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FERTILITY MAINTENANCE AND SOIL RECOVERY IN SUGARCANE CROPS

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INTRODUCTION

The search for quality of life among current and future generations is the central issue behind human activities. Agriculture in the 21st century can no longer be dissociated from the principles of sustainability, in which economic development must necessarily walk hand in hand with social development and environmental conservation. The sugarcane industry, known in the past as environmentally degrading and polluting, after significant changes, is moving towards sustainability.

Soil is considered a heritage of a nation. It is a constantly changing limited resource. In this sense, it is essential that it be understood as a resource to be preserved for future generations. There are many definitions of "soil". The Brazilian Soil Classification System (EMBRAPA) defines soil as: "a natural body consisting of three-dimensional, dynamic, solid, liquid and gaseous parts, formed of mineral and organic matter, which occupies most of the surface cover of continents on our planet, containing live matter, and vegetated in the nature within which it occurs, eventually having been modified by anthropic interferences". This definition contains important concepts: the existence of live matter as a soil component; its three-dimensional nature, in other words, soil is not only the land surface that is visible, but also has depth; and the fact that soil may have undergone anthropic interferences, in other words, change by agriculture or other human activity.

THE IMPACT OF SUGARCANE CULTIVATION ON SOIL

Traditional agricultural operations and their consequences

From ancient civilizations to this day, agriculture starts with soil preparing operations, in which layers are revolved to control weeds break up compaction, thereby improving the physical conditions for root growth and water storage.

Soil preparation also aims to incorporate corrective amendments such as limestone or gypsum or organic fertilizers, thus preparing for good crop yields. However, soil plowing and disking operations involve oxygenation, which encourages microbial and small animal communities to develop; these communities degrade the soil organic matter. Such organisms use organic matter as a source of C and other nutrients, decomposing it and, as part of its respiratory mechanism, eliminating CO_2 into the atmosphere.

For this reason, converting an area of native vegetation into an agricultural plot for any crop, especially when applying traditional farming operations (plowing, soil disking), results in a decline of soil organic matter concentrations (Lal, 2002), and consequently loss of C in soil, usually quantifiable in chemical analysis. Added to the loss of soil organic matter is an undesired environmental effect: loss of CO_2 and other gases into the atmosphere, which increases the greenhouse effect. For this reason, adding organic matter is a highly recommended practice for sustaining agricultural systems.

BLUM (1988) defined soil degradation as loss of quality, or partial or complete loss of one or more soil functions. Ecological functions of interest for agriculture are: soil as an agent supplying nutrients, air, water, support for roots, facilitating the production of plant material, and renewable energy. Another soil function is its filtering, buffering or storage ability, for instance, of rainwater. Soil is also a *habitat* for the flora and fauna. The intensity with which soils perform each of its functions is very important for its sustainability. Soil degradation decreases its ability to carry out its functions, leaving it unable to support vegetation. The extreme case is desertification. Agricultural operations done without due respect for soil conservation techniques cause major losses and accelerate the degradation process.

Surveys of degraded areas, done in Brazil in 2005 (FAO 2008), have shown that 15.97% of Brazilian soils are degraded in some measure, as follows: 1.29% (110 mil km^2) mildly degraded; 4.99% (427 mil km^2) moderately degraded; 7.29% (624 mil km^2) severely degraded; and 2.4% (205 mil km^2) very severely degraded.

The main causes of soil degradation are physical (erosion, compaction), chemical (loss of organic matter, contamination, salinisation), or biological (loss of organic matter and the resulting reduction of microbiological communities). Once degraded, soil recovery is a long-term task involving multidisciplinary actions to reestablish the previous balance and sustainability (Griffith and Dias, 1998).

Soil fertility and the longevity of sugarcane crops

Contrary to what has been observed in other countries after decades of sugarcane plantation in the same soil, productivity in Brazil has remained unchanged or even increased significantly. Novel management technologies developed during years specifically for Brazilian soils may explain this situation; examples include: improved soil preparation techniques, mechanization of agricultural operations, soil conservation techniques, the development of superior varieties, nutrient recycling, fertilization and irrigation techniques, and several others.

Naranjo *et al.* (2006), from Mexico, have studied the effects of long-term sugarcane crops on the fertility of a fluvisol cultivated for 5, 10, 20 or 30 years. No changes in soil organic matter or exchangeable K, Ca and Mg and CEC were found across the years of farming. The authors found that total C (17%), total N (21%) and total P (37%) soil content declined in 30 years of farming. Losses occurred mainly within the first 20 years. However, these fertility losses were not accompanied by decreased sugarcane yield; in fact the yield increased 67% between the 5th and 30th year of farming due to agricultural practices such as bred varieties and more adequate N and P fertilization.

Sugarcane farming for long period on the same soil may improve its chemical and physical attributes, as demonstrated by Mubarak *et al.* (2005) in clayey soils (> 54% clay) in the Sudanese semiarid region. In that study, the soil attributes after long-term sugarcane farming (more than 40 years) were compared with farming for less than10 years and with the native soil vegetation. Agricultural practices included: deep sub-soil tillage, disk cultivation and leveling followed by plot formation every 4 or 5 years, with plots reformed every year. Soil organic matter content was significantly higher in the sugarcane crop cultivation period(8.2 g kg^{-1}) compared with that of native vegetation (2.1 g kg^{-1}) and a shorter time of sugarcane cultivation (6.6 g kg^{-1}).Farming had no effect on total soil N, organic C or soil density in the 0-10 cm layer. At 10-20 cm depth more total N accumulated in long term-cultivated soils (0.46 g kg^{-1}) compared to native vegetation and short term cultivated soils (0.26–0.33 g kg^{-1} respectively). In this layer, soil density in the long-term cultivation period was lower than that of native vegetation and short term cultivated soils. At 20 to 30 cm depth, total N and soil density remained unaltered, but organic C content was significantly higher under native vegetation (4.9 g kg^{-1}) compared to short-term farming (1.7 g kg^{-1}).

Organic matter content did not decline when sugarcane was farmed over 25 years on a same soil (cohesive latosol in the coastal board region of Alagoas, Brazil)compared with native plant soil (content of C= 26 g kg^{-1}). There was a decline in total C content (C=19 g kg^{-1}), in organic matter and aggregate stability in soils cultivated for only 2 years, suggesting that agriculture disturbs soils, especially in the initial phases of its implementation (SILVA *et al*., 2007).

Cerri and Andreaux (1990) assessed the content of C in forest soils cultivated for 12 or 50 years in the state of São Paulo, and found that C content declined by 46% after 50 years farming compared to forested areas. Based on the natural abundance of C technique, which evaluates the 13C/12C ratio – which is lower in forest-originated organic matter (C3 plants) compared to sugarcane=originated matter (C4 plant – the authors estimated that after 12 years farming, 80% of the organic matter was still originated from the forest, white after 50 years farming, this number was 55%. The increase of C in sugarcane-originated organic matter is slower than the decline of forest-originated C in organic matter, resulting in lower C values in sugarcane cultivated soil across the years compared with the content of C in forests.

Skjemstad *et al*. (1999) compared soil samples from uncultivated sites with soil samples from recently planted sugarcane crop areas, and also with regions where sugarcane had been cultivated for many years (with burning of trash); there was little change in total C and the labile fraction in soils. These authors concluded that sugarcane farming increases organic matter humidification in proportion to the duration of sugarcane farming. Evidence of this has been gathered from organic C redistribution in the profile of sugarcane cultivated soils. Areas where sugarcane has been cultivated for many years have soils with lower levels of surface organic; these levels increase in the subsoil compared to recently implanted areas. Magnetic resonance imaging spectroscopy of C-13 found no differences in the chemistry of organic matter molecules in soil layers in the same site, but suggested differences among sites.

