REFEREED PAPER and KEYNOTE ADDRESS

OUT OF SIGHT OUT OF MIND: SUBSURFACE FACTORS IN SUGARCANE YIELD DECLINE

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Abstract

Although sugarcane production is heavily dependent on what happens below the soil surface, seldom are roots excavated as part of the diagnostic process involved in formulating remedial measures. As a result of much field experience consulting on a wide range of crops in many countries of the world, it has become clear that without a careful look at the roots of a crop, appropriate remedial measures for the problems ailing the crop are not possible. The effects on root growth and performance of subsoil acidity, including calcium deficiency and aluminium toxicity, hard and compacted layers, excessively wet soil conditions, root pathogens and pests and inappropriate use of herbicides will be discussed together with the possible strategies available for their amelioration.

Introduction

It is a great honour and pleasure to have been invited by SASTA to present the opening Keynote Address at this year's Congress. I have had an association with SASTA dating back to 1964 when I first presented a paper here, but it is over 35 years since I last addressed this body and now welcome this new opportunity. Since retiring from the University of Georgia in 2000, I have been actively engaged in consulting at many locations throughout the world, during which I have had extensive experience with numerous crops and soils. This work has focused my attention on subsurface growth limiting factors often forgotten because they are out of sight and, therefore, out of mind. In order to make meaningful diagnoses of yield limiting factors in the quest to solve recalcitrant problems involved in sugarcane production, it is imperative to excavate roots because they are so vital to the wellbeing of the plant. If unseen roots are negatively impacted by unfavourable conditions below the soil surface, the plant can suffer stress without the cause being evident.

The material that I propose to present here today is drawn largely from my consulting experience augmented by research findings where appropriate. These subsurface factors, which in great measure regulate and determine the extent and efficacy of root growth, operate below the soil surface, making them somewhat more difficult and laborious to assess and quantify. Nevertheless, they govern the uptake of water and nutrients by the crop, which ultimately determines the yield, quality and profitability of the cropping system. For a variety of reasons, scant attention and effort have been devoted to this most important segment of the soil/crop continuum. In an attempt to rectify this situation, the discussion to follow is offered in the hope that it will stimulate more interest and research in this arena. What I intend to present today should not be considered a definitive treatment of the topics, but rather a

collection of examples which I have selected from my experiences that hopefully will act as stimuli for further investigations, in the context of South Africa and the sugar industry, in particular. This endeavour is pertinent to the current problems associated with the yield plateau/decline syndrome which is a serious concern in the worldwide sugar industry and that of South Africa, in particular. Hopefully, some of the insights presented here will be of assistance in solving the problems associated with this condition.

To facilitate the discussion to follow, four subsurface problems that I have encountered in the field with many crops over the past 10 years will be presented, followed by a discussion of their most likely causes and the tools available to ameliorate these conditions hostile to healthy root growth and development. Their relevance to the South African sugar industry will be evaluated.

SCENARIO I

PROBLEM: Inadequate root penetration into the subsoil

In many soils, one finds a paucity of roots in the subsoil, which renders the crop more susceptible to drought stress, because it is unable to access available water and nutrients beyond the root penetration front.

Possible cause

Inadequate levels of soluble calcium in the subsoil

To set the stage for this discussion, it is necessary to visit the factors essential to the growth and development of healthy roots. Howard and Adams (1965) were amongst the first to show that the elongation of cotton tap roots was determined by the proportion of Ca^{2+} ions in the soil solution, with much subsequent supporting evidence being published later (Reeve and Sumner, 1972; Hammel *et al*., 1985; Farina and Channon, 1988; Noble and Sumner, 1988). For a root to elongate, sufficient Ca^{2+} in solution must be present at the root tip (Hanson, 1984). Consequently, for roots to penetrate the entire soil profile, adequate concentrations of Ca^{2+} in solution must be present with depth. Calcium concentrations in the soil solution of a range of South African soils are presented in Figure 1. In both top and subsoils, the Ca^{2+} concentrations are very low (<15 mg/L), even in relatively un-weathered soils such as the Rensburg and Shortlands series where exchangeable Ca levels are quite high (6-20 $cmol_c$/kg). On the other hand, in highly weathered soils such as the Balmoral, the values are even much lower (<5 mg Ca/L) with concomitantly low exchangeable Ca values (0.1-1.3 $cmol_c$/kg) (le Roux and Sumner 1967). As can be seen from Figure 2, soybeans as well as other crop roots require solution Ca concentrations well in excess of these values for normal growth.

In most agricultural production systems, lime is used as the primary source to supply Ca for crop needs, to raise the pH and neutralise toxic concentrations of Al^{3+}. However, in variable charge soils, most of the added Ca is adsorbed on additional exchange sites created when the pH is raised, thereby leaving very little Ca in solution (Sumner, 1995), as illustrated in Figure 3. Despite the fact that eight times more Ca was applied in the 8 t/ha lime rate than in the 2 t/ha gypsum treatment, far less Ca remained in solution in the lime than gypsum treatment. These data together with the work of Sumner (1995) show that because of the variable charge nature of many soils in the South African sugar industry, particularly in high rainfall areas, lime is unlikely to generate sufficient soluble Ca^{2+} in the topsoil for appreciable movement

into the subsoil to occur. On the other hand, when ammoniacal N is applied to the crop, downward mobility of Ca in the form of $Ca(NO_3)_2$ increases markedly (Figure 4).

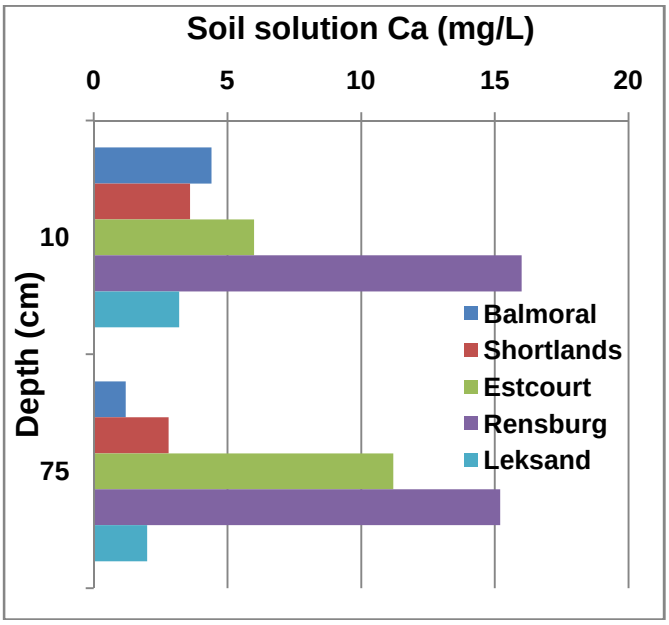

Figure 1. Soil solution calcium concentration in a selection of South African soils (data from le Roux and Sumner, 1967).

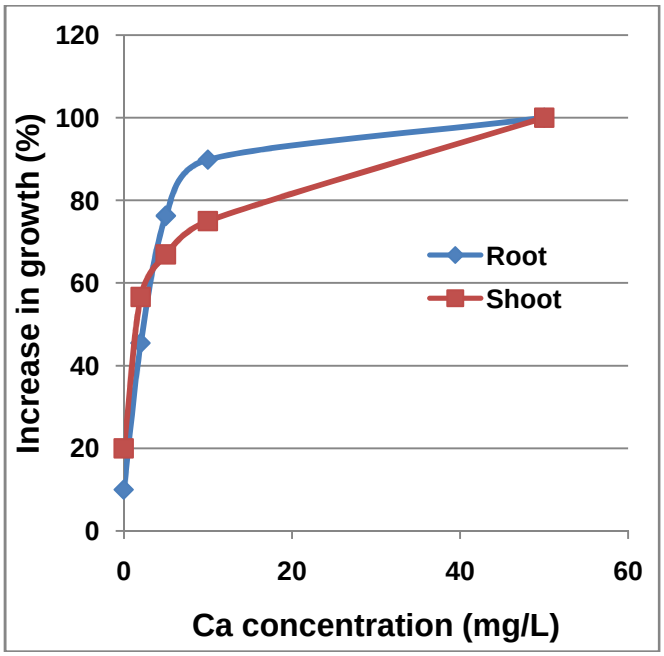

Figure 2. Soybean shoot and root response to increasing calcium concentration in solution.

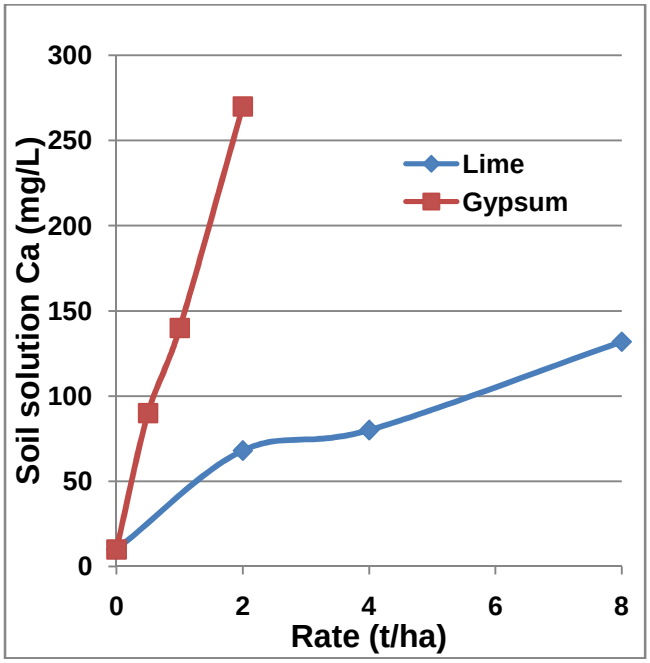

Figure 3. Effect of rates of lime and gypsum on soil solution calcium concentration in a Cecil sandy loam topsoil.

