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Fertilizing for High Yield and Quality

Sugarcane

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INTERNATIONAL POTASH INSTITUTE

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Ross Ridge
7 Robert John Circuit
Coral Cove, Qld. 4670
Australia

INTERNATIONAL
POTASH INSTITUTE

International Potash Institute
Baumgärtlistrasse 17
P.O. Box 260
CH-8810 Horgen, Switzerland
T +41 43 810 49 22
F +41 43 810 49 25
ipi@ipipotash.org
www.ipipotash.org

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1 Introduction

Sugarcane belongs to the genus Saccharum, and is a grass that stores energy as sugar (sucrose) in stalks, rather than as starch in seed heads, compared to grasses cultivated for grain production.

The archetypal sweet 'noble canes' belong to the species *Saccharum-officinarum*, which appears to have evolved from its wild relatives in Papua-New Guinea. Three close relatives with low sugar levels and higher fiber content are also found in Papua-New Guinea. These are the very vigorous *S. spontaneum*, the heavier stalked *S. robustum*, and *S. edule* which has an edible flower. Two other species, *S. sinense* and *S. barberi*, were widely cultivated in China and India, and these may have evolved from natural hybrids between *S. spontaneum* and *S. officinarum* (Bull, 2000). Daniels and Roach (1987) reported that the genera *Miscanthus* and *Erianthus* may be involved in the parentage of some of these historical hybrids.

Fig. 1 shows the characteristics of these historical species in comparison to modern commercial varieties, which are complex hybrids between two or more Saccharum species (Bull, 2000).

Modern varieties are more vigorous, heavy yielding and disease and pest resistant than the old noble canes. While cane breeding programs in modern sugar industries aim to achieve these desirable characteristics, the primary target is maximum sugar production. Many countries have successful cane breeding programs to produce cultivars suitable for their particular conditions, and commercial cultivars receive a designation corresponding to the country where they were selected. Some typical examples are Indonesia (POJ), India (CO), South Africa (N), Australia (Q, KQ), Brazil (CB, IAC, PB, RB, SP), Cuba (C), Argentina (NA), USA (CP), Colombia (ICA), Formosa (F), Philippines (Phil), Egypt (E), Peru (PCG), and Mauritius (M). Due to co-operation between plant breeders in different countries varieties selected in one country are sometimes successful commercial varieties in other countries.

Sugarcane was initially used for chewing, but crystallized sugar was reported 3,000 years ago in the Indus Valley and by around 327 B.C. it was an important crop in the Indian subcontinent. It was introduced to Egypt around 647 A.D., and, about one century later, to Spain (755 A.D.). Since then, the cultivation of sugarcane has extended to nearly all tropical and subtropical regions, initially mainly through the activities of Portuguese and Spanish traders (Malavolta, 1994).

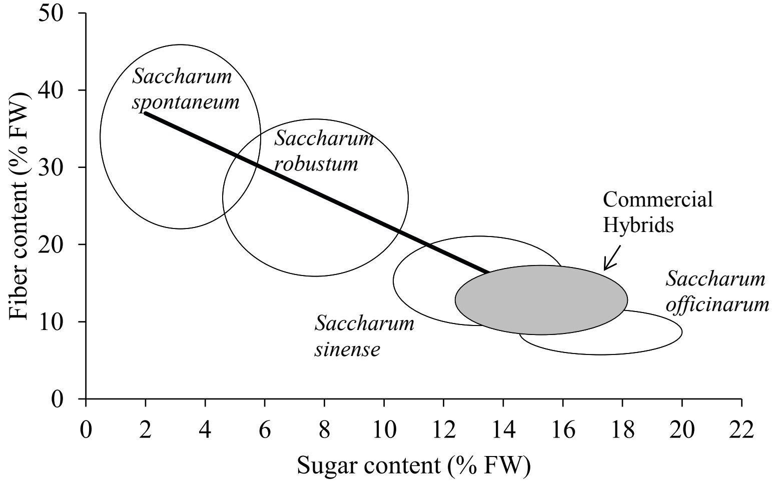


Fig. 1. Progressive change in fiber and sugar levels from wild to noble canes (Bull, 2000).

1.1 Area, yields and trends in major regions for sugarcane production

The sugarcane industry has continued to expand in the last 20 years, particularly in South America, Asia and Africa. According to FAO (2012) the total area harvested worldwide increased from 17.1 million ha in 1990 to 23.8 million ha in 2010 (Table 1.1). Production of sugarcane increased from 1,052 mt to 1,685 mt in the same 20 year period. The major producing region is South America, followed by Asia, North and Central America (including the Caribbean), and Africa.