Noble *et al*. (2003) compared soil attributes in areas with sugarcane crops with and without burning to assess the changes in soils under different forms of management 6 to 9 years after implantation. These authors also compared long-term sugarcane crops, grass pasture areas and fallow areas. The increased addition of protons to the system with trash compared to burning was 0.71 kmol H$^+$ ha^{-1}.year. The added amounts of protons according to management were 1.38, 3.81 and 0.87 kmol H$^+$ ha^{-1}.year respectively for continuous sugarcane farming, pasture, and fallow periods. Although acidity, in the case of sugarcane, may be due to trash decomposition, both acidity and decreased amounts of bases may be reverted with management strategies, such as liming. Organic C increased by 4 t.ha^{-1} after treatments with cane trash (treatment without burning) compared with treatment with burning, after a 9-year period. For treatments with pasture coverage, organic C increased to 9 t.ha^{-1} in a 6-year period compared with the time under continuous sugarcane plantation, clearly demonstrating the huge potential of pastures to sequester C in tropical environments. Exchangeable cation data show variations only in the surface layer (up to 10 cm depth), suggesting that the influence of cane trash and pasture coverage occurs only superficially. Increased CEC (pH 5.5) in the treatment with cane trash, compared with burnt cane, and pasture compared with the continuous cane system, were 0.67 and 0.75 cmolc kg^{-1} in the 0–10 depth layer. From 9 to 31% of the amount of cations in the soil were not retained by the CEC, suggesting a potential for loss of these cations in the soil. In this study, analysis of oxidizable organic C by potassium permanganate showed a linear correlation with total organic C in all situations, indicating that the proportion of different organic matter functional elements were not affected by burning, continuous cane farming, or pastures.

Maia and Ribeiro (2004) evaluated morphological and physical property changes of an abrupt fragipanic dystrophic yellow argisol under continuous sugarcane farming in Coruripe, Alagoas state. These authors compared three different cane plots, one with native forest vegetation and two with sugarcane crops for 2 and 30-year periods. Sugarcane farming changed the surface horizon morphologically, yielding an Ap horizon, and changing the structure of the first two horizons of the profile. Continuous cane farming decreased macroporosity, and thus increased available water, since more micropores were available. Because microporosity increased, there was a significant decline in the hydraulic conductivity of superficial horizons. No significant soil density variation was observed. Compaction in Ap and AB horizons was observed, due to sugarcane farming and the presence of densification (cohesive nature) in the Bt horizon in all profiles.

The C content in soil is generally recognized as an important component of soil fertility and its physical processes. Moreover, there is a strong connection between the organic matter content and the biological life of soils, which are important for the sustainability of the system. Recent studies have suggested that the quantity and quality of organic matter returning to the soil system, such as roots and rhizomes, may be important factors for systems in future. Bell *et al*. (2007) emphasized the importance for "soil life" of maintaining organic matter, and have indentified more indicative lines of management.

With the aim of investigating the presence of worms in different management forms and cultures in the KwaZulu tropical region, Natal, South Africa, Dlamini and Haynes (2004) found that pastures (kikuyu) contained more worms than the native forest, and that cane under a raw cane harvest system contained more worms than burnt cane. Burnt cane was the situation with fewer worms in this study, which evaluated 11 different crop and/or management situations. The number and mass of worms correlated positively with soluble C; C linked to microbial biomass and soil pH. Eleven different worm species in several crops were found, although sugarcane supported only two or three species.

Erosion

Erosion results from water and wind removing finer soil particles, which are transported to other sites, resulting in decreased soil depth, loss of functions and, in extreme cases, loss of soil itself. Erosion may also contaminate water bodies.

Prove *et al*. (1995) have measured erosion in cultivated soils under traditional operations or minimal cultivation in Australia. Losses ranged from 47-505 t.ha^{-1}.year-1, with an annual mean of 148 t.ha^{-1}.year^{1} in areas under traditional ratoon farming. This wide range was due to rainfall differences between the study sites. Erosion losses were below 15 t.ha^{-1}.year^{1} with minimal cultivation practices.

Sparoveck and Schnug (2000) applied remote sensing and the universal soil loss equation (USLE) in Brazil to estimate mean losses due to erosion at 31 t.ha^{-1}.year^{1} in the Central-South region in sugarcane cultivated areas.

The impact of erosion on sugarcane cultivation occurs mostly because of the extension of cultivated areas and the fact that soil preparation and planting takes place during the intensely rainy season. Impact is minimal when the full soil conservation technology is applied. Sugarcane is generally known as a conservationist agricultural activity, wherein soil losses are small compared to other annual crops, especially if burning is not done before harvest and the trash is left to protect the soil. Major movement of soil takes place only during planting, every 5 or 6 years on average. Data from the Agronomy Institute of Campinas (Instituto Agronomico de Campinas) in the state of São Paulo, reported by De Maria and Dechen (1998), have estimated soil losses due to burning of trash at 8.3 to 23.2 t.ha^{-1}.year depending on the soil type, on a 5-year average. These numbers are 62% lower than those of soybean plantations.

Cultivation of cane over trash with harvesting without burning of trash required drastic technological developments. Maintaining the trash results in drastically decreased soil erosion losses, which were already low compared to other crops. Table 1 shows soil loss data as a function of differentiated trash management. It can be seen that losses decrease by 32% when trash is kept on the surface compared to the conventional burning of sugarcane plantations.

Izidorio *et al*. (2005) presented a case study assessing nutrient losses due to erosion in a red eutroferric latoso in Guariba (São Paulo state) with burning of trash for harvesting,showing that eroded sediment analyses indicated enrichment rates of 1.62 (organic matter), 4.30 (P), 1.17 (K),

TABLE 1 Soil losses due to erosion in sugarcane with or without trash.

	Soil losses (t/ ha^{-1})
Sugarcane – no trash	39 to 108.6
Sugarcane – (mean plant cane + 5 harvests), no trash	8.3 to 23.2
Sugarcane with surface trash	6.5
Sugarcane with incorporated trash	13.8

Source: DE MARIA and DECHEN (1998); BERTONI *et al.* (1982).

1.33 (Ca), and 1.24 (Mg) times compared to the original soil. Soil and nutrient losses as a function of the type of erosion obeyed the following order: furrows > global > inter-furrows. These losses were spatially dependent, and the authors found few sites with losses above the estimated limit for the type of soil being studied; they further stated that even without trash, conservation conditions of physical and chemical properties occurred in nearly of the study area.

AGRICULTURAL PRACTICES FOR SOIL SUSTAINABILITY

Several agricultural practices have been developed for sustainability. Such practices constantly undergo changes, and are evidence of multidisciplinary efforts. The efforts of private initiatives together with public institutions for seeking technological development in the sugarcane industry are noteworthy.

Production environments for sugarcane

Sugarcane cultivation that respects agroecological zoning is a determining factor for sugarcane yields and a starting issue for sustainability. Production environments – the sum of interactions among surface and especially subsurface soil attributes – may be defined in the appropriate sites for sugarcane; the declivity grade where soils occur, associated with climate, may also be taken into account. Production environment components are represented by depth, which is directly related with water availability and the volume of soil explored by roots; by fertility, such as the source of nutrients for plants; by texture, which is related with the level of organic matter, cation exchange ability and hydric availability; and by water as part of the soil solution, which is vital for plant survival. Adequate management, such as soil preparation, using lime, vinasse and irrigation, may increase soil yield and, therefore, its production environment. Chemical conditions of soils directly affect production environments.

Table 2 shows the chemical criteria of the subsurface layer of soils, adopted by EMBRAPA (1999), with specific modifications for sugarcane crops in italics, made by Prado (2004). According to Landell *et al.* (2003), the chemical status of the subsurface horizon is a determining factor for sugarcane yields, where the correlation with yields (TCH) increases with subsequent harvests. This study also showed that ratoon yield decreased significantly according to the following order of soil chemical attributes: eutrophic > mesotrophic > dystrophic > acric > alic (Figure 1).