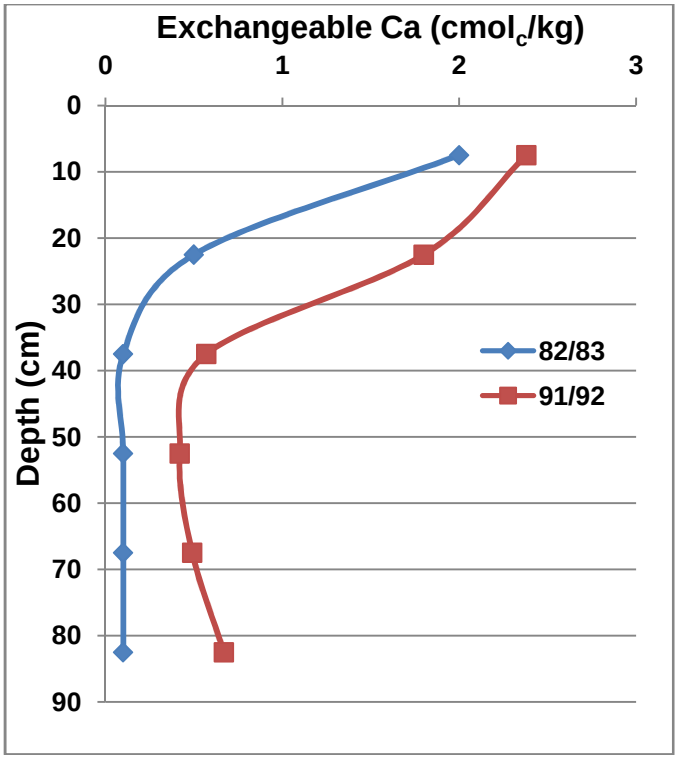

Figure 4. Downward Ca movement over time in a limed Ultisol profile with the application of 1521 kg N/ha over 10 seasons (data from Farina and Channon 1988 and Farina *et al.* 2000).

Potential solution

Use of gypsum to supply soluble calcium

The difference illustrated in Figure 3 is partially due to the differential solubility of gypsum (2.4 g/L) versus lime (0.015 g/L) and partially due to the charge generating characteristics of lime. As a result, gypsum moves readily into the subsoil under the influence of rain or irrigation providing a cheap and practical solution to this problem of low soil solution Ca, as illustrated in Figure 5 for a Brazilian Oxisol, where much more Ca entered the subsoil in the gypsum than lime treatment, despite the fact that only one-third the amount of Ca was applied in the former. Consequently, both lime to overcome acidity in the topsoil and gypsum to supply soluble Ca for the subsoil may be required to sustain optimal sugarcane root growth in the South African industry.

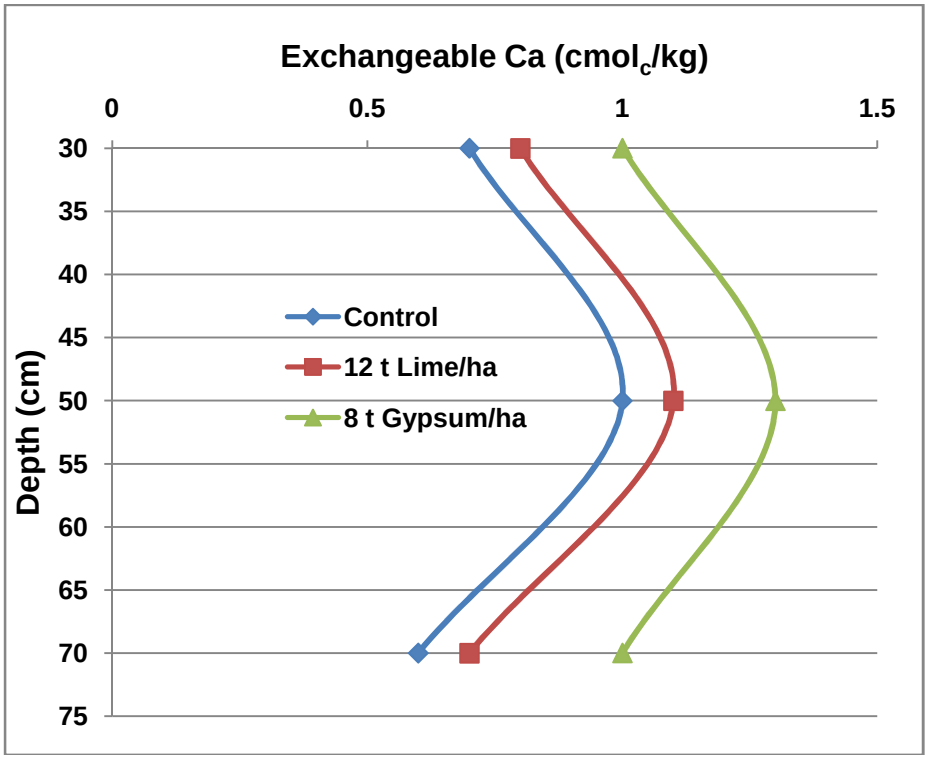

Figure 5. Effect of lime and gypsum applied at 4800 and 1600 kg Ca/ha, respectively on exchangeable calcium at three depths in a Brazilian Oxisol (van Raij 2008).

Possible cause

Toxic concentrations of aluminium in the subsoil

Many South African soils, including those in the high rainfall areas of the sugar industry, have naturally acid subsoils that subtend levels of Al^{3+} sufficient to impair root growth and extension (Reeve and Sumner, 1970; Sumner, 1970; Sumner and Meyer, 1971). The extent to which soluble Al^{3+} takes a toll on root growth is illustrated in Figure 6, where a sharp decrease in root length occurs with increasing Al concentration in solution.

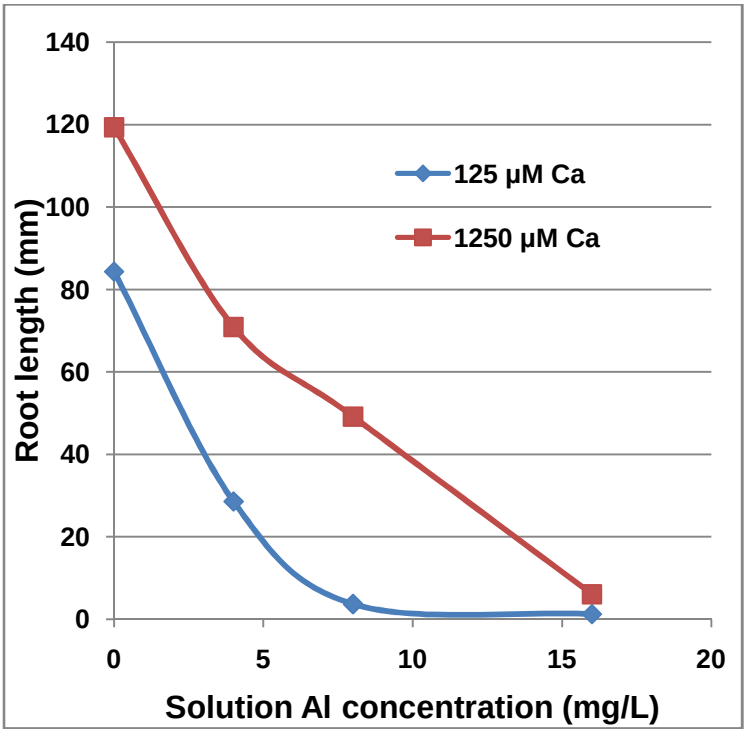

Figure 6. Effect of aluminium on soybean root growth at two calcium concentrations in solution (Data from Noble and Sumner, 1988).

Potential solution

Application of gypsum

This negative effect of Al^{3+} on root growth can be partially offset by substantially increasing the level of soluble Ca^{2+} and sulphate in the solution which leads to the formation of a non-toxic $Al(SO_4)^+$ ion pair in solution (Pavan *et al.*, 1987). In addition, Reeve and Sumner (1972) demonstrated the 'self-liming effect' in which SO_4^{2-} replaces OH^- on sesquioxidic surfaces in the subsoil resulting in the neutralisation of Al^{3+} with the precipitation of $Al(OH)_3$. As gypsum is the only economical way of markedly increasing soluble Ca^{2+} and SO_4^{2-} in subsoils, its effects together with those of lime in ameliorating an acid Brazilian Oxisol and promoting sugarcane yield are demonstrated in Figures 7 and 8 as an example of the possibilities. Clearly gypsum is much more effective in increasing subsoil Ca than lime alone, but when applied together there is an additive effect to further increase Ca in the subsoil (Figure 7A). On the other hand, lime is more effective than gypsum in neutralising Al in the topsoil whereas in the subsoil gypsum is more efficient (Figure 7B). This soil chemical amelioration results in significant increases in yield due to lime and gypsum alone but again there is a marked positive effect on yield when both are applied together (Figure 8). Similar results on a wide variety of other Brazilian Oxisols have been reported by Morelli *et al.* (1992) and Penatti and Forti (1993) and presented in summarised form by van Raij (2008). The results of Nixon *et al*. (2003) indicated that similar results could be expected with some varieties on some South African soils. These yield increases stem from improved rooting throughout the soil profile, which allows the crop to access water previously beyond its reach, as illustrated in Figure 9. It is important to note that gypsum is often much more effective in promoting water uptake than lime while the magnitude of the effect on root length varies a little between soils. A note of caution is appropriate in the implementation of this strategy. It should only be used on soils with naturally acidic subsoils, as anthropogenically acidified and

sandy soils do not necessarily respond in the same way because they might not contain sesquioxidic surfaces (Farina, 2011).