The major sugar producing countries are Brazil, India and China, with Brazil dominating world sugar exports based on sugarcane. The other major exporters are Thailand and Australia (FAO, 2012). There is increasing diversion of sugarcane towards ethanol production as a replacement for fossil fuel petroleum products, most notably in Brazil where around 50% of the crop is used for ethanol production. There is also increasing co-generation of power from sugarcane bagasse.

Table 1.1. World production of sugarcane.

Country/region	Area (1,000 ha)		Yield (mt ha^{-1})		Production (million mt)	
	1990	2010	1990	2010	1990	2010
South America	**5,291**	**10,238**	**63**	**79**	**335.0**	**811.7**
Argentina	256	355	61	82	15.7	29.0
Bolivia	84	164	46	45	3.9	7.4
Brazil	4,273	9,081	61	79	262.7	719.2
Colombia	318	172	87	118	27.8	20.3
Ecuador	85	107	93	81	5.7	8.3
Paraguay	60	100	41	51	2.4	5.1
Peru	62	77	109	125	6.7	9.7
Venezuela	102	125	65	76	6.6	9.5
Asia	**7,234**	**9,370**	**60**	**65**	**433.5**	**610.4**
Bangladesh	186	121	40	44	7.4	5.3
China	1,077	1,695	59	66	63.5	111.5
India	3,439	4,200	66	66	225.6	277.8
Indonesia	345	420	81	63	28.0	26.5
Iran	25	68	66	83	1.7	5.7
Myanmar	48	180	40	54	1.9	9.7
Pakistan	854	943	42	52	35.5	49.4
Philippines	318	363	80	94	25.5	34.0
Thailand	686	978	49	70	33.6	68.8
Vietnam	131	266	41	60	5.4	15.9
America (N, C)	**2,978**	**2,175**	**62**	**68**	**184.3**	**148.7**
Cuba	1,420	431	58	26	81.8	11.3
Dominican Rep.	206	85	32	57	6.5	4.8
El Salvador	32	63	93	81	3.0	5.1
Guetemala	112	213	86	86	9.6	18.4
Honduras	41	76	71	103	2.9	7.8
Mexico	571	704	70	72	39.9	50.4
Nicaragua	39	54	61	90	2.4	4.9
United States	321	355	79	70	25.5	24.8
Africa	**1,168**	**1,577**	**61**	**58**	**71.3**	**91.1**
Egypt	111	135	100	117	11.1	15.7
Kenya	40	69	117	83	4.8	5.7
South Africa	265	267	68	60	18.1	16.0
Sudan	66	67	64	112	4.2	7.5
Swaziland	37	52	105	96	3.8	5.0
Zambia	12	39	94	105	1.1	4.1
Oceania	**406**	**455**	**70**	**74**	**28.6**	**33.5**
Australia	332	405	73	78	24.4	31.5
World	**17,079**	**23,815**	**62**	**71**	**1,052**	**1,685**

Source: FAO, 2012.

1.2 Botany and physiology

Sugarcane is a perennial grass which produces seed under suitable conditions, but for commercial production it is propagated from stalk cuttings. It is very efficient in converting the sun's energy into biomass, and particularly sucrose.

Park *et al*. (2003) report mean maximum radiation use efficiency for sugarcane biomass production in different sugar districts of Australia of 1.70 g/MJ in plant cane, and 1.46 g/MJ in ratoon cane.

Publications by Van Dilliwijn (1952) and Alexander (1973) are classical sources of information about the botany and physiology of sugarcane, respectively.

1.3 Propagation

The traditional method of sugarcane propagation is with stalk cuttings containing one or more buds, termed setts. Buds are located at the nodes of the cane stalk and are horizontally opposed on the setts. Each bud may germinate after planting to produce a primary shoot. Adjacent to the buds are root primordia which produce sett roots that help maintain moisture in the setts until shoot roots develop. At this stage the young plant utilizes reserves in the sett, supplemented by the uptake of water and nutrients by sett roots, and later, shoot roots. Shoots usually emerge from one to three weeks after planting, depending on soil temperatures and cane variety. The emerging shoots quickly become independent of the parent setts as leaves develop and photosynthesis supplies energy to the developing plant. In due course secondary shoots are produced from the base of the primary shoots.

The morphology of setts and shoot development is illustrated in Fig. 2 (Blackburn, 1984).