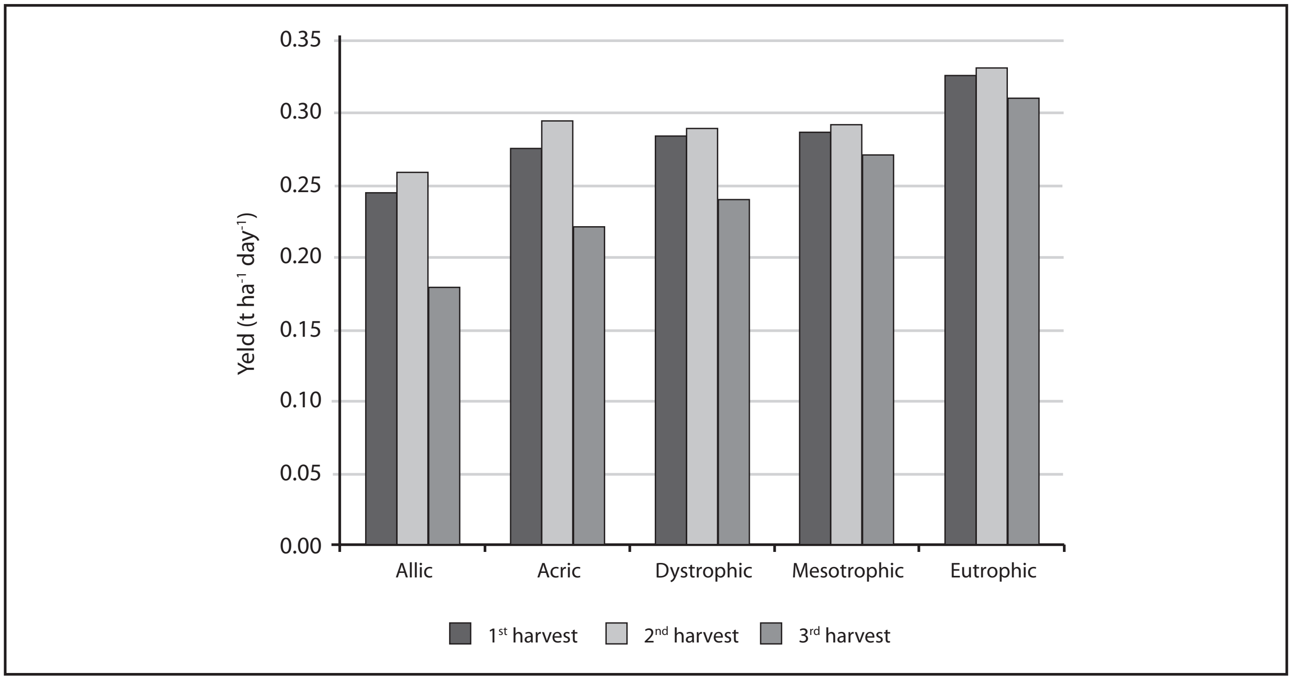
In Prado *et al.* (2007) work, the same cane varieties were planted in Goianésia and Ribeirão Preto (São Paulo state). Both regions had similar rainfall (1,435 mm), but with a more irregular yearly distribution in Goianésia, which has a longer deficiency period compared to Ribeirão Preto. There is also more evapotranspiration in Goianésia, which results in more water loss in soils. Soils were similar, a red acriferric latosol with a very clayey A moderate (LVwf) texture, a representative soil class in central-southern Brazil. Five varieties (IAC87-3396, RB72454, RB855486, SP80-1816, and SP80-1842) in three harvests were evaluated in both sites. Higher water deficiency and evapotranspiration in Goianésia resulted in lower sugarcane yields compared with the Ribeirão Preto region. The mean reduction of the three harvests was 16.8% in stalk yield. Although the soil class was similar at both

TABLE 2 Chemical-pedological criteria of the soil subsurface layer.

Soil	V	SB	m	Al^{3+}	RC
Eutrophic	≥ 50	*≥ 1.5*			
Mesotrophic	*30-50*	*≤ 1.2*			
Mesotrophic	*> 50*	*< 1.5*			
Dystrophic	*< 30*		*< 50*		*> 1.5*
Acric					≤ 1.5
Mesoallic			*15-50*	*≥ 0.4*	
Allic			> 50	0.3-4.0	
Alluminic			≥ 50	> 50	

V = base saturation (%).
SB = sum of bases ($\text{cmol}_c\ \text{kg}^{-1}$ soil).
m = aluminum saturation (%).
RC = retention cations ($\text{cmol}_c\ \text{kg}^{-1}$ of clay).

Source: PRADO (2004).



Source: LANDELL *et al*. (2003).

FIGURE 1 Sugarcane yield across harvests.

sites, the production environment classification differs. The higher climate restriction in Goianésia moves the production environment classification from D1 in Ribeirão Preto to E2 in Goianésia.

Among the five varieties, RB72454 interacted with the production environment, where its yield was more affected by the water restricted conditions of Goianésia (GO). Other varieties (IAC87-3396, RB835486, SP80-1842 and SP80-1816) did not interact, showing that these varieties are more stable.

Sugarcane production environments in central-southern Brazil may be found in Prado (2005). A1 environment soils, considered as high potential soils for sugarcane yields, include argisols, latosols, nitisols, gleysols, cambisols, andchernosols, as long as they are eutrophic, eutroferric or mesotrophic, with medium/high CEC and high water availability. Lower yield potential soils are those that do not store water, such as acric soils, or shallow and allic dystrophic soils with a low CEC, such as neosols, allic argisols, and allic latosols.

Soil conservation – direct drill planting and minimal cultivation systems

Sugarcane cultivation in Brazil has been carried outwith intensive use of agricultural machinery and implements and significant movement using plows and heavy disking. The first studies for implementing direct drill planting or minimal cultivation aimed mostly to reduce planting operational costs. Perticarrari and Ide (1986) tested and developed implements for deep sub-soil tillage and elimination of ratoons to reduce and optimize soil preparation operations. In these authors' experiments, ratoon yields increased in both clayey and sandy soils in a comparison between minimal and traditional cultivation.

The main reported advantages of minimal cultivation are less machine use, decreased soil preparation operating costs, maintenance of trash on the surface, decrease or elimination of terraces (below 5% declivity) without erosion issues, increased soil conservation, decreased soil compaction, increased operational yield, the possibility of planting during rainy seasons, increased ratoon yield and longevity; in the middle and long terms, improved physical conditions of soils and increased soil organic matter content and fertility.

In general, direct drill planting similar to grain farming practices is difficult to adopt for sugarcane crops. Compaction is practically inevitable, because of intensive mechanization requirements and long term farming without movement of soil. Maintenance of trash has made drastic compaction avoidable, although even in this case deep sub-soil tillage operations are often required. In this context, minimal cultivation has been more successful.

Coleti (2008) listed the following situations for minimal cultivation and the operations involved in this process:

1) Over preexisting sugarcane plantations – chemical or mechanical elimination of ratoon cane (two-row eradicator), rectification of tracings, application of corrective agents, deep sub-soil tillage with roller and front disks, furrowing and planting.
2) Over pastures – chemical desiccation of pasture, marking and building conservationist structures (terraces and paths), application of corrective agents, deep subsoil tilling/roller, furrowing and planting.
3) Associated with legumes to form dry matter – chemical desiccation of the previous sugarcane plantation, correction and/or adaptation of conservationist structure, application of corrective agents, broadcast sowing of leguminous crops (*Crotalaria juncea*, *Crotalaria spectabilis*, guandu beans), deep sub-soil tilling/roller, summer fallow, incorporating plant mass preferably with knife roll, wait for drying of plant mass, furrowing and planting. Development and use of deep sub-soil tilling/roller facilitated minimal cultivation operations for sugarcane by decompacting the soil without causing it to lose its structure. Direct drill planting and minimal cultivation systems for sugarcane are not indicated in low fertility acid soils, in which case liming is indicated. Because of the need to incorporate lime and, with other practices, "build" soil fertility, it is suggested that this step be carried out before adopting the new system. Sites with significant soil pest attacks should also undergo pest control approaches before adopting minimal cultivation.

Spacing of cane rows, permanent plots and controlled traffic

Soil compaction and treading on cane rows are two factors that recognizably reduce sugarcane yields and the lifetime of sugarcane plantations. Intensive mechanization has compounded these issues; for this reason, traffic control in sugarcane plantations has become paramount for sustainability.

It is common to control traffic in sugarcane plantation in Australia. Machine tracks always compact the same inter-row, separating the plots where cane rows are present. Spacing generally is 1.5 m, but the gauge of machines is 1.83 m. An option is to control traffic and to investigate spacing to reduce treading on rows. A possibility is double spacing (known in Brazil as pineapple spacing). Braunack and McGarry (2006) studied the physical properties of soil in a double spaced sugarcane plantation (0.3 m between cane rows) reaching 1.8 m spacing and with controlled traffic, comparing it with a single spaced (1.5 m) sugarcane plantation with normal traffic. Soil density and resistance to the penetrometer measured on cane rows were higher in the 1.5 m spacing plantation, and hydraulic conductivity was lower, indicating that the double spaced system resulted in less compaction. Cane yields were not significantly different between these two planting systems.

Braunack and Peatey (1999) studied the effect of treading on the haulout unit on wet and dry soils. Treading on rows in wet soils reduced yields significantly. The most significant changes occurred at 20 cm depth, resulting in increased soil density and decreased hydraulic conductivity.