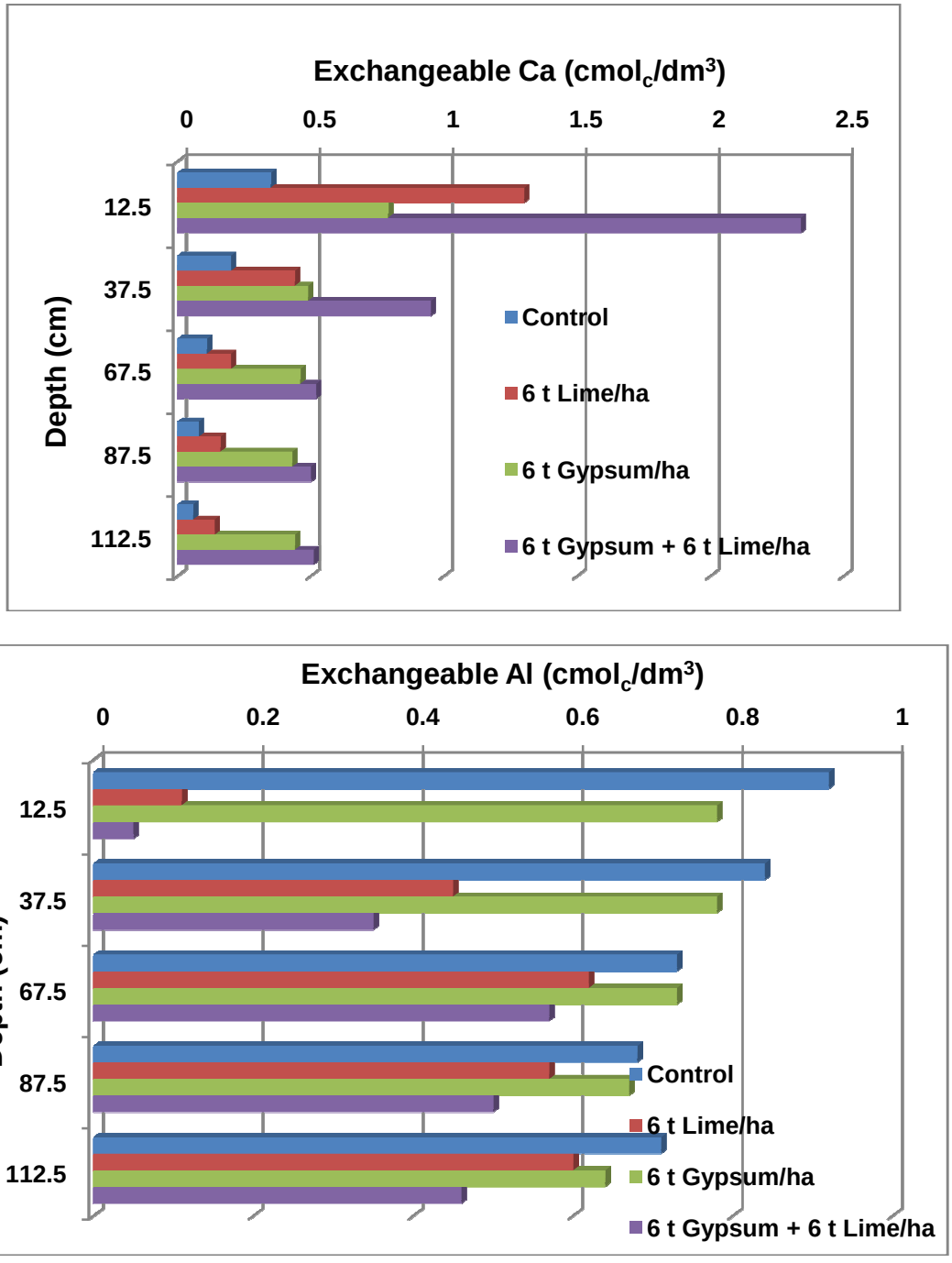

Figure 7. Effect of combinations of lime and gypsum on: (A) exchangeable Ca and (B) exchangeable Al with depth in a Brazilian Oxisol (Morelli *et al*. 1992).

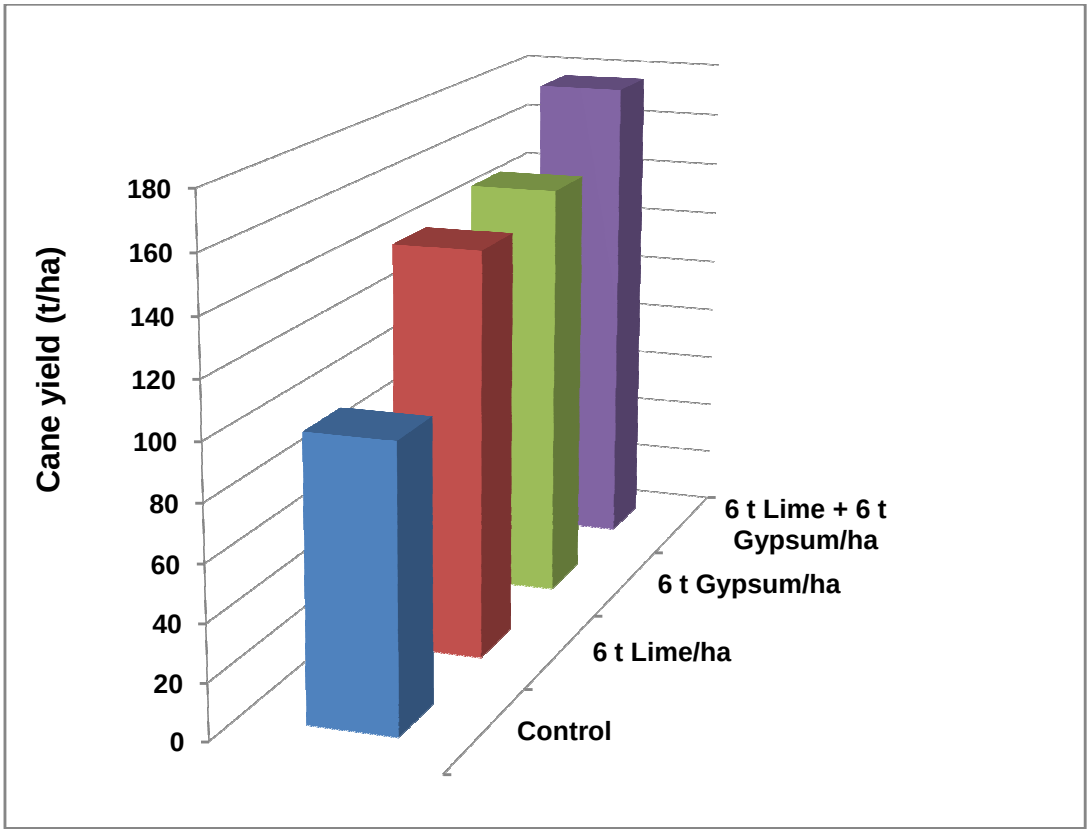

Figure 8. Effect of combinations of lime and gypsum on average sugarcane yield over a plant and three ratoons on the acid Brazilian Oxisol in Figure 7 calculated from the data of Morelli *et al.* (1992).

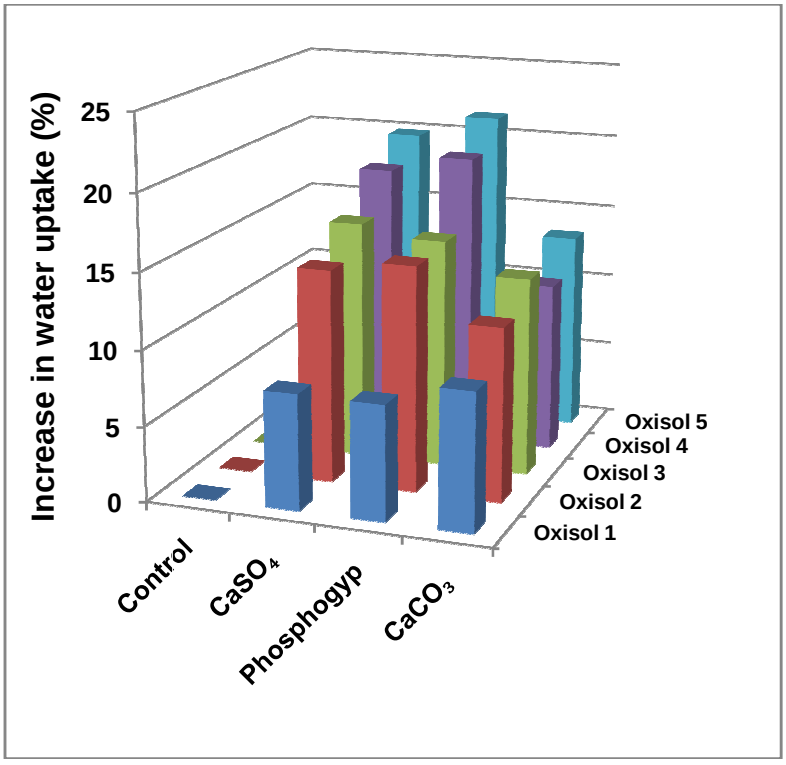

Figure 9. Effect of gypsum and lime on water uptake by maize from five Brazilian Oxisols (Carvalho and van Raij, 1997).

Possible cause

Hard and compacted subsoil layers

Many soils present limitations to rooting because they are shallow with rock barriers at <50 cm depth. On the other hand, soils, particularly those in the Ultisol and Alfisol orders, naturally have textural B horizons that present challenges for root penetration; mechanised agriculture has greatly exacerbated this problem in recent times, and soil compaction has long been a problem in the sugar industry worldwide. Factors that have contributed to compaction include the loss of soil organic matter promoted by tillage and burnt cane harvesting resulting in structural breakdown (Mills and Fey, 2004) and the use of heavy infield machinery required for mechanical harvesting, particularly when soils are wet (van Antwerpen, 2001). In addition, there is evidence that long-term use of ammoniacal N fertilisers have increased penetrometer resistance as a result of the removal of Ca from the exchange complex arising from the acidity produced when ammonium ions are oxidised in the soil (van Antwerpen and Meyer, 1997). Tillage and traffic over the soil, particularly under wet conditions, lead to the rearrangement of soil particles, resulting in reduced macro-porosity as illustrated in Figure 10. This severe loss in porosity due to infield harvester traffic is greatest in the largest pore category both at the soil surface and at 10 cm depth. In addition, this rearrangement of the soil architecture increases the cohesion between clay particles that results in the formation of hard or compacted layers (hardpans) in the soil profile on drying. These layers negatively impact the crop by presenting physical barriers to optimal root growth and development, as illustrated in Figure 11. Note the sharp decrease in root growth as bulk density increases. In the case of sugarcane, compaction reduces sucrose yield as presented in Figure 12, from which it can be seen that an increase in bulk density of 18% can lead to a loss in sucrose of over 39%. In addition to physically restricting root extension, this reduction in macro-porosity negatively impacts the ability of soil to supply adequate quantities of oxygen for root respiration (Hamza and Anderson, 2005). This, in turn, limits nutrient uptake.