The germination of buds is temperature sensitive, and adequate but not excessive soil moisture levels are required for early cane growth. Varieties differ in their temperature sensitivity, but in general terms germination will be very slow when soil temperatures drop below about 17°C to 18°C, and will fail at temperatures below about 11°C. When temperatures are below 18°C soil rots and pathogens are more likely to cause the death of setts (Bull, 2000). In temperate regions, planting is usually carried out in late summer, autumn or spring to ensure suitable temperatures for germination and shoot development. In the warm tropics planting can also be carried out in winter.

1.4 Root development

Sugarcane root systems are commonly depicted as comprising highly branched superficial roots, downward-oriented buttress roots, and deeply penetrating vertical roots known as rope roots (Fig. 3; Blackburn, 1984). The superficial roots are responsible for supplying water and nutrients to shoots, particularly in the early stages of growth. The buttress and rope roots assist with anchorage of cane stalks and supply of water and nutrients deeper in the soil profile. It is uncertain whether rope roots play an important role in modern varieties and under mechanical harvesting practices where soils are more compacted.

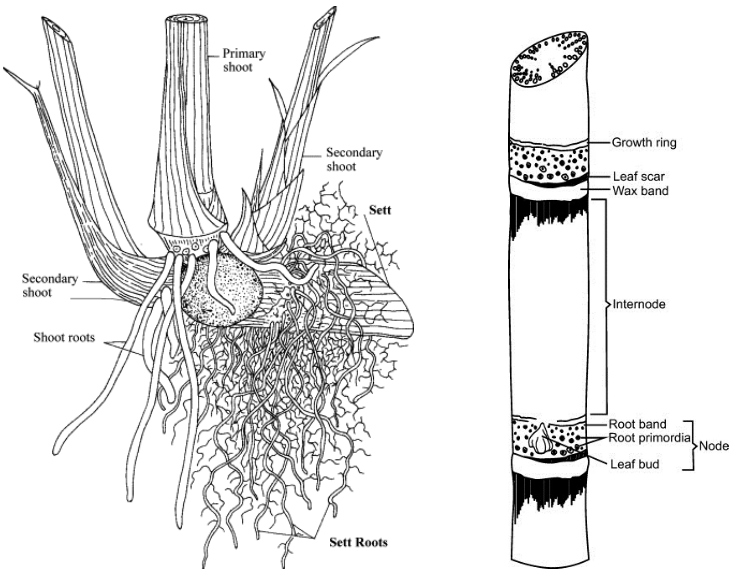


Fig. 2. Sugarcane sett morphology and shoot development (Blackburn, 1984).

Root distributions for sugarcane generally show an exponential decline with depth, with maximum values for root length density as high as 5 cm cm^{-3} (Smith *et al.*, 2005). A majority of roots are located in the top 2 m of soil, but there is some evidence of root growth below this depth (Antwerpen, 1999).

There is also evidence that depth of penetration of roots is restricted by shallow water tables and dense subsoil layers, while the zone of greatest activity is influenced by the soil moisture conditions.

There is little information available on root turnover in sugarcane, but evidence shows that the root system is not completely replaced when ratooning occurs (Smith *et al.*, 2005).

1.5 Tillering and early growth

The production of shoots following planting, or ratooning after harvest is termed tillering. The tillering process is affected by several factors such as solar radiation, temperature, water, nutrients, density of planting (row spacing), depth of planting, condition of stubble left after harvesting or planting material, and pests and diseases.

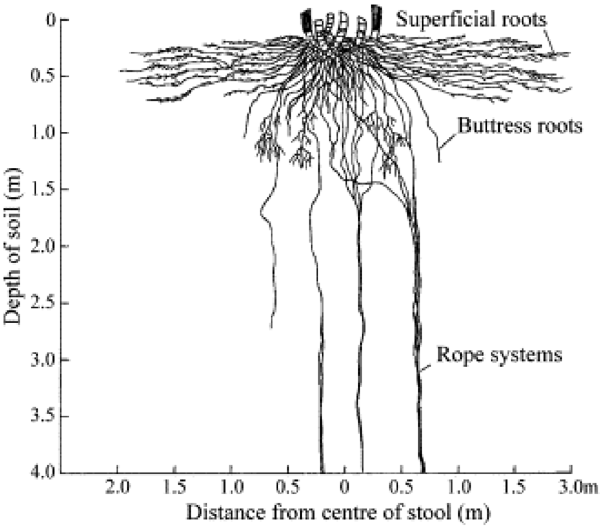


Fig. 3. Sugarcane root systems (Blackburn, 1984).