In Australia, after years of declining sugarcane yields because of factors such as orange rust, soil pests, and intense mechanization, minimal soil movement concepts together with crop rotation, green fertilization, and lower fertilizer doses (especially nitrogen) are practices that have gained acceptance. Minimal cultivation is done with soil preparation in plots, where the inter-rows remain always as such, compacted and never reformed, and the row is the soil preparation site, where plots are made for cane cultivation. In this technique, cane is planted in double rows with wider spacing (1.8 m). Carr *et al.* (2008) reported increased yields by changing from the traditional soil preparation system to the permanent plot system at the Herbert River district, Australia. In this new sustainable agriculture trend, farmers in this region of Australia are replacing fertilizers such as urea and potassium chloride with calcium nitrate, ammonium nitrate, ammonium sulfate and potassium sulfate, believing that the latter are less harmful to soils. With the current high prices of fertilizers, use of alternative nutrient sources and conservative doses should become more widespread. Table 3 shows the nutrient doses used in the traditional system and in the minimal cultivation system with plots used in Australia. Cane yields, which from 1997 to 2001 never surpassed 70 t.ha^{-1}, have always been over 80 t/ha^{-1} since 2002, even with reduced nutrient doses. It should be noted that pests and diseases against which the variety had no tolerance also caused low yields during that period.

Cane cultivation in an organic production system

Production of cane in organic systems used to be restricted to small brown sugar, (dried sugarcane juice) or cane spirit. In the past ten years, large-scale production was the aim of several industrial units in the state of São Paulo; these units currently cultivate over 20,000 ha for these products.

TABLE 3 Nutrient management strategies in traditional and minimal cultivation strategies with plots in Australia.

	Plant cane		**Ratoon cane**	
	Conventional	**Plots**	**Conventional**	**Plots**
	kg.ha^{-1}			
Nitrogen	105	42	171	94
Phosphorous	30	–	–	
Potassium	56	36	77	80
Sulfur	18	22	–	48

Source: CARR *et al*. (2008).

Soil and environmental conservation is emphasized in organic sugar production, since herbicides, agrochemicals and mineral fertilizers are not allowed. In these areas, vinasse and filter cake are added to provide nutrients – especially N, P and K – and organic matter. Maintaining trash also adds organic matter, thus protecting the soil from raindrop impact and erosion. Meeting environmental regulations, conserving ecosystems, such as forest corridors and biodiversity reservations, and preserving water resources are necessary requirements for certification. Rossetto (2004) discusses the advantages and advances of environmental issues as represented by organic cultivation techniques.

Crop rotation – green fertilization

Crop rotation is one of the oldest farming practices and has gained "current airs" under the focus of sustainable farming. Rotation for sugarcane – a semi-perennial plant – is only possible when the plantation is reformed, which occurs every 5, 6 or more years. Some advantages of crop rotation are well known, such as savings when reforming the plantation because of income gained from another crop; soil conservation and major erosion control because of coverage during a heavy rainfall season; weed control; indirect pest control, such as the cane borer and the lesser cornstalk borer; increased sugarcane yield. Certain green fertilizers, such as crotalarias, may help combat nematodes. More recently, after the polemic on soil use for biomass production for fuels and the need to produce food, use of sugarcane reform sites has resulted in increased grain production in the state of São Paulo. Sertãozinho, São Paulo state, a well-known sugarcane plantation region, is one of the major peanut producing areas in this state.

Sugarcane plantations harvested from June to September that will be reformed are the best sites for rotation. Sugarcane ratoon is destroyed chemically with glyphosate. It is possible to plant early soybean, peanut crop or green fertilizers from September to March, after which the area may be prepared for a one-year and a half sugarcane plantation. Cane should be about 60 cm high to be desiccated. The ratoon root system is a source of organic matter, and may eventually help form water infiltration channels. The crop should be planted over the trash of desiccated cane.

Rotation with a leguminous crop (Fabaceas) may be more advantageous because of biological fixation of atmospheric nitrogen. Soybean, for instance, may fixate from 100 to 160 kg/ha^{-1} ofatmospheric N (Mascarenhas *et al.*, 2002).

Mascarenhas *et al.* (1994) studied the effect of soybean fertilization on the yield of a sugarcane plantation reform area. These authors found that cane only made use of the residual effect of soybean fertilization when it was higher than 0-126-90 kg.ha^{-1} of N-P_2O_5-K_2O. A mean soybean yield of 1,700 kg/ha^{-1} exported only 20 kg/ha^{-1} of P_2O_5 and 38 kg/ha^{-1} of K_2O, leaving a considerable amount of primary nutrients for cane.

Pankhurst *et al.* (2005) studied crop rotation with pastures, grains or fallow periods on soils farmed with sugarcane for over 20 years in five sites in Queensland State, Australia. Rotation remained for 30 to 42 months in four sites and for 12 months in a fifth site. Cane was cultivated again after this period. Microbial biomass increased on pastures in the first four sites and declined in the fallow site; it remained unchanged in the grain-cultivated areas compared with continuous sugarcane farming. *Pratylenchus zeae* nematode populations, which reduce cane yields, declined in sites where rotation was done longer; nematode populations, however, increased in pasture areas and decreased in fallow areas. Cane yields in areas under rotation were significantly higher compared to continuously farmed areas.

Liming and correction of deep layers

Liming is essential to form and maintain soil fertility. The cost/benefit ratio is highly positive for sugarcane crops. Calcium corrects acidity, neutralizes toxic aluminum, and stimulates root growth. In many cases, however, the effect of liming is restricted to the soil preparation layer. With the current trend for less movement in both minimal preparation and direct drill planting, subsurface acidity is not corrected. A practice often associated with increased sugarcane yield is to improve the subsurface environment by deepening the root system, thereby increasing resistance to lack of water. Thus, a measure that possibly increases yield is to incorporate lime in depth with amold board plough.

Liming is indicated whenever the aluminum saturation in soils is over 30% and/or the calcium content is below 1 $cmol_c$ dm^{-3} and the magnesium content is below 0.4 $cmol_c$ dm^{-3}. In general, by monitoring soil analysis and the liming need equation that aims to increase base saturation to 60% of the CEC, every ton of lime applied to a hectare of soil (PRNT 100) raises calcium by 1 $cmol_c$ dm^{-3} in the 0-20 cm layer. A recommendation is to add 15 to 20% more to compensate for the acidification that occurs due to fertilizer use (Rossetto *et al*., 2004). The purpose of liming is to correct the 0-20 cm layer; if preparation goes deeper, more lime should be expected. If preparation reaches 30 cm depth, the recommended value should be multiplied by 1.5.

It is important to consider that liming improves the availability of existing phosphorous and molybdenum in the soil, raises the CEC (caption exchange capacity), and increases bacterial activity. Efficient use of phosphorous provided by soluble fertilizers is increased because of liming.

Sugarcane is quite tolerant to soil acidity. This crop may grow in a wide pH range. In several cases, liming increased yields not by raising the pH, but by providing calcium. Marinho and Albuquerque (1983) reviewed liming and sugarcane and found a linear correlation between aluminum saturation and relative production. For aluminum saturation close to 100, the relative yield was estimated to be 70, which indicates strong tolerance to acidity.

Liming may raise the pH and increase the content of Ca and Mg in deeper layers of soil if long-term management is undertaken. Noble and Hurney (2000) found a significant decrease in exchangeable acidity with increased Ca and Mg content up to 1 m depth. Calcium was applied 3 times in 18 years at a dose of 5 $t.ha^{-1}$ on the surface of an acid and dystrophic soil (oxic humitropept) in Australia. As lime was applied on the surface and the pH was seen to increase up to 1 m depth, this was attributed to ionic pairs with NO_3 being formed on the surface and then leached, evidenced also by the difference in NO_3 absorption by roots at different soil depths.

Orlando F. *et al*. (1996) observed that changes in chemical attributes, such as the pH, Ca and Mg content, and base saturation in the arable layer, persist in soils as residual effects for a long time, up to 56 months after application.

Noble and Hurney (2000) found increased sugarcane yields and progressive rises in CEC and pH up to 1 m depth 18 years after a first application of lime. The dose was high, 5 $t.ha^{-1}$, in an acid and dystrophic soil (oxic humitropept) in Australia, and liming was carried out more than three times during the 18-month study period.

Application of gypsum and phosphate

Application of gypsum in soils may be advantageous when the calcium content at 40 to 60 cm depth is equal to or below 0.4 $cmol_c$ dm^{-3}; the Al^{+3} content is higher than or equal to 0.5 $cmol_c$ dm^{-3} and/or Al^{3+} (m) saturation above 30%; and sulfur content is low. Gypsum ($CaSO_4.2H_2O$) is much more water soluble than lime; when it solubilizes, the resulting SO_4^{2-} anion remains in the solution and may be leached, carrying with it calcium, aluminum, magnesium or potassium cations. Chemical complexes formed between sulfate and aluminum decreases the availability of these ions for plants, although they are not neutralized. Furthermore, a high calcium concentration displaces negative charge bonded Al^{3+} into the soil solution. Gypsum carries calcium to deeper soil layers, which results in the benefits of improving the subsurface environment, thereby promoting deep root growth.