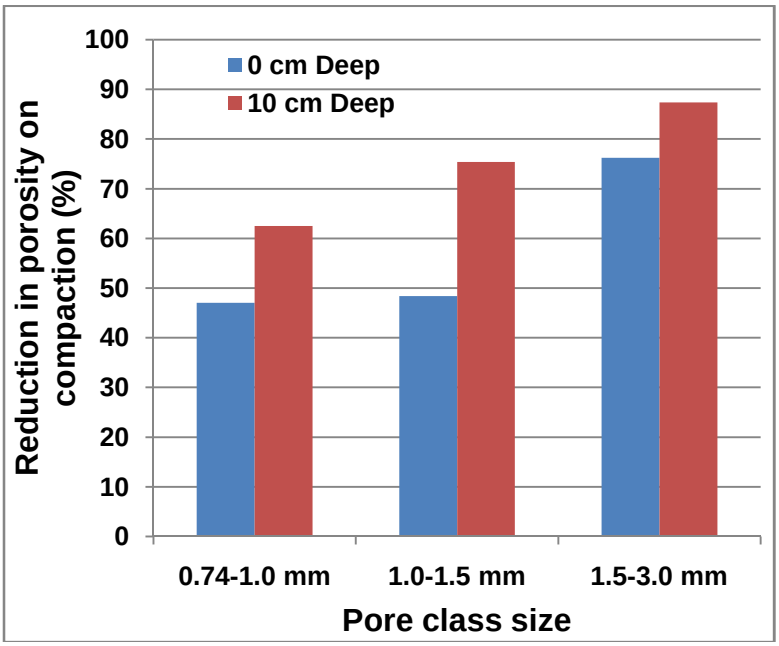

Figure 10. Effect of compaction due to infield combines on the reduction in porosity of a Vertisol (Data from Radford *et al.* 2000).

Figure 11. Effect of soil compaction on maize root and seedling growth at three soil bulk densities (Low - 0.7, Medium - 1.1 and High - 1.6 g/cm^3) (Al-Kaisi and Hanna, 2006).

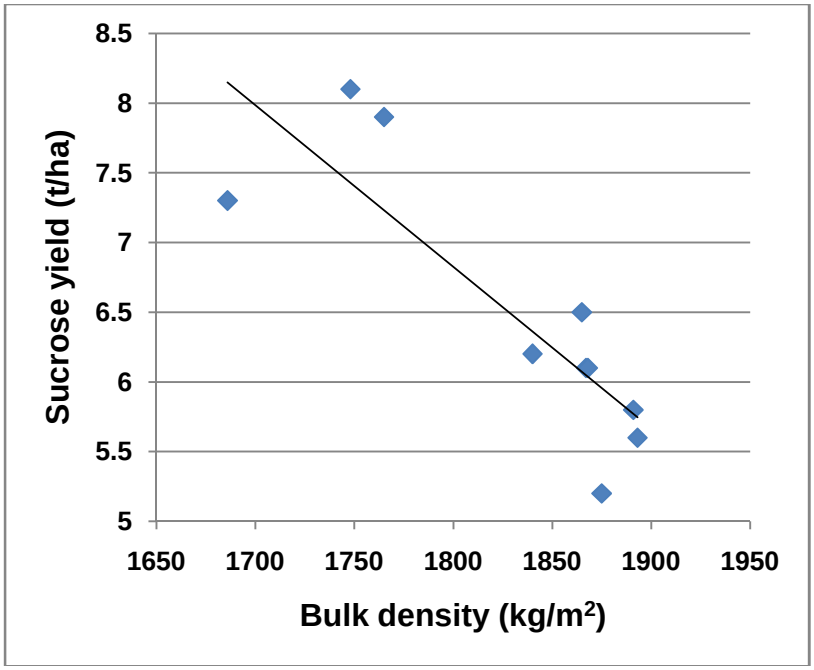

Figure 12. Relationship between wet bulk density of a Longlands soil and sucrose yield at La Mercy (Swinford and Meyer, 1985).

Similar effects can occur at the bare soil surface as a result of the compacting and dispersive action of raindrops exacerbated by the presence of dispersible clay which results in the formation of soil crusts. In addition, there is evidence that burning plant residues can, significantly and substantially, reduce soil organic matter content (from 2.8 to 0.8%) and electrical conductivity (12 to 8 mS/m), and increase exchangeable Na percentage (ESP) (from

8 to 17.5%), particularly near the soil surface (0-5 cm) (Mills and Fey, 2004). All of these changes promote crust formation and reduce infiltration (Figure 13). Small increases in ESP (~6.5%) can have profound negative effects on clay dispersion, infiltration rates, runoff and erosion as illustrated in Figure 14. Crusts, in addition to limiting the emergence of seedlings, restrict the exchange of gases between the soil and the atmosphere. As a result, roots can suffer anoxia and experience difficulty in taking up nutrients such as P and K (Laker, 2001). Because of its negative effects on soil properties, burnt cane culture clearly takes a serious toll on soil health and wherever possible should be avoided at all costs.

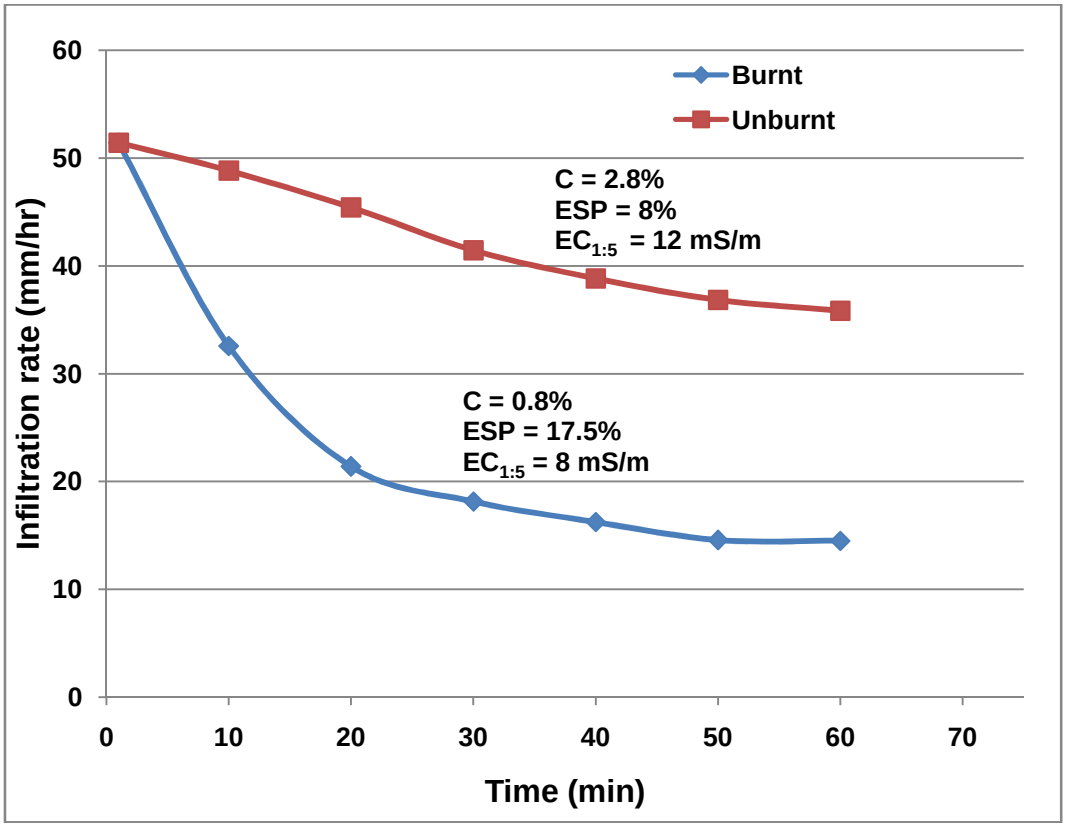

Figure 13. Effect of burning residues on infiltration rate and related parameters in long-term burning plots (>40 years) in the southern Kruger National Park (data from Mills and Fey 2004).

Potential solutions

Build up organic matter

While, in certain instances, this has proven to be a beneficial tool to offset the effects of compaction, there are many cases where little or no response has been obtained. The type of organic matter seems to be important, with the readily oxidisable forms being more relevant than the total organic matter content of the soil (Ball *et al.*, 2000). Undecomposed residues, however, are effective in increasing porosity and thereby, decreasing tensile strength (Zhang, 1994; van Antwerpen, 2001). Basically, very large applications of organic matter are necessary in order to increase the baseline organic carbon content of the soil. In all cases, such organic matter applications have their origins elsewhere, which means that the carbon

and nutrients applied to a given site have been acquired from another piece of land that is now the poorer. This constitutes nutrient theft and cannot be considered as a remedy.