Tillers compete strongly for light and there is usually a high mortality rate as the canopy closes in and deprives them of light (Bull, 2000). Typical final stalk numbers are strongly influenced by varietal characteristics and fall in the range 6 to 12 per m^2 for conventional single row spacings. Stalk density may be higher for narrow row spacings or dual row planting, particularly in plant cane.

Stalk elongation during the main growth phase following tillering is sensitive to both temperature and soil moisture (Kingston and Ham, 1975; Shannon *et al.*, 1996), and to cane nutrition.

Stalk elongation rates of 20-30 mm per day are common in the summer under low soil moisture stress, falling to 5-10 mm per day as soil dries out after irrigation or rainfall, or mean daily temperature falls below 24°C.

At the end of the early growth stage the sugar level in the stalks is still quite low, usually around 4 to 6 units.

1.6 Maturation, ripening and yields

During stalk growth, each internode tends to function as a single unit and the length and diameter of internodes reflect growing conditions. The lower internodes are more mature than the internodes towards the tip of the stalk, and contain a higher level of stored sugar. Leaves attached to each internode may be shed as growth and maturation is completed (Bull, 2000).

The stored sugar can be utilised to support tillering and/or growth when conditions are not favorable for photosynthesis. As the crop ripens, more internodes up the stalk reach maturity and sugar levels increase.

Generally, the ripening phase corresponds to the cooler and drier time of year. While growth slows, photosynthesis continues, and this is channelled into sugar production. The typical pattern of fiber and sugar production in sub-tropical regions of the southern hemisphere is shown in Fig. 4 (Bull, 2000).

In the tropics where there is less pronounced cooling in winter, sugar levels in mature cane are likely to be lower, so it is important that there is a pronounced dry season to slow growth and promote maturation. Alternatively, where cane is fully irrigated, a limited drying off period prior to harvest will promote sugar accumulation without sacrificing cane yield. In most situations sugar levels can be enhanced by the use of ripening chemicals, most of which act by checking apical growth of cane.

The fiber content of sugarcane stalks generally falls in the range 9 to 17%, depending upon variety and growth conditions. The sucrose content is influenced by several factors, including variety, crop age, time of harvest, growth conditions, ripening conditions, and cane nutrition. The typical range is 7 to 15%, with the higher values reflecting high solar radiation levels and good ripening conditions.

As shown in Table 1.1, average cane yields in different countries vary considerably, reflecting factors such as soil fertility, rainfall reliability, availability of irrigation, solar radiation levels and crop management inputs.

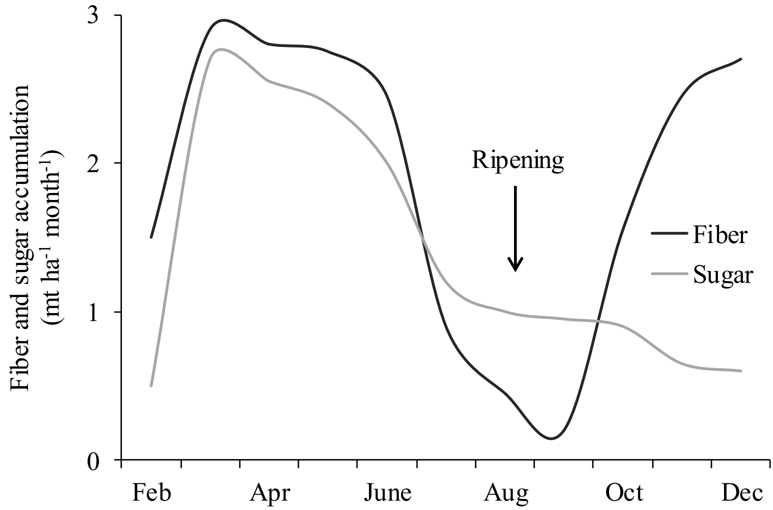


Fig. 4. Pattern of fiber and sugar accumulation for sugarcane in the southern hemisphere with cool, dry conditions in winter (Bull, 2000).

1.7 Flowering

When day length, temperature and stage of cane growth are favorable, the stalk undergoes a physiological change which initiates flowering (or arrowing). The apical meristem switches from vegetative growth to flower production and stalk elongation ceases.

While flowering is crucial for breeding new varieties, there is conscious selection against flowering in commercial production due to the cessation of growth and limited capacity for further sugar accumulation after flowering.

Plant breeders use controlled environments to simulate day length and temperature conditions favorable for flowering in order to obtain flowering from most varieties. This gives a greater range of potential parents for new varieties than would be available under field conditions.