Studies of gypsum in sugarcane have demonstrated the significantly favorable effects of this practice on yield and soil fertility, reaching deeper soil layers, compared to the improvements attained with liming only. Morelli *et al*. (1992) carried out one of the best-known experiments in this area, where increasing lime and gypsum doses (0, 2, 4 and 6 $t.ha^{-1}$) were applied to an allic dark red latosol in Lencois Paulista, São Paulo state. The subsurface layer of this soil was poor in calcium

(1.2 $\text{mmol}_c\ \text{dm}^{-3}$) and rich in Al^{+3} (6.5 $\text{mmol}_c\ \text{dm}^{-3}$), which suggested a good response to gypsum application. Liming at a dose of 6 $t.ha^{-1}$ raised the content of calcium and magnesium, and decreased the content of aluminum at 25 to 50 cm depth. Gypsum increased much further the content of these element sand its effect reached a depth of 100-125 cm. Combining lime with gypsum reduced Al^{+3} more effectively compared to such practices done separately (Table 4). Similar results were seen on yields. Looking at the 4 years of the study, lime (at a 4 $t.ha^{-1}$ dose) raised yields by 54 t, and gypsum (at a 6 $t.ha^{-1}$ dose) raised yields by 51.6 t. Both practices combined increased yields by 76.8 t.

Raij (2008) analyzed several results of studies on lime and gypsum in sugarcane, and concluded that liming and gypsum application are highly economic for sugarcane; if well applied, they may increase longevity by at least one ratoon harvest. This author also concluded that the official liming and gypsum recommendations for São Paulo state, given by Spironello *et al.* (1996), are underestimated.

Figure 2 illustrates the decreased base saturation in sandy middle texture low CEC latosol, in which soil preparation involved lime application at 2.5 $t.ha^{-1}$ and gypsum application at 1.5 $t.ha^{-1}$. The initial base saturation in the 0-20 cm layer was 15%; at 20-50 cm depth, it was 7%. Liming raised these values within the first year of farming. Subsequently, however, base saturation decreased and nearly reached the initial values at the end of the fifth harvest. Increased acidity may also result in decreased yields in subsequent harvests, since fertilizer nutrients are less utilized. These data suggest that lime should be applied again after the second harvest.

Gypsum has an important function in correcting saline and saline-sodic soils. Choudhary *et al.* (2004) aimed to investigate the effect of irrigation water with added gypsum and found that the beneficial effect of gypsum was more pronounced in sodic soils (30% increased yield) compared to saline-sodic soils (13% increased yield).

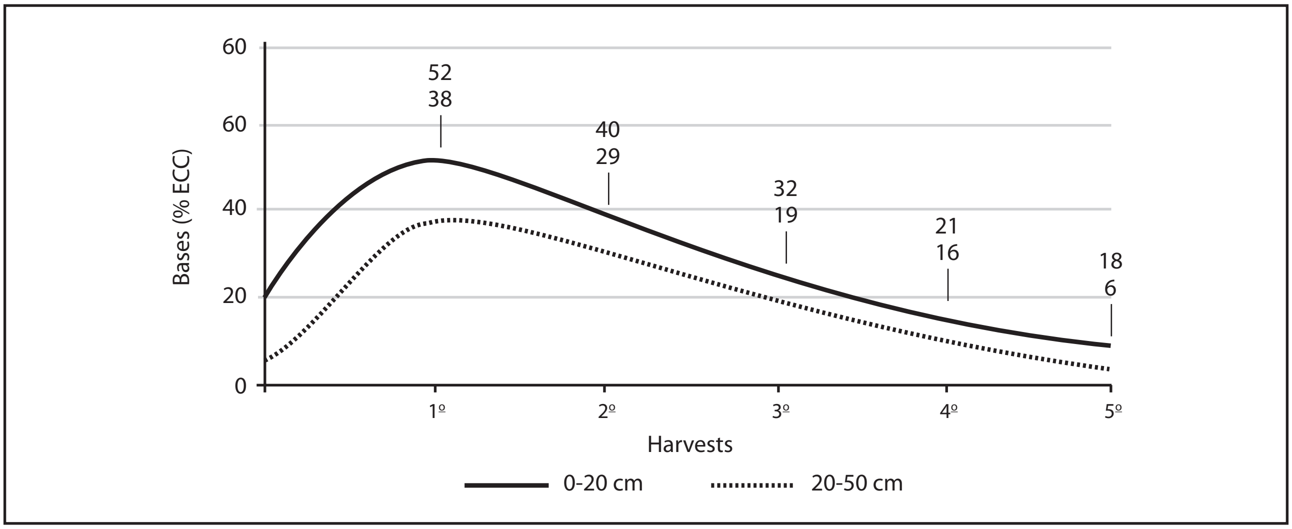
In Australia, the properties of soils with 7.9% Na to which gypsum was applied (10 $t.ha^{-1}$) followed by five irrigations, showed a significant decreased in clay dispersal and higher stability of soil aggregates. The authors of this study combined gypsum applications with molasses (10 $t.ha^{-1}$) and found a higher proportion of aggregates and lower electrical conductivity (Suriadi *et al.*, 2002).

One of the main issues in soil fertility in Brazil is a low P content, especially in sugarcane expan-

TABLE 4 Chemical attributes of soil after liming and gypsum application, 27 months later.

Depth (cm)	Ca^{+2} ($\text{mmol}_c\ \text{dm}^{-3}$)		Mg^{+2} ($\text{mmol}_c\ \text{dm}^{-3}$)		SO^{4-2} ($\text{mmol}_c\ \text{dm}^{-3}$)		Al^{+3} ($\text{mmol}_c\ \text{dm}^{-3}$)	
	Gypsum (0 $t\ ha^{-1}$)	Gypsum (6 $t\ ha^{-1}$)	Gypsum (0 $t\ ha^{-1}$)	Gypsum (6 $t\ ha^{-1}$)	Gypsum (0 $t\ ha^{-1}$)	Gypsum (6 $t\ ha^{-1}$)	Gypsum (0 $t\ ha^{-1}$)	Gypsum (6 $t\ ha^{-1}$)
Lime (0 $t.ha^{-1}$)								
0-25	3.5	7.9	0.9	0.8	0.8	2.4	9.2	7.8
25-50	2.0	4.9	0.5	0.6	0.9	2.6	8.4	7.8
50-75	1.1	4.6	0.5	0.6	0.8	3.4	7.3	7.3
75-100	0.8	4.3	0.5	0.8	0.7	4.1	6.8	6.7
100-125	0.6	4.4	0.5	0.7	0.7	4.4	7.1	6.4
Lime (6 $t.ha^{-1}$)								
0-25	13.0	23.4	9.3	6.1	0.3	2.8	1.1	0.5
25-50	4.4	9.5	2.8	2.1	0.8	2.9	4.5	3.5
50-75	2.0	5.2	1.1	1.1	0.8	3.6	6.2	5.7
75-100	1.6	5.0	0.8	1.2	0.9	4.7	5.7	5.0
100-125	1.4	5.1	0.7	1.4	0.8	4.7	6.0	4.6

Source: MORELLI *et al.* (1992).



Source: MORELLI *et al*. (1987).

FIGURE 2 Bases (% of the exchangeable cation capacity) in a sandy middle texture latosol across several sugarcane harvests.

sion areas in western São Paulo. Phosphate application, which is total area application of sources of P at soil preparation time before planting cane, is a recommended practice for low and very low phosphorous content soils (below 12 mg.dm^{-3}) and preferably low clay content.