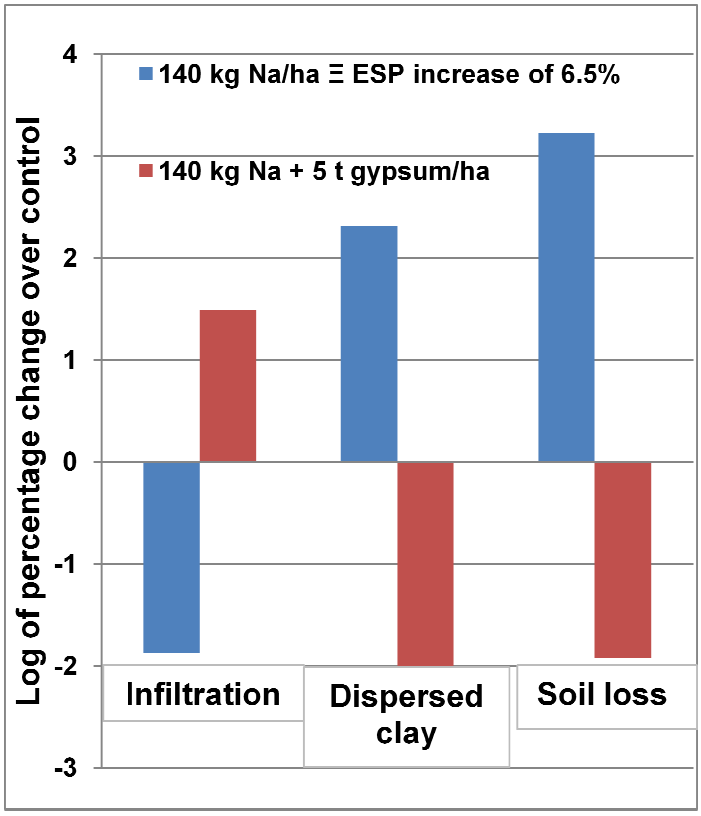

Figure 14. Effect of small additions of sodium and the beneficial effects of gypsum on clay dispersion, infiltration and soil loss from a Georgia Ultisol (data from Miller and Radcliffe, 1992).

In terms of the sugar industry, green cane harvesting is the most likely system that is available to increase soil organic matter content so that compaction can be mitigated. Under this system, roots are more evenly distributed across the field, allowing the crop to better forage for nutrients. In addition, the large amounts of organic matter retained on the field relative to burnt cane harvesting keep the soil cool before the crop canopies and result in increases in the organic matter status of the soil, and the size and activity of the microbial and earthworm communities which, in turn, improve aggregate stability. The conditions prevailing under green cane harvesting are much more beneficial to earthworm activity which is exceedingly important in terms of generating the macro-pores responsible for the free flow of air and water in the soil. An example of these benefits is presented in Figure 15. These data emphasise the importance of the quality of soil organic matter in terms of the labile fractions which clearly are responsible for the increases in the microbial biomass and earthworm activity obtained under green cane harvesting. Improvements in soil physical condition and health stemming from improved biological activity under green cane harvesting are likely to improve nutrient turnover and infiltration, and reduce crusting, runoff and erosion, particularly on the steep slopes in many cane fields in KwaZulu-Natal (Graham *et al.*, 2002).

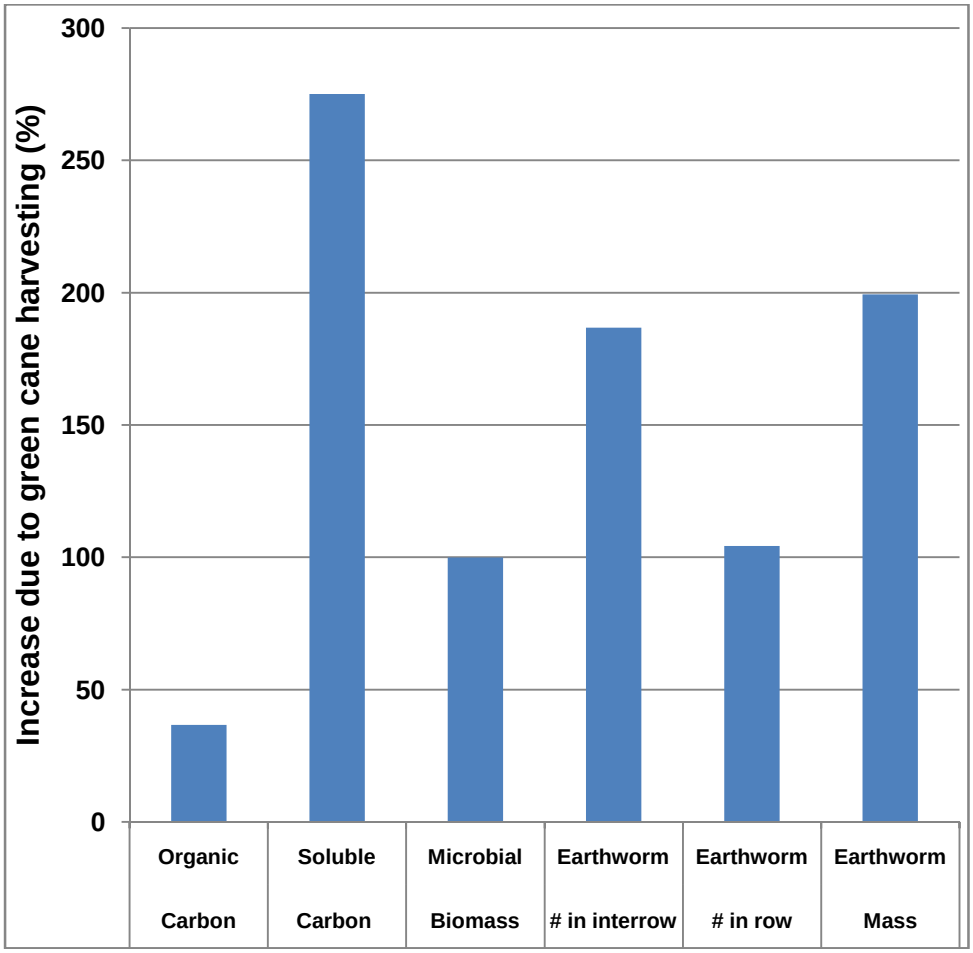

Figure 15. Increase in soil biological components due to long-term (>15 years) green cane over burnt cane harvesting on a Glengariff series soil near Eshowe (data from Dlamini and Haynes 2004). Organic C was measured by the Walkley-Black procedure (Blakemore *et al.* 1972), soluble C by extraction with K_2SO_4 and microbial biomass by the fumigation-extraction method (Vance *et al.* 1987).

The use of green manures as break crops in the cane cycle have received attention over the years but current soil conditions extant in the sugar industry indicate a need for this practice to be resuscitated, particularly if green cane harvesting is not being practiced (Schumann *et al.*, 2000). In addition to supplying N and adding organic matter, many of the leguminous green manures such as sunn hemp (*Crotolaria junceae)* are effective in reducing soil bulk density and controlling parasitic nematodes such as *Meloidogyne javanica* which causes significant yield losses in sugarcane (Berry and Wiseman, 2003; Berry and Rhodes, 2006). An example of the benefits to be expected from green manuring is presented in Figure 16. The substantial increase in air-filled porosity reflects the improved soil physical condition that resulted in a substantial cane yield increase over a plant crop and three ratoons. The importance of improving air-filled porosity in a soil cannot be over-emphasised, because it is the superhighway for water and air. Consequently, maintaining a trash blanket on the soil surface will not only reduce evaporation, keep the soil cool and provide protection from the energy of raindrops but will also prevent the accumulation of Na near the surface, which means that more water will become available to the crop potentially resulting in greater yields.

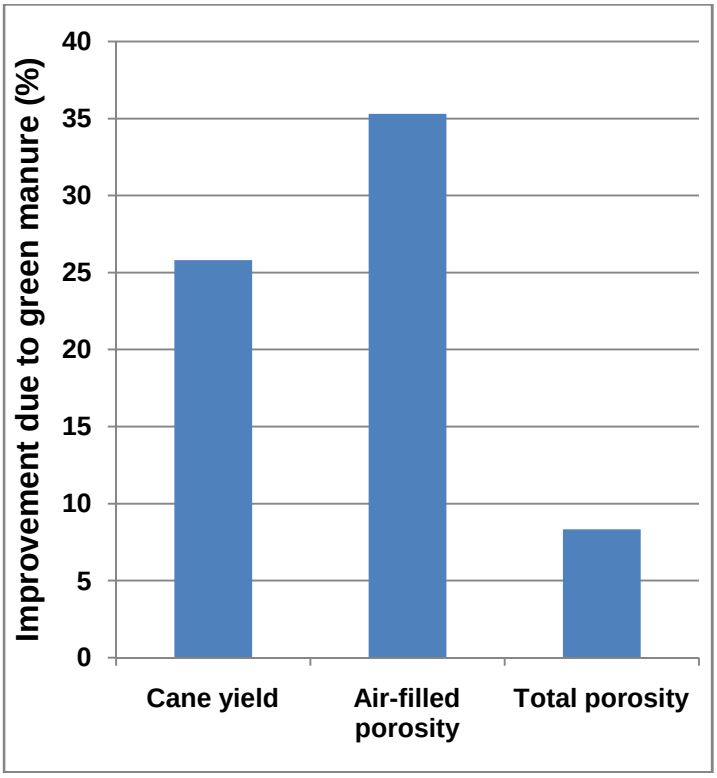

Figure 16. Improvements from a sunn hemp/cowpea green manure under irrigation in Swaziland (data from Schumann *et al.*, 2000).

Controlled traffic

Confining traffic to preplanned permanent zones, using flotation tyres and not allowing heavy machinery into fields when soils are wet, are obvious solutions which will reduce soil compaction (van Antwerpen *et al.*, 2000). Other machinery related factors that can be controlled such as avoiding traffic when the soil is wet, reducing the number of passes and weight of trailers, and matching tractors to actual power requirements have been discussed by Mitchell and Berry (2001). Management of soil compaction has recently been facilitated by the introduction of the SOCOMO model based on sound mechanistic principles (Marx *et al.*, 2006). Every effort should be made to reduce the footprint of machinery on soil.

Deep tillage

Where soil degradation has taken place, deep ripping is a commonly used tool to shatter dense subsoil horizons that limit water and root penetration (Hamza and Anderson, 2005). The beneficial effect of subsoiling on root growth is illustrated in Figure 17. However, this effect decreases over time if the dispersibility of the clay present is not addressed. Physical improvements resulting from subsoiling can improve soil health and the ability of plants to resist disease (Laker, 2001). Subsoiling with a vertical mulcher can further improve soil physical conditions by providing macro-pores through which water and air can move.