1.8 Sugar accumulation

Photosynthesis in sugarcane follow what is termed the C4 Pathway. C4 plants possess a characteristic leaf anatomy, with the vascular bundles surrounded by an inner layer of bundle sheath cells and an outer layer of mesophyll cells. The bundle leaf cells contain starch rich chloroplasts lacking grana, which differ from the chloroplasts in the mesophyll. In the mesophyll cells CO_2 is fixed firstly as oxaloacetate which converts to malate. The malate is transported to the bundle leaf cells where it undergoes decarboxylation to CO_2 andpyruvate. The CO_2 enters the Calvin cycle to produce carbohydrates and the pyruvate returns to the mesophyll.

This is distinct from C3 plants where CO_2 is fixed as 3-phospoglycerate, and some carbon is lost by photorespiration in the conversion to carbohydrates.

Sucrose rather than starch is the major end product of carbohydrate production in sugarcane and is transported from the leaves through the leaf sheath to the stalk, and through the stalk via the xylem and phloem (Hartt *et al*., 1963). Sugarcane is considered to be one of the most efficient plants in conversion of light into chemical energy.

1.9 Soil and climate

1.9.1 Climate

Sugarcane is grown in regions between 35°N and 35°S (Fig. 5), and largely at altitudes below 1,000 m. Humbert (1968) characterized the "ideal" climate for sugarcane production as: a long, warm summer growing season with adequate rainfall; a fairly sunny and cool, but frost free season for ripening and harvesting; and freedom from typhoon and hurricane conditions. The majority of world production areas meet these criteria, but some cane is grown in areas with fairly severe frosts (e.g. Louisiana in the US and Argentina); there may be considerable damage from strong winds on an irregular basis in some producing areas (e.g. Australia); there are relatively poor conditions for ripening in some tropical regions (e.g. Indonesia); and irrigation is required for economic production in areas with low rainfall (e.g. Peru and Iran) or poorly distributed rainfall (e.g. Australia, South Africa).

Analysis of stalk elongation rates versus mean daily temperature in irrigation trials in Australia (Kingston and Ham, 1975) showed that stalk elongation rates increase rapidly once mean daily temperature exceeds 24°C. In irrigated tropical and sub-tropical regions of Australia the peak growing periods with temperatures above 24°C are late September to April, and November to March, respectively. Fig. 6 shows the typical pattern of growth during the peak growing period in the dry tropics of Australia (Shannon *et al.*, 1996), with growth rates slowing as soil dries out after irrigation or rainfall.

The various climatic and agronomic factors determining potential yield in different sugar producing areas have been integrated in models such as APSIM (Keating *et al.*, 1999). The model utilises soil moisture storage characteristics, daily maximum and minimum temperatures, daily solar radiation, nitrogen fertilizer inputs, daily rainfall and scheduled irrigations to determine cane growth. These are considered to be the main drivers in determining potential cane yield, and yields predicted broadly reflect those achieved under commercial production.

The requirement for irrigation in different cane producing areas is dependent on several factors, including rainfall amounts and distribution, and potential evapotranspiration by the crop under the prevailing climatic conditions.