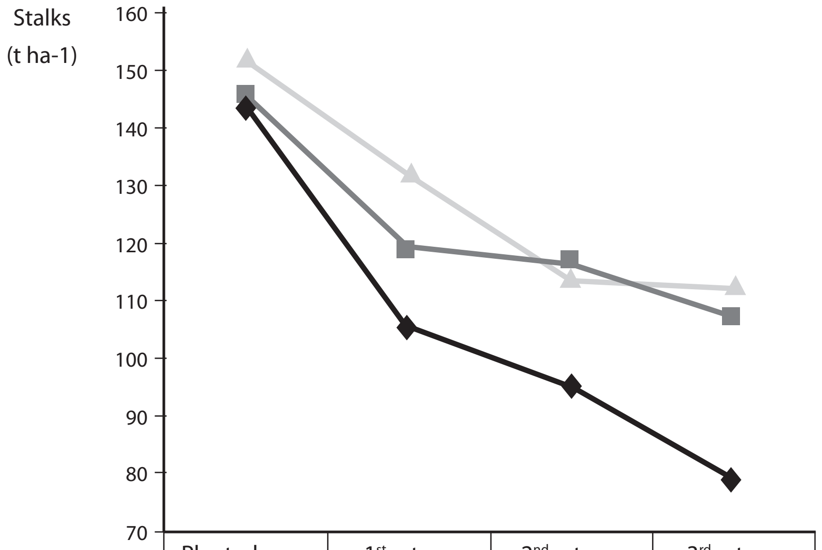
Fertilization – yield and maintenance of soil fertility

Fertilization aims to increase yields and replenish the nutrients exported by crops, to maintain and even raise the nutrient stock across the years.

In general, under favorable climatic conditions, sugarcane yields decrease gradually after each harvest, such that plant cane and first ratoon yield differences are higher than the differences found after the fifth and sixth harvests. The degree of yield decrease in subsequent harvests is a feature of the genetic potential of each variety, because much energy is used for regrowth each year, besides the soil fertility status and other production factors that need to be maintained. Adequate fertilization increased the crop yield, reduces any decrease in yields between harvests, and thereby increases the longevity of sugarcane plantations.

Figure 3 contains data gathered by Orlando Filho *et al*. (1993) and presents decreased sugarcane yields in different crop cycles, and how fertilization may reduce the impact of lower yields. In this experiment on a quartzarenic neosol, the yield reduction after the third ratoon was 45%. After NPK+S fertilization (with gypsum) the yield fell by 26% after the third ratoon. The yield reached 424 tin an unfertilized reference plantation in a sum of four harvests, which the yield reached 511 t, nearly 100 t more, in four years with the NPK+S treatment; it should be borne in mind that this was a rather sandy and low fertility soil.

Clay soils are highly able to fixate P applied as fertilizer, which reduces the efficiency of fertilization. In this case, it is convenient to limit any contact between the fertilizer and soil particles, which is why application in furrows is recommended. Since application of phosphate in plantation furrows is the only opportunity of placing phosphorous at depth, close to roots, a possible strategy would be to subdivide the recommended P_2O_5 dose into soluble phosphate in furrows and poorly soluble phosphate. This is because natural or reactive phosphorous or thermophosphate, which are slowly soluble, would have a residual effect and could provide P to ratoons. In this context, Cantarella *et al*. (2002) investigated fertilization with P_2O_5 at 120 kg.ha^{-1} applied during planting of the IAC89 3396 variety in a quartzarenic neosol in Assis, São Paulo state, in the following proportions:



	Planted cane	1^{st} ratoon	2^{nd} ratoon	3^{rd} ratoon
◆ Control	144	106	95	79
■ NPK	145	120	116	107
▲ NPK+G	152	132	114	113

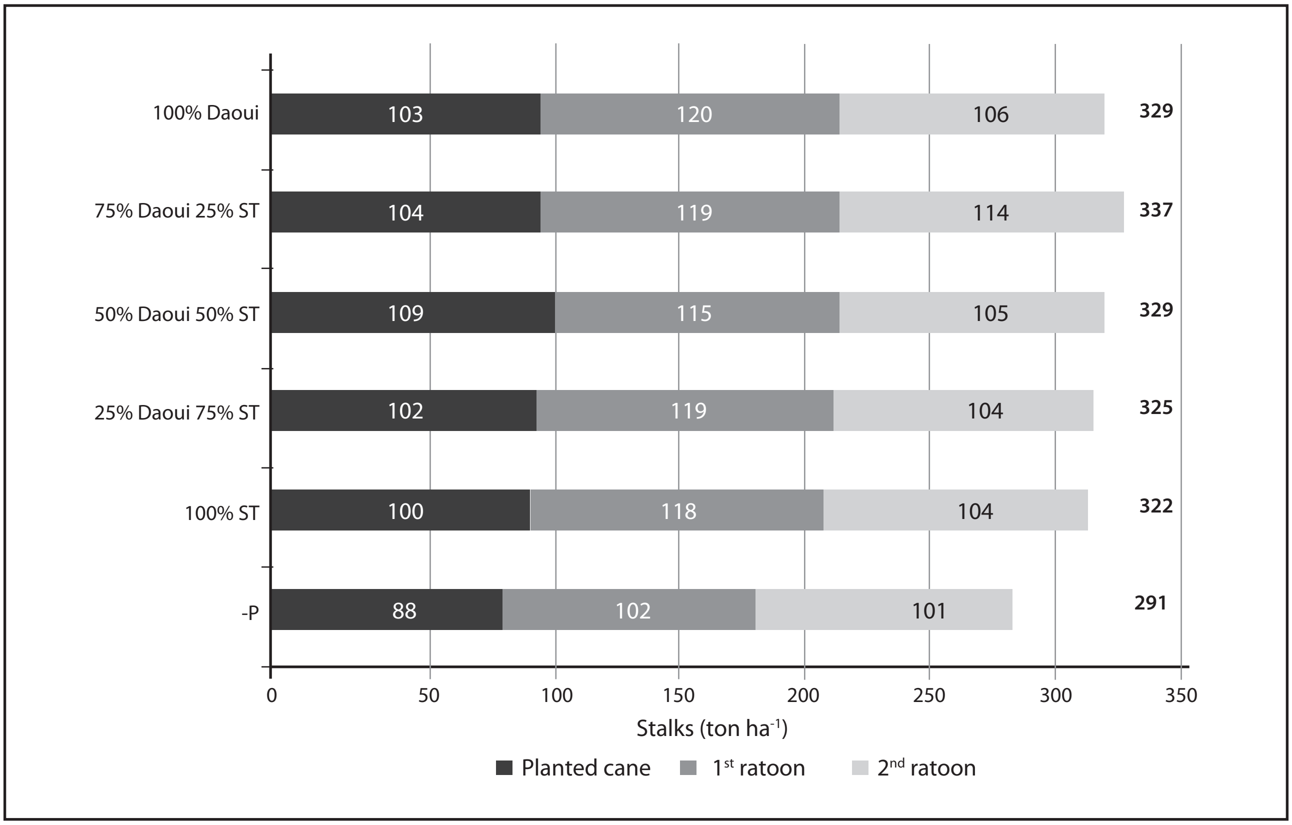
Obs.: NPK plant cane (CP) = 41-180-200 kg.ha^{-1} de N-P_2O_5-K_2O; ratoon = 80-00-200kg.ha^{-1} de N-P_2O_5-K_2O; gypsum (G) = 65 kg.ha^{-1} de S.

Source: Adapted from ORLANDO FILHO *et al.* (1994).

FIGURE 3 Variation in yields of the SP70-1143 (t/ha^{-1}) sugarcane variety in 4 years of cultivation, with fertilization and non-fertilization.

0, 25, 50, 75 and 100% of triple superphosphate (TS) or Daoui reactive phosphate. The experiment was conducted for 3 consecutive years; only N and K were applied on ratoons. Yield differences in plant cane – not favored because of lack of water – occurred only between the reference plantation without P and fertilized treatments; there were no differences in the proportions of TS and Daoui reactive phosphate. The same occurred with the first ratoon. There was a higher residual effect of treatment with Daoui reactive phosphate at 75% and TS at 25%in the second ratoon, such that the sum of yields in three years resulted in an accumulation of 46 t extra compared to the non-fertilized reference, and 15 t more than with the TS treatment (Figure 4).

Goals for sustainable management of sugarcane include increasing the efficiency of fertilizer use and reducing nutrient losses in the system. Parceling the fertilizers may be advantageous in sandy soils, although it involves an extra farming operation, especially if fertilization is done during a season with strong rain. In sandy soils, with a low CEC (cation exchange capacity), cations like potassium, are not adsorbed and may be lost by leaching. Trash also alters the management of fertilization. Urea applied over trash without being incorporated incurs in volatilization losses of N, which may reach 60% of applied N. Incorporation into soil avoids such losses, which become almost zero. However, incorporating fertilizers in the presence of trash incurs in certain operational difficulties. For this reason, the nitrogen sources ammonium nitrate and ammonium sulfate are indicated, although the cost of these fertilizers should be taken into account. There are also fertilizers with added urease inhibitors, such as the NBPT, which can delay losses and in a way increase the time after fertilizer application and the next rain that would incorporate urea into soil. Applied urea losses of 12% were reduced to 7% with a sugarcane inhibitor (Cantarella *et al.*, 2002).