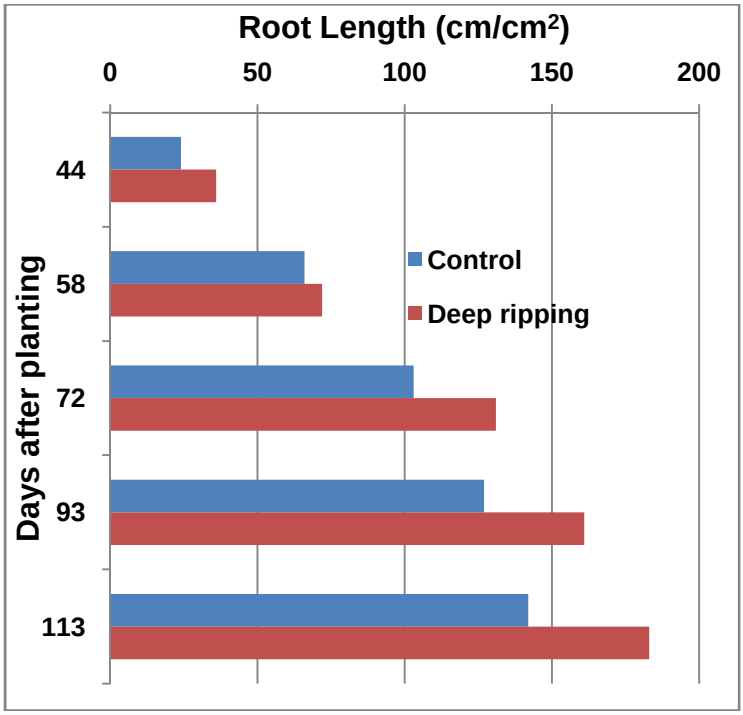

Figure 17. Effect of deep ripping on wheat root growth with depth in Western Australia (Tennant, 1986).

Use of gypsum and plant roots

Before discussing the use of gypsum for this purpose, it is necessary to outline the effects of soluble Ca^{2+} ions on clay flocculation and its consequences on soil physical properties. In many soils, appreciable quantities of organic matter have been lost as a result of cultivation, which results in the breakdown of soil aggregates with soil physical properties suffering as a consequence. In many moderately to well weathered soils, the total electrolyte concentration in the soil solution (le Roux and Sumner, 1967) is often well below 2 mmol/L, at which point clay in the soil begins to disperse and become mobile (Figure 18). This dispersible clay facilitates the re-orientation of soil particles under the pressure applied in tillage and traction alluded to above. Application of gypsum slowly reverses this dispersion allowing soil architecture to be improved with the help of advancing roots, a process referred to as 'bio-tillage'. Over time, this results in a reduction in the penetration resistance measured as the cone index of subsurface hard compact layers, as illustrated in Figure 19. This treatment with gypsum results in a significant increase in large water-stable soil aggregates, particularly at depths between 30 and 60 cm, due to the effect of the increased root growth (Radcliffe *et al.*, 1986). This beneficial effect of roots in overcoming soil compaction has also been reported by Jayawardane and Chan (1994). In addition, this profile amelioration resulted in substantial yield increase in lucerne, particularly over time (Figure 20). The initial small responses were due to the time required for the gypsum to reach the subsoil to effect amelioration. By adding gypsum during the deep ripping process described above, the mechanical benefit achieved can be stabilised as illustrated in Figure 21. Note how the infiltration rate decreases over time in the deep ripping, but not in the deep ripping plus gypsum treatment. Gypsum alone was also effective in maintaining infiltration, but there was a positive additive effect with deep ripping. In the event that green cane harvesting cannot be practiced such as on steep slopes, the negative effects of burning can be overcome by the addition of gypsum which reduces dispersible clay and increases infiltration resulting in less soil loss (Figure 14).

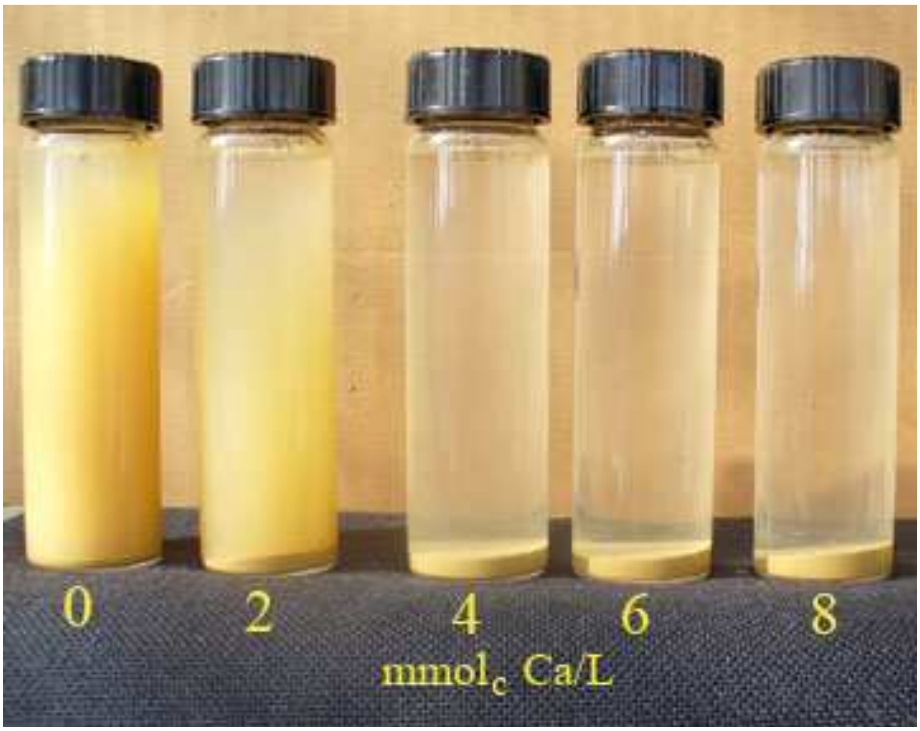

Figure 18. Effect of additions of Ca^{2+} ions as gypsum on the flocculation of clay.

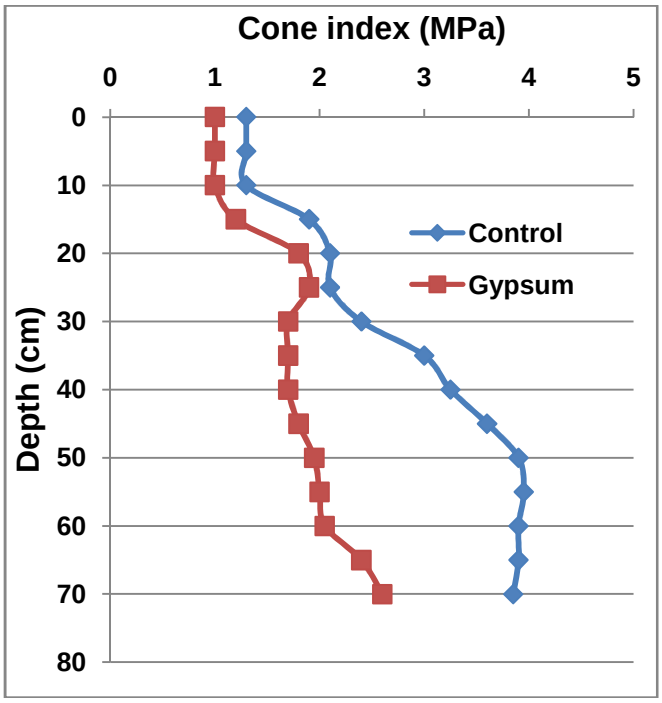

Figure 19. Effect of gypsum (10 t/ha applied on the surface) on penetration resistance (cone index) with depth in a Georgia Ultisol 4 years after application on a crop of lucerne. Differences between control and gypsum were significant at p = 0.01 down the entire profile. The vertical line at 2.5 MPa indicates the point at which root growth ceases (Radcliffe *et al.*, 1986)

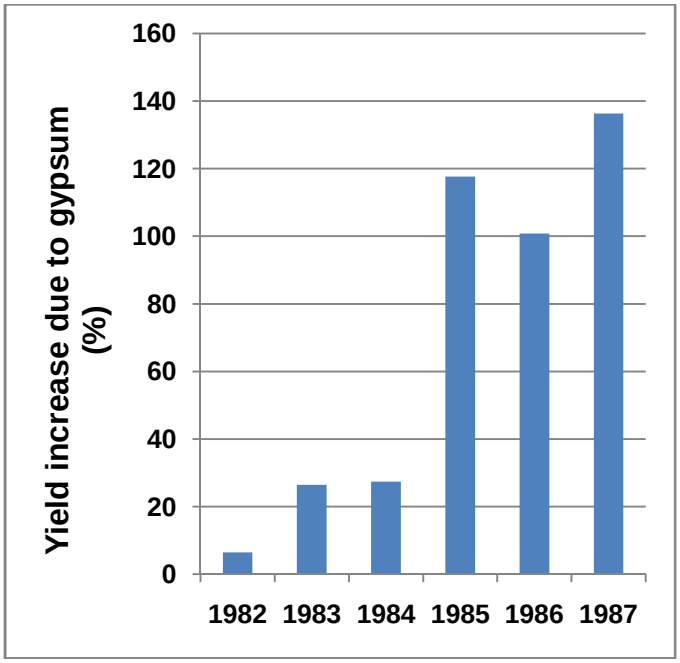

Figure 20. Increase in lucerne yield on a Georgia Ultisol due to physical and chemical profile amelioration resulting from the surface application of 10 t gypsum/ha in 1981.