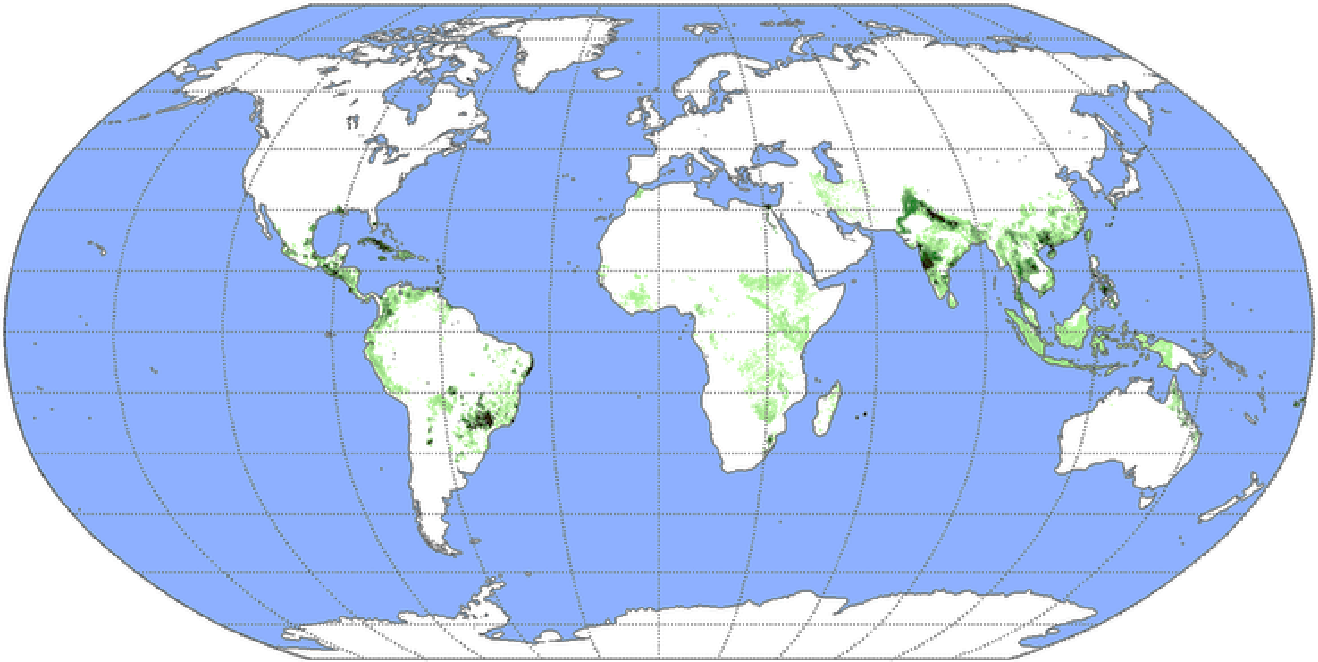


Fig 5. The main world sugarcane growing areas (redrawn from Wikipedia, 2012).

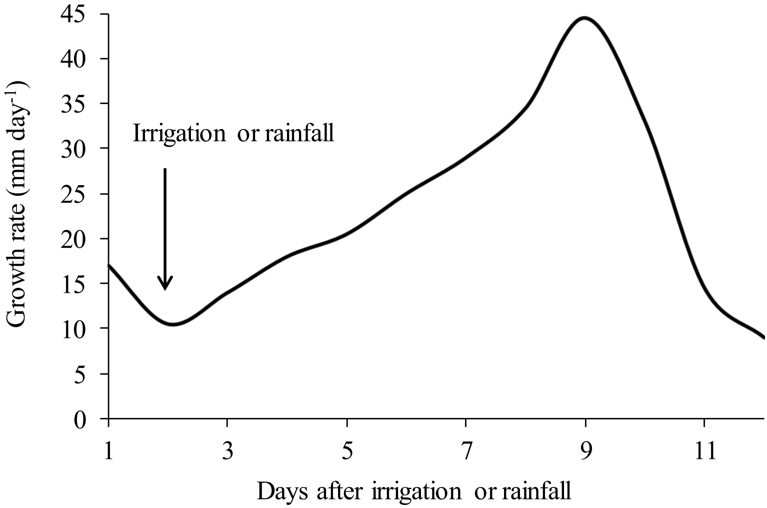


Fig. 6. Summer growth rates after irrigation or rainfall on a clay soil in the dry sub-tropics of Australia (Shannon *et al.*, 1996).

In general, where effective rainfall is significantly less than the potential crop water use in a growing season, irrigation is likely to be an economic proposition. This is illustrated in Table 1.2 for Australian conditions (Ham *et al.*, 2000). The effective rainfall may be significantly less than total rainfall due to runoff and deep drainage losses, and the ineffectiveness of small falls of rain on most soil types.

Table 1.2. Irrigation requirements under different climatic conditions in Australia.

District	Annual crop water use	Effective rainfall	Irrigation requirement	Level of irrigation
	---------------------	*mm*	---------------------	
Wet tropics	1,310	1,500	Nil	None
Dry tropics	1,520	450	1,070	Full
Sub tropics	1,360	580	780	Supp/full

Source: Ham *et al.*, 2000.

In many areas of Brazil, effective rainfall is adequate for cane production and this is one reason for the rapid growth of sugarcane production in the country.

Kingston (1994) demonstrated a linear relationship between yield of sugarcane and crop water use. Given adequate growing conditions, approximately 100 mm of irrigation or effective rainfall is required to produce 10 tonnes of cane per ha (Ham *et al.*, 2000), and responses similar to this have been noted under commercial irrigation in Australia.

Efficient irrigation is dependent on scheduling of irrigation to maintain crop growth, matching of water applications to soil water storage capacity, and achieving efficient distribution of applied water to minimise wastage. The most efficient practices aim for optimum sugar production, rather than maximum cane yield. This is due to some water stress being required to promote optimum ripening of cane (Ham *et al.*, 2000). In fully irrigated conditions, controlled drying off of cane prior to harvest will optimize sugar yields (Robertson *et al.,* 1999).