Source: CANTARELLA *et al.* (2002).

FIGURE 4 Effect of mixing different solubility sources on the yields of three sugarcane cycles.

New inputs, such as micronutrient-coated fertilizers, provide more uniform and efficient application. Polymer-coated fertilizers, which release nutrients slowly and minimize losses, require further studies, but already indicate inputs with good yield and environmental quality responses. Soil fertilization in expansion areas of São Paulo state should also take into account possible micronutrient and silicon deficiencies or poor availability. Precision agriculture will be an important tool for rationalizing fertilizer use, increasing the efficiency and reducing losses, resulting in more sustainability.

Rossetto *et al.* (2008) presented a review on sugarcane mineral nutrition and fertilization, and their relation with yields and soil fertility.

Maintenance of trash on soils

Changes in the production system whereby fire is no longer used to facilitate harvesting operations result in a large quantity of trash left over the soil, which significantly alters its physical and chemical attributes. One of these modifications – of major relevance for certain production environments – is the fact that trash significantly raises water retention and infiltration in soils, which avoids surface crusts from forming. Trash significantly reduces evaporation rates. (Tominaga *et al.*, 2002; Ball Coelho *et al.*, 1993).

Ivo *et al.* (2003), in a study of a yellow argisol where the mean annual rainfall is 1,500 mm, showed that trash may contribute significantly for water conservation in Brazilian northeastern soils. When the dry season started during an atypical year (rainfall was 2,049 mm), water was not available in the 0-80 cm layer in burnt sugarcane plots. During the wet season, soil where sugarcane was harvested with no burning had available water values above those of soils where cane was burnt in 87% of the evaluations. On average, trash conserved 15.7 mm of water available during the dry season, and 19.8 mm during the wet season.

Trash over soil facilitates nutrient recycling, thus reducing fertilizer use. Wood (1991) calculated that trash in Australian productive sugarcane plantations might add to the system a mean 99 kg. ha^{-1} of N and 86 kg.ha^{-1} of K_2O every year. Most nutrients, except for K, need to be mineralized by microorganisms before being absorbed by crops. Robertson and Thorburn (2007a) studied the effect of trash on soil fertility at five sites in Australia.

The amount of trash ranged from 7 to 12 t.ha^{-1}; C ranged from 3 to 5 t.ha^{-1} and N ranged from 28 to 54 kg.ha^{-1}. The high C/N ratio (over 70) caused trash to take over a year to decompose; there were two phases to this process. The first decomposition phase took place while the C/N ratio remained high; in this case, gains or losses of N were not related with the losses of C. During the second phase, when the C/N ratio was low, losses of N were correlated and directly proportional with the losses of C. The decomposition rate of N during the first year was 1 to 5 kg per month, thus providing little of this nutrient to the crop. The offer of N in trash occurs in the middle and long-term.

McGuire (2007), in a long-term study at Mount Edgecombe (South Africa), showed that about 40 kg.ha^{-1} of N and 70 kg.ha^{-1} of K_2O return to the system annually. Altered soil fertility is not expected immediately after changing to sugarcane management under trash; it is a long-term process. Robertson and Thorburn (2007b) found that organic C and total N increased over 21% because of the presence of trash (no burning) at 10 to 25 cm depth after 3 to 6 years of management. Microbial activity was also much higher. Most of the C in trash was metabolized and lost as CO_2 to the atmosphere. Increased mineralization of N in trash does not follow stimulation of the initial microbial activity due to trash; initially, N is immobilized. Estimates by these authors of possible C and N gains in soils after long-term trash maintenance (20 to 30 years) are: 8 to 15% organic C; 9 to 24% total N, and a 37 kg.ha^{-1}.year increase in inorganic N. These authors also suggested that fertilization with N should not be decreased in the first 6 years of trash maintenance.

In the state of São Paulo, Brazil, Faroni *et al.* (2003) found that 40 to 50% of the dry matter in trash remained in soils one year later. The C/N ratio, which initially was 85, fell to 34 after one year. Oliveira *et al.* (1999) found trash decomposition rates of 20 to 70% after a year.

Oliveira *et al.* (1999), aiming to verify whether mineralization of cane trash was stimulated or not by adding urea or vinasse, undertook a study wherein 100 m^3 $ha^{-1}$of vinasse combined with urea was applied over trash(equivalent dose at 100 kg.ha^{-1}) or buried in the soil; also, a mixture of potassium chloride (equivalent dose at 120 kg ha^{-1} of K_2O) with urea (equivalent dose at 100 kg ha^{-1}) was applied over trash or buried in the soil. These treatments did not alter the degradation of trash lignocellulose or nutrient release; significant statistical differences were found only between the results of recently harvested cane trash and the remainders. The mass decreased by about 80% (hemicellulose and cell content), 30% (lignine), and 50% (cellulose). The mean N, P, K, Ca, Mg and S nutrient release percentages were respectively 18, 67, 93, 57, 68, and 68%relative to the total contained in recently harvested cane trash.

Franco *et al.* (2007) measured the amount of nutrients from trash in two sites in the state of São Paulo. The nutrient stock in crop waste at two sample sites had the following decreasing order of magnitude: N > K > Ca > S > Mg > P. Table 5 shows the amounts of these nutrients in both sites. The amount of N (200 kg.ha^{-1}) is nearly five times higher than what would be indicated for sugarcane fertilization in the state of São Paulo. Differently from K, N is slowly released, since it is bonded to organic molecules. The amount of N in trash that is released in the next sugarcane cycle is relatively low: 3 to 30%, as demonstrated in several studies (Oliveira *et al.*, 1999; Faroni *et al.*, 2003; Basanta *et al.*, 2002). The amount of trash N that is absorbed by the crop in the next cycle is about 5 to 10% (Ng Kee Kwong *et al.*, 1987); thus, most of this N supplies the soil stock, as evident in studies with 15 N-marked trash (Basanta *et al.*, 2002).

Maintaining trash also alters carbon dynamics and organic matter humification in soils. Busato *et al.* (2005) identified organic species of P in humic acids of an eutrophic vertic Ta haplic cambisol located in Campos dos Goytacazes, Rio de

TABLE 5 Dry matter and nutrients in two sugarcane plantations in the state of São Paulo. (Sum of results found in the root system – aerial portion of regrowth and trash.

Dry matter						
t ha^{-1}	N	K	P	Ca	Mg	S
	kg.ha^{-1}					
Site A 28.9	196.7	149.5	20.4	59.8	24.7	29.3
Site B 16.7	83.3	64.6	9	36.8	11.3	17.6

Source: FRANCO *et al.* (2007).

Janeiro state, a sugarcane cultivated area with preservation of trash with added vinasse for over 50 years. Decomposition of trash along 55 years increased the participation of labile organic forms of plant origin in humic acids, such as P in diesteric bonds. Where cane was burnt there was a higher precipitation of more stable organic forms, such as orthophosphatein monoesteric bonds. Accumulation of more labile forms of Po in humic acids in sugarcane under trash, especially in the 0-20 cm layer, may be established by the balance between the input of plant waste and its subsequent decomposition by microorganisms. Organic matter is an important reservoir of available organic P for crops. Labile forms of organic P are readily mineralized in soils. This dynamic is helped by a higher content of available P in the management of raw cone, which make it possible for organic forms of labile P to accumulate in humic acids. Canellas *et al.* (2003) studied these same areas and found that organic matter was more humidified in areas of burnt cane, compared with areas under trash for many years.

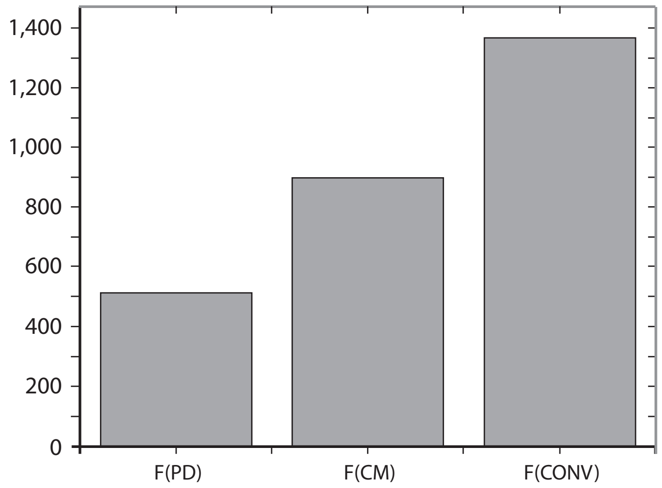
The total C and labile C contents were evaluated in three studies, two in Australia and one in Brazil (Blair *et al.*, 1998). Burning of trash resulted in higher losses of total C and labile C at 1cm soil depth compared with the unburnt system. Total C declined in one of these areas, although in this case labile C increased. In the state of Pernambuco, Brazil, management under trash for one year did not alter total C but increased labile C. The presence of trash on fields results in sequestration of 1.5 Mt C $year^{1}$ and avoided methane emissions of 0.05 Mt C $year^{1}$ (Cerri, 2004).