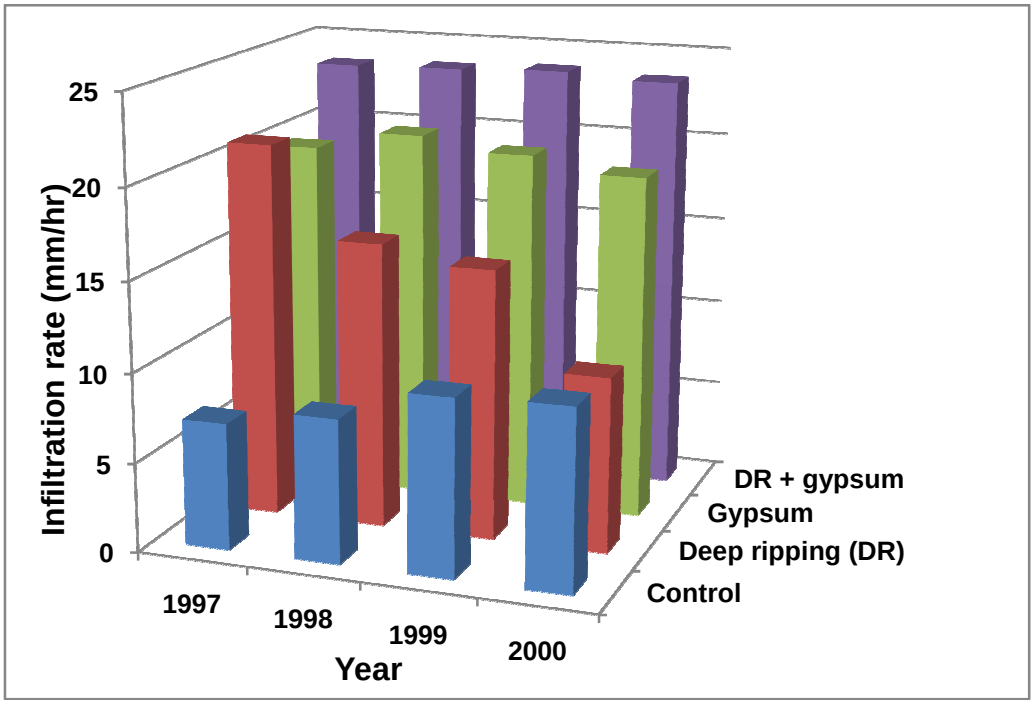

Figure 21. Effect of deep tillage and gypsum on the infiltration rate of a clay soil in Western Australia (data from Hamza and Anderson 2002).

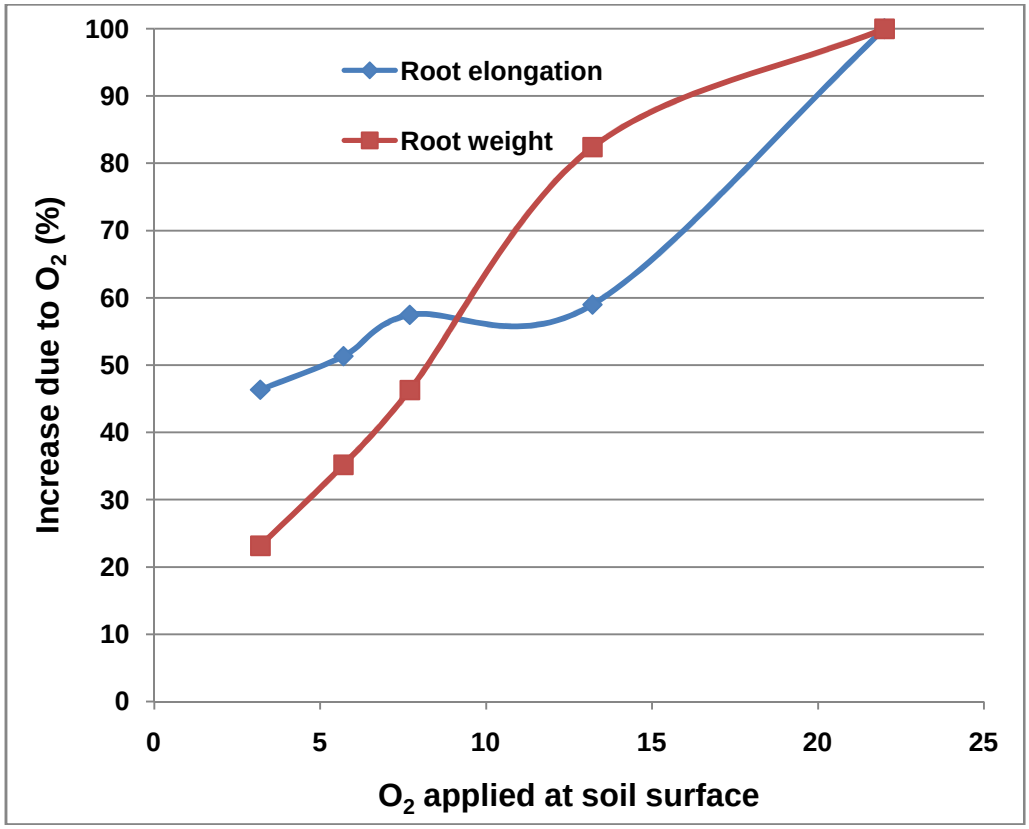

Figure 22. Effect of oxygen concentration at soil surface on sugarcane root elongation and weight (Banath and Monteith, 1966).

Figure 23. Sugarcane roots suffering from anoxia in a poorly-drained Vertisol in Costa Rica. Note the complete absence of white healthy roots.

Figure 24. Banana roots in Guatemala showing death of fine root structure as a result twice daily irrigation which does not allow the soil to breathe in order to supply oxygen to roots for respiration.

SCENARIO II

PROBLEM: Soil that is maintained in too wet a condition

When soils are maintained under excessively wet conditions for extended periods of time, anoxia which causes root death, results in substantial yield losses. For roots to receive adequate supplies of oxygen for respiration, rapid gaseous exchange with the atmosphere must take place. When the pore space is largely filled with water, diffusion of oxygen and carbon dioxide are severely retarded because gas diffusion through liquid is approximately 10 000 times slower than that through a gaseous phase. In addition, carbon dioxide and ethylene (particularly under wet conditions), which both inhibit root elongation (Tackett and Pearson, 1964; Crossett and Campbell, 1975), tend to build up with depth in the profile. In many high value crops such as banana, managers often have an unnatural fear of the consequences of drought stress. This leads to irrigation regimes where water is applied too frequently, even multiple times in a day. Such management does not allow the soil to breathe and exchange gases with the atmosphere, because the diffusion pathway is constantly full of water. The response of sugarcane root growth to changes in the oxygen concentration maintained at the soil surface to exchange with the soil air is illustrated in Figure 22. As soon as the O_2 level in the soil falls below that in the atmosphere, root growth becomes increasingly inhibited. Under anoxic conditions where ethylene production is favoured, roots typically appear brown to black and not white, as illustrated in Figure 23. Such roots are not efficient in absorbing nutrients and this results in yield decline.

Possible cause

Over-irrigation
Often, particularly when valuable crops are raised under irrigated conditions where the cost of water is zero or minimal, the natural tendency has been to over-apply water, resulting in suboptimal conditions of soil aeration. Soil pore space, which usually comprises less than 50% of the total soil volume, is occupied by varying proportions of air and water, depending on the incidence of rain or irrigation. In general, the micro-pores are preferentially filled with water, while the macro-pores serve as the repository for air. For optimal root growth to take place, these two components must be in a balance that allows roots to respire in order to take up nutrients while accessing adequate moisture to compensate for transpirational demand. Field experience shows that maintaining soils in a condition that is too wet is often worse than when the soil is a little too dry. Under excessively wet conditions, all the micro-porosity and some of the macro-pores are filled with water. If such conditions persist for extended periods, roots suffer anoxia when the supply of oxygen runs out. This, in turn, fosters the growth of pathogenic organisms leading to root decline, as illustrated in Figures 23 and 24. Because fine roots, which are responsible for the uptake of nutrients from the soil, are the first to be impacted, anoxia can induce nutrient deficiencies in the crop resulting in yield decline.

Potential solution

Irrigation scheduling
Despite the fact that many tools are available for use to correctly schedule irrigation according to the evapo-transpirational requirements of the crop, its adoption in the sugar industry has been disappointing, because of its complexity and inappropriateness to practical constraints in the field (Smith *et al.*, 2005). Given the tools available (Olivier and Singels, 2004), there is really no excuse for poor irrigation management.

Possible cause

Structural degradation and poor internal drainage
Many heavy-textured soils such as Vertisols and sodium-affected soils naturally have poor internal drainage which can result in suboptimal rooting conditions.

Possible solution

Drainage, deep tillage and gypsum
Application of gypsum in such cases has resulted in considerable improvement in soil physical conditions as a result of the flocculation of clay as discussed above. To take full advantage of the benefits of gypsum, drainage and deep tillage are also often required.

SCENARIO III

PROBLEM: Unacceptable levels of root pathogens

It has been my experience that whenever I excavate roots I find that, in many cases, they are compromised to some extent and often appear black and not white in colour. In addition, predation by nematodes is also often visible. While this aspect is very important, it is not in my purview of competency to discuss this matter in detail.

Possible cause

Nematodes
Throughout the world sugarcane industry, nematodes take a substantial toll on yields, with responses to nematicides being common in many countries (Bond *et al.*, 2000; Blair, 2005). Predation on roots reduces the efficiency of the plant to take up water and nutrients leading to yield decline as populations build up. Sites of injury are also potential infection loci for pathogenic bacteria and fungi. Yield losses from nematodes can be substantial, with estimates ranging from 11 to 30% of the crop in experiments in South Africa. This amounts to a total loss of more than 1.6 million tons of cane/an (Spaull, 1995, 2003). The overall effects of nematodes are similar to those of other root pruning factors such as soil acidity.

Potential solution

Nematicides
Nematodes are effectively controlled by nematicides (Berry and Spaull, 2008), but on the other hand, many of these control agents such as Temik® are highly toxic and environmentally unfriendly. Their use, in the future, is likely to come under more stringent control requirements. A more benign approach of using nematode resistant varieties is showing signs of promise (Spaull *et al*., 2006). Filter cake, when applied as a protective sheath, reduces nematode populations around cane roots while certain green manure crops such as sunn hemp have nematicidal properties (Berry and Wiseman, 2003). Rhizobacteria have been shown to be effective in paralysing juveniles of *Meloidogyne* spp (Vogel *et al.*, 2002). Wherever possible, such environmentally friendly approaches should be exploited. In any event, it is exceedingly important to constantly monitor soils for infection and if the concentrations reach economically significant levels, control measures, if available, should be instituted in an effort to promote yield and to extend the length of the crop cycle (Cadet *et al.*, 2005).