Crop water requirements are related to crop canopy development and potential evapotranspiration for the prevailing climatic conditions (Kingston and Ham, 1975). Class A pan evaporation has been used to determine commercial irrigation intervals in different soil types in Australia (Shannon *et al.*, 1996) and modelling of evapotranspiration has been used for a similar purpose in South Africa (Singels *et al.,* 1999). Other scheduling tools include tensiometers and gypsum blocks which record soil moisture tension, and instruments such as the *EnviroSCAN* which record actual soil moisture levels.

The readily available water (RAW) for crop use in different soil types varies with soil particle size distribution (texture), soil structure and depth of the effective rootzone. RAW is determined approximately as the amount held in the effective rootzone between soil moisture tensions of 0.2 and 15 bars. Typical figures for Australian soils are given in Table 1.3 (Ham *et al.*, 2000).

The most common irrigation systems used in sugarcane cultivation are furrow irrigation (e.g. Colombia and Burdekin region of Australia), high pressure travelling irrigators (e.g. Australia and South Africa), hand shift sprinklers (e.g. South Africa), low pressure lateral move irrigators, centre pivot spray irrigators (e.g. Australia and Mauritius), and drip irrigation (e.g. Australia and Swaziland). The most efficient commercial systems are generally centre pivot irrigators and drip irrigation, followed by high pressure travelling irrigators and furrow irrigation. Efficiency of furrow irrigation systems has been improved in Australia by the use of modelling techniques such as Sirmod (Raine and Bakker, 1996) which allow optimizing of furrow lengths, slopes, furrow shape and furrow flow rates.

Table 1.3. Typical RAW levels for a range of Australian soil types.

Soil type	RAW
	-----*mm*-----
Cracking clay	90-100
Clay loam	80-90
Loam	70-80
Sandy loam	50-60
Loamy sand	30-40
Sodic clay(1)	40-90

(1)Low values correspond to high sodicity levels.

Source: Ham *et al.*, 2000.

1.9.2 Soils

Sugarcane is grown in a wide diversity of soil types worldwide, and has proved to very adaptable to different soil conditions. Chemical constraints in soils such as low fertility, acidity, salinity and sodicity can in most cases be corrected, but poor physical soil conditions are much more difficult to ameliorate. Humbert (1968) in his discussion of soil as a factor in sugarcane growth, gives much emphasis to soil physical properties.

Soil properties depend on a range of factors including parent materials, climate, relief (including drainage), age of soils, and the organic matter content in surface soil (Schroeder and Kingston, 2000). Parent material determines properties such as color, soil particle size distribution, level of base saturation, structure, and inherent soil fertility. Worldwide, parent materials in the sugar industry include basic volcanic rocks such as basalt, acidic volcanic rocks such as granite, metamorphic rocks such as schist, sandstone, limestone and recent and ancient alluvial soils.

Soil color, texture and structure are important indicators of secondary soil properties (Schroeder and Kingston, 2000). Table 1.4 shows some of the secondary soil properties related to soil color. Soil color often reflects position in the landscape and/or drainage conditions. The influence of soil texture on secondary soil properties is summarised in Table 1.5 which indicated that sandy soils are more likely to develop nutrient deficiencies.

Table 1.4. Secondary properties related to soil color.

Soil property	Black	Light grey	Red	Brown	Yellow	Grey/blue grey
Drainage	Often slow	Well drained	Well drained	Well/moderate	Less well drained	Poorly drained
Waterlogging potential	Medium	Low	Low	Low	Low/medium	High
Organic matter level	High	Low	Medium	Medium/high	Medium/low	Low
Nutrient leaching	Low	High	Moderate	Moderate	Moderate	Low

Source: Schroeder and Kingston, 2000.

Table 1.5. Secondary properties related to soil texture.

Soil property	Sand	Loam	Silty clay loam	Sandy clay loam	Clay
Internal drainage	Excessive	Good	Fair	Fair	Fair to good
Plant available water	Low	Medium	High	Medium	Medium/high
Suitability for flood irrigation	Low	Medium	High	Medium	High
Ease of cultivation	High	High	Medium	Medium	Low
Leaching of nutrients	High	Medium	Medium	Low	Low
Nutrient reserves	Low	Medium	Medium	Medium/high	High

Source: Schroeder and Kingston, 2000.