Chaves and Farias (2008) studied the spatial variation of the C stock in a dystrophic gray argisol that had been conventionally farmed with sugarcane. There was significant spatial variation of the carbon stock. In the surface layer, it was on average 33.82 Mg ha^{-1}; in other horizons, it was respectively 26.37 and 21.21 Mg ha^{-1}. Canellas *et al.* (2007) found that the carbon stock in soils of a burnt area decreased 40% compared with an unburnt trash-covered area. This study investigated a sugarcane cultivated cambisol, where the C stock at 0-20 cm depth was 36 Mg ha^{-1}, and 37.3 Mg ha^{-1} at 20-40 cm depth in the burnt area.

Bolonhezi *et al.* (2004) compared the conventional sugarcane preparation system (plowing and disking) with the direct drill and minimal cultivation system and concluded that in an unburnt sugarcane plantation, incorporation of 17 t ha^{-1} of dry matter in the conventional preparation system resulted in extra total emissions (in a 27-day period) of 3.5 t ha^{-1} of CO_2 compared to minimal cultivation and 9 t ha^{-1} of CO_2 compared with direct drill plantation (Figure 5).

Nutrient recycling – use of waste

Because of extensive farming areas, waste generated by the sugarcane industry causes an impact due to its volume. However, waste such as bagasse, filter cake, and vinasse have high added value, and are important sources for recycling soil nutrients. All waste in the sugarcane production chain is reused in the production process itself. Nutrient recycling based on this waste has contributed significantly towards the sustainability of soils and the



Source: BOLONHEZI *et al.* (2004).

FIGURE 5 Total emission of CO_2 (g CO_2 m^{-2}) in conventional (CONV), minimal cultivation (CM), and direct drill planting (PD) systems for sugarcane without burning. Twenty-seven day period after soil preparation.

sugarcane industry. Filter cake and vinasse used in soils significantly recycles nutrients and organic matter. Filter cake is a waste product of sugar production and of modern distilleries, originating from the syrup clarification process. This waste product applied to sugarcane plantations has been shown to increase yields and soil fertility, since it provides organic matter, phosphorous, calcium, and other nutrients. Filter cake is used routinely in sugarcane mill, partially or fully replacing P. In general, 50% of P from filter cake is readily available for cane. Filter cake is more efficiently used in plantation furrows, where mineralized P is close to the roots. Water in the cake also facilitates cane sprouting.

Cake filter applied in furrows stimulates root proliferation. Composting of filter cake to which gypsum, thermophosphate, reactive phosphate, and other organic sources are added, yields a highly nutritional organic fertilizer. Braga *et al.* (2003) found a strong interaction effect with 50 mm irrigation every months and application of filter cake or gypsum. In this study, cake filter associated with irrigation increased yields (Figure 6).

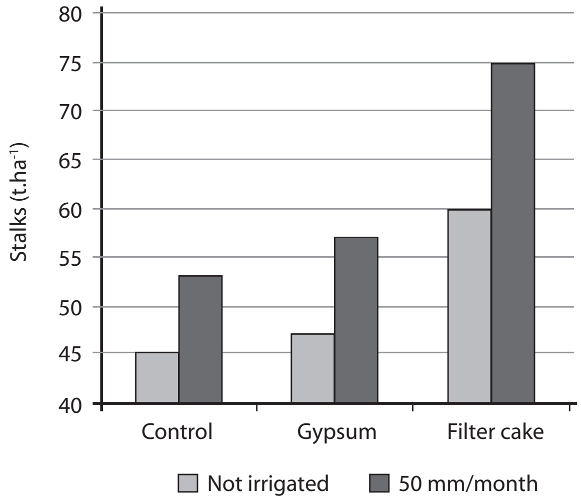
Vinasse is an organic material without metals or other contaminants that might hinder its use in farming. Characterization of vinasse, its effects after application on soils, and the potential risk of ion leaching to subsurface waters are described in Chapter 10, Part 3, of this book.

Biological fixation of N and growth-promoting bacteria in sugarcane

Sugarcane is farmed in several regions of the world; it is able to associate with endophytic bacteria, which are found inside leaves, stalks and roots, and that are able to fixate atmospheric N and produce plant hormones such as indol acetic acid and gibberellins. Practices that increase the efficiency of these associations are helping to increase the sustainability of soils and sugarcane plantations.

Doctor Johana Dobereiner, a researcher at Embrapa, in Rio de Janeiro, Brazil, discovered the association between N-fixating bacteria and sugarcane. The fixating species that may associate with sugarcane are: *Gluconacetobacter diazotrophicus* (Cavalcante and Döbereiner, 1988), *Azoarcus* spp. (Reinhold-Hurek *et al.*, 1993), *Herbaspirillum seropedicae* (Baldani *et al.*, 1986), *Herbaspirillum rubrisubalbicans* (Baldani *et al.*, 1996), and *Burkholderia* spp. (Yabuuchi *et al.*, 1992; Baldani *et al.*, 1997).

The potential of N for fixation through these associations is not clear. There are differences



Source: BRAGA *et al.* (2003).

FIGURE 6 Effect of gypsum application, filter cake, and irrigation on sugarcane yield (3rd harvest) in Goianésia, state of Goiás.

among varieties; furthermore, studies have indicated that crop management with nitrogen fertilizers may significantly affect this process. In this context, Polidoro *et al.* (2001) found that the RB72454 and SP80-1842 varieties had a high nitrogen biological fixation potential in their samples; however, managing soil fertility and plant nutrition tended to affect the degree of contribution, and monitoring of the plant nutrition status became necessary.

Controversy exists on the presence of mineral nitrogen and its possible influence on the N-fixation process. It has been suggested that high-dose application of nitrogen fertilizers are responsible for decreased populations of *Gluconacetobacter diazotrophicus* in sugarcane varieties cultivated in Mexico (Fuentes-Ramírez *et al.*, 1999), India (Muthukumarasamy *et al.*, 1999), and Brazil (Reis Junior *et al.*, 2000). Among the nutrients, limitations in molybdenum nutrition may be the most important issue because of its role in the nitrogen nutrition of sugarcane plants; this element is part of the enzymes nitrogenase and nitrate reductase, both of which are involved in N-acquisition metabolic processes (Polidoro *et al.*, 2001).

The contribution of biological fixation in sugarcane plants (18 months) inoculated in laboratories with a mixture of *Gluconacetobacter diazotrophicus* strains was 20 to 30% of the total nitrogen accumulated in plants (Oliveira *et al.*, 2003). In another study, different strains were inoculated into cane, resulting in significantly increased sprouting and plant weight compared to controls. The population concentrated in the roots and was higher after application of nitrogen at 75 kg.ha^{-1}, compared with 0 and 150.kg ha^{-1}, suggesting that an initial dose is needed (Moraes and Tornisielo, 1997). Bastian *et al.* (1998) showed that both *Herbaspirillum seropedicae* and *Gluconacetobacter diazotrophicus* produce gibberellins and indol acetic acid (IAA). This may explain partly the beneficial effects of these bacteria in the plants.

FINAL CONSIDERATIONS

The sugarcane crop is becoming more sustainable because of technology. Its development and support, as discussed above, demonstrate a clear change in production systems, currently allied with environmental issues. Adoption of several technologies has raised yields in sugarcane plantations, even after more than 100 years of sugarcane farming. Soil quality and function have been maintained – and even improved – across the years.

In expansion areas under old pasture soils, many of which were degraded or had low fertility soils, sugarcane farming has raised yields, which has made it possible to occupy such soils as possible farming areas.

Several technological innovations should contribute further to sustainability, such as soil recovery and continued fertility. These include precision farming, low input use production systems, new fertilizer sources, the use of improved and more efficient inputs that cause less impact to the environment, judicious mechanization, soil conservation techniques, microbiological systems for increased nutrient use efficiency, genetic breeding for higher yields in borderline soils and lower fertilizer requirements, and more adequate plans for allocation of cultivars according to production environments.

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