Brazil.

Gonzalez EE (1976). Effect of depth of lime incorporation on the growth of corn in Oxisols of central Brazil. PhD Thesis, University of North Carolina, Raleigh, NC, USA.

Lemes GC, Chaves U, de Lima WP and Pereira W (2009). Aplicação de calcário e gesso para a correção de solos de Cerrado para o cultivo da cana-de-açúcar. *Revista Cognitio* 1: 1-5.

Lorenzetti JM, Rodrigues JC Morales SH and Demattê SLI (1992). Uso de calcário e gesso em soqueiras de cana-de-açúcar. *Rev STAB* 16: 14-18.

Mazza JA, Demattê SLI, Vitti GC and Aloisi RR (1991). Utilizacão de calcário, gesso e fósforo em solos de baxia fertilidade com soqueiras de cana-de-açúcar. *XXIII Congr Bras Ciên Solo* p 233.

Medina CC, Junior RAHR, Neves CSVJ and Brinholf O (2000). Sistema radicular de cana-de-açúcar submetida a doses de gesso, calcário e vinhaça. *Ci Agr Londrina* 21: 71-75.

Morelli JL, Nelli EJ, Demattê SLI and Dalben AE (1987). Efeitos do gesso e do calcário nas propiedades quimicas de solos arenosos álicos e na producão de calcário e gesso. *Rev STAB* 6: 24-31.

Morelli JL, Dalben AE, Almeida JOC and Demattê SLI (1992). Calcário e gesso na productividade da cana-de-açúcar e nas caracteristicas quimicas de um Latossolo de texture media álico. *Rev Bras Ciên Solo* 16: 187-194.

Oliveira RA, Daros E, Zambon JL, Weber H, Ido OT, Zufellato-Ribas KC, Koehler HS and Silva DKT (2005). Cresimento e desenvolvimento de trés cultivares de cana-de-açúcar, em cana-planta, no estado do Paraná: taxas de crescimento. *Sci Agr* 6: 85-89.

Pernatti CP and Forti JA (1994). Calcário e gesso em cana-de-açúcar. In: *Semin Tecnol Agron* 6 Copersucar, Piricicaba, Brazil.

Reeve NG and Sumner ME (1972). Amelioration of subsoil acidity in Natal Oxisols by leaching of surface applied amendments. *Agrochemophysica* 4: 1-6.

Ritchey KD, Silva JE and Sousa, DMG (1981). Lixiviação de cálcio e crescimento de raízes em solos de Cerrado. In: *Cong Bras Ciên Solo*, Salvador, Brazil p. 96.

Ritchey KD, Souza DMG, Lobato E and Correa O (1980). Calcium leaching to increase rooting depth in a Brazilian Savannah Oxisol. *Agron J* 72: 41-44.

Shainberg I, Sumner ME, Miller WP, Farina MPW, Pavan MA and Fey MV (1989). Use of gypsum on soils: A review. *Adv Soil Sci* 9: 1-111.

Sumner ME (1970). Aluminum toxicity - growth limiting factor in some Natal sands. *Proc S Afr Sug Technol Ass* 44: 1-6.

Sumner ME (1993). Gypsum and acid soils: The world scene. *Adv Agron* 51: 1-32.

Sumner ME (1994). Amelioration of subsoil acidity with minimum disturbance. pp 147-186 In: Jayawardane NS and Stewart BA (Eds.) *Subsoil Management Techniques.* Lewis Publishers, Boca Raton, FL, USA.

Toma M, Sumner ME, Weeks G and Saigusa M (1999). Long-term effects of gypsum on soil chemical properties and corn yield. *Soil Sci Soc Am J* 39: 891-895.

van Raij B (2008). *Gesso na agricultura*. Instituto Agronômico, Campinas, São Paulo, Brazil.

Vitti GC (1991). Comparação dos efeitos da aplicação de gesso e calcário em caracteristica quimicas de dois tipos de solos. CNPq Report, Piracicaba, Brazil. Mimeo unpublished.

Vitti GC, Mutton MA, Magalhães P, Ferreira ME and Carvalho MJ (1984). Efeitos de doses de gesso e de calcário na cultura da cana-de-açúcar (*Saccharum* spp.) variedade NA 56-79. *Resum XVI Reun Bras Fertil Solo*. p 40.

Vitti GC, Mutton MA, Fornasieri FD, Perecin D, Posolen CA, Nocitti PR, Mendes JM, Paranhos SB, Piccin CR, Malavolta ML and Malavalta E (1989). Efeitos de doses e fonts de enxofre em culturas de interesse enconômico. V. Cana-de-açúcar (*Saccharum* spp.). Boletin Téchnico 5. Centro de Pesquisa e Promoção Sulfato de Amônio, São Paulo, Brazil.

Walworth WL, Letzsch WS and Sumner ME (1986). Use of boundary lines in establishing diagnostic norms. *Soil Sci Soc Am J* 50: 123-128.