The inherent poor structure of some soils, and the effects of heavy machinery traffic in highly mechanized sugar industries often have an adverse effect on sugarcane production. In sodic soils, with a strong prismatic structure in the subsoil, root depth and water penetration may be restricted, leading to reduced access to nutrients and water. Similarly, compaction caused by mechanical operations, such as planting, cultivation, weed control, harvesting and transport of cane may restrict soil aeration, root growth, and available soil moisture levels. Research in Australia (Braunack and Hurney, 2000), Colombia and several other countries has shown that wheel traffic on or close to the cane row reduces cane yields. This has led to increased emphasis on matching of row spacings to the wheel spacing of mechanical equipment to provide controlled traffic zones away from the cane row.

Another important factor for mechanization is soil slope. Slopes greater than approximately 12% lead to difficulty in operating mechanical equipment and also increase the potential for soil erosion.

Several other factors influence susceptibility to erosion including soil texture and stability of surface and subsoil soil structure. Sodic soils are particularly susceptible to erosion.

The move to green cane harvesting and trash blanketing in many sugar producing countries has shown benefits both in reducing soil erosion and improving utilization of rainfall and irrigation by the crop.

The diversity of soils used for growing sugarcane is illustrated by reference to a few selected regions. Limited information on Australia, Cuba, India, South Africa and the USA is provided by Halliday (1956). Various systems of soil classification are used in different sugar producing countries, the most common being the USDA Taxonomy and the FAO system.

Australia: The Australian industry is restricted to the east coast region between latitudes 16 and 30° South. The soils consist of residuals derived mainly from basalt, granite, schist and sedimentary rock parent materials, and a range of recent and old alluvial soils developed on fresh water or marine sediments. The dominant soils include texture contrast soils such as Chromosols, Kurosols and Sodosols (Alfisols and Ultisols); soils with gradational textures such as Ferrosols, Kandosols and Dermosols (Oxisols, Alfisols and Mollisols); uniform textured clay soils such as Vertosols (Vertisols); and poorly drained Hydrosols which may be uniform in texture or gleyed, texture contrast soils.

Brazil: There are three main sugarcane regions, two located in the south east (São Paulo and Rio de Janeiro), and one in the north east (the states of Alagoas and Pernambuco). In São Paulo almost half the area is represented by Red Latosols (Oxisols) developed from basic igneous rock (deep, well-drained soils with 40 to 60% clay); the next most important soils are Red Yellow Latosols, derived from sandstone (deep, well-drained soils with 15 to 30% clay); Sandy Red Yellow Podzolics (Ultisols and Alfisols) are the other main soil type (Malavolta, 1994). In the state of Rio de Janeiro, Red Yellow Latosols, Sandy Red Yellow Podzolics and poorly-drained Hydrosols (or Hydromorphic soils) dominate. In the North East, the Red Yellow Latosols and Sandy Red Yellow Podzolics are the major soil groups. There is also a significant area of low fertility and low Cation-exchange capacity (CEC) Red and Yellow Sands here and in São Paulo.

The fertility level standards for sugarcane soils in Brazil is summarised in Table 1.6 (modified from Malavolta and Kliemann , 1985). In general sugarcane soils, when first cultivated, fall in the low to medium category, and fertility is improved by the use of lime, fertilizer, by products such as filter press cake, vinasse and composted bagasse, and green manuring to achieve adequate levels.

Colombia: Data on soils from Colombia are supplied by Guerrero (1991) and Garcia Ocampo (1991). The main sugarcane growing region is the Valle del Cauca. Mollisols - soils with a base saturation above 50%, which are deep and well-drained and have good fertility - occupy about one-third of the total area. Vertisols, cracking clay soils which are very rich in montmorillonite and Inceptisols with fine to medium texture and medium to high CEC, are other important soils. There are lesser areas of Alfisols, Entisols and Ultisols.

Cuba: Sugarcane production in Cuba is concentrated in four main geographical areas (Highland, North Coastal Plain, South Coastal Plain and Denuded Interior Plain) and is grown on a range of soil types (FAO, 1988). The dominant soil type is the Matanzas clay which is a deep, well-drained red clay soil (Oxisol). Other important soil types include Inceptisols, Vertisols, Mollisols, Alfisols and Entisols.

India: Sugarcane is grown in two main belts: the fertile Indo-Gangetic alluvial region, and residual soils of the peninsula. The alluvial soils include Alfisols, Ultisols and Entisols, and the Peninsula region contains Alfisols, Inceptisols and Vertisols (Soils of India, 1985).

South Africa: Sugarcane in South Africa is grown on soils derived from a range of parent materials including basalt, dolerites, granite