Possible cause

Fungal and bacterial pathogens
Root pathogens have been identified as one of the causes of yield decline in the Australian sugar industry (Garside, 1997), but their control is difficult. Excessive water in soil and lack of oxygen have been associated with sugarcane root rots caused by *Pythium arrhenomanes* in Louisana (Yin and Hoy, 1998). Cane susceptibility to root rots may be exacerbated by glyphosate and other herbicides (Dissanayake *et al.*, 1998). Roots damaged by nematodes present loci for infection by parasitic microorganisms such as *Leifsonia* (*Clavibacter*) *xyli*, which causes ratoon stunting disease (Spaull and Bailey, 1993). Clearly, this root damage also encourages infection by other organisms whose predation on roots may be stimulated by

other factors such as excessive moisture contents. In South Africa, these pathogens, if they exist, have not been identified and studied to any appreciable extent (Rutherford *et al.,* 2002).

Potential solution

Improving soil physical conditions, particularly in terms of water relations, may be one avenue worthy of investigation based on observations made in banana culture in Central America, where reducing the frequency and amount of irrigation resulted in markedly improved root growth. This strategy reduced the incidence of black roots presumably infected with pathogens and increased the production of healthy white roots. Encouraging the growth of beneficial organisms such as mycorrhizae and *Trichoderma harsianum* and *T. viride* that attack other parasitic fungi, by the addition of organic matter may also hold some promise. Filter press cake and other organic amendments have been shown to suppress root diseases in the field (Dissanayake and Hoy, 1999). Some micro-organisms which thrive in filter cake are antagonistic to *Pythium arrhenomanes,* the cause of a root disease in sugarcane (Roth, 1971). Fluorescent rhizobacteria such as *Pseudomonas* spp. can also suppress soil-borne pathogens and nematodes (Rutherford *et al.,* 2002). Bacterial isolates also show promise in controlling diseases caused by fungal pathogens such as *Ustilago scitaminea* that causes smut and *Fusarium* spp. causing stalk rot (van Antwerpen *et al.,* 2002)

SCENARIO IV

PROBLEM: Herbicide toxicity to roots

Possible cause

Glyphosate
Over the past 10 years, much information has been accumulated to show that glyphosate applied as a herbicide can be exuded by the target species' roots into the soil, where it accumulates as it is not readily decomposed. This has been shown to negatively impact N-fixing microbes, the bacterial shikimate pathway where it inhibits the EPSPS (5-enolpyruvylshikimate-3-phosphate synthase) enzyme, mycorrhizae, earthworms, plant growth promoting rhizobacteria and biological control organisms. In addition, the glyphosate or its metabolite AMPA (aminomethylphosphonic acid), which is more persistent in soil, is toxic to root tips and may be responsible for the death of fine roots important in the uptake of nutrients (Huber, 2010). Glyphosate is a strong chelator of essential divalent metals (Ca, Mg, Cu, Fe, Mn, Ni and Zn) rendering these less available for uptake (Cakmak *et al.,* 2009). It is usually strongly adsorbed by soil, but the addition of P can reactivate the glyphosate by desorption. These perturbations resulting from the use of glyphosate change the dynamics of soil microbes, enhancing soil-borne pathogens (Johal and Huber, 2009) such as *Marasmius* spp, which can cause root and stem rot in sugarcane.

As glyphosate is used to kill old cane stools (Chedzey and Findlay, 1985), it is pertinent to investigate its potential negative effects. What effect the killing of old stools with glyphosate has on root infections and divalent micro-nutrient uptake in the next crop is unknown. In Costa Rica, damage to young ratoons was observed after a slight overdose of glyphosate ripener in the previous crop. The bleached leaves are symptomatic of the greatly reduced concentrations of divalent cations in the leaves (Figure 25). In addition, the large reductions in Ca, which would reduce cell wall strength, could render the plant more susceptible to parasitic infections. Donaldson and Inman-Bamber (1982) reported yield declines of 11 to

17% in the next crop due to glyphosate application as a ripener when moisture was limiting, although they suggested the differences were due to variety. Fortunately, glyphosate is no longer used as a ripener in South Africa.

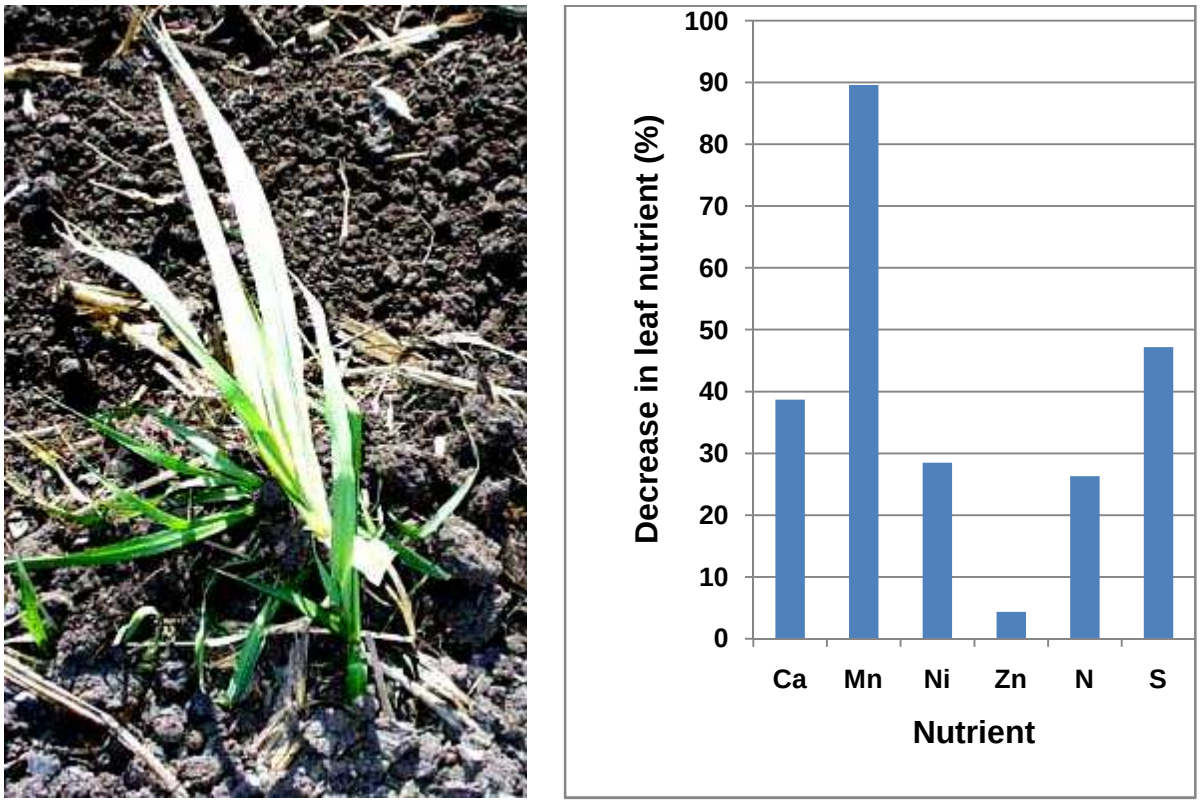

Figure 25. Damage to ratoon shoots of sugarcane subsequent to a slight overdose of glyphosate ripener in the prior crop and the effect on leaf nutrient content of the shoots in Costa Rica.

Potential solution

Use other herbicides

When glyphosate is used as a herbicide for killing old stools, its residual activity in the soil should be investigated to determine whether this is a problem of economic significance in the South African sugar industry. Because glyphosate activity is greatly reduced in the presence of Ca^{2+} ions, the application of gypsum may be an effective solution.

Conclusions

Many factors limit optimal root extension in cultivated soils which is crucial in promoting crop yield and quality. The presence of soluble calcium ions and the absence of toxic levels of Al are essential to the elongation of roots. Normally in acid topsoils, lime is the ameliorant of choice to effect these required changes, but because lime is not very soluble and generates variable charge, little Ca from this source reaches the subsoil. In many acid soils, subsoils are more Ca deficient and Al toxic than topsoils, making it essential to overcome these limitations to root growth so that water stored at depth in the profile can be accessed. Gypsum is an ameliorant which, when used in conjunction with deep tillage, can effect positive changes in soil such as (a) supplying Ca ions and neutralising toxic Al, (b)

flocculating clay, which leads to improved structure, (c) reducing the strength of hard layers, (d) improving water transport through the soil and (e) improving aeration. It is exceedingly important that roots be maintained in a healthy condition throughout the life of the crop. The absence of white roots and the presence of black roots are signs that conditions in the root zone are suboptimal. While all the above soil improvements promote better root growth and ultimately crop yield, attention must be paid to other factors such as irrigation efficiency and the judicious use of herbicides in order to maintain favourable conditions in the soil profile for rooting. All these factors contribute positively to improved soil health by contributing to the control of soil conditions that favour soil pests and pathogens and by promoting conditions conducive to good root growth. However, pesticides will also be required to control recalcitrant pests such as nematodes.

In terms of the yield plateau/decline syndrome that is plaguing the sugar industry throughout the world, adopting a 'multiple stress syndrome' approach, which has proved extremely helpful in overcoming the coffee yield decline in Central America (Sumner and Hylton, 1994) is key to gaining an understanding of all the factors in play. In the case of sugarcane, the stresses that should be considered as potentially contributing to yield decline are: soil acidity, declining organic matter contents, soil structural degradation leading to crusting, runoff, erosion, compaction and hardpans, lack of soil cover, nutrient imbalance, inappropriate balance between water and air in the pore space leading to anoxia and inefficient nutrient uptake, drought and length of dry season, pests and diseases such as nematodes, root stunting disease, root infections, white grubs, stem borers, rusts and other diseases, poor irrigation practices, salinity and sodicity and inappropriate use of pesticides amongst others. For decline to occur, a combination of a few of these factors is all that is necessary. The combination of factors limiting crop growth and performance is often different at different locations but the end result is the same, a loss of cane yield and sucrose content. To overcome the problem, it is necessary to identify the factors operating at a given location in order to develop a strategy to address the situation. The cure will NOT lie in a solution of 'one size fits all'!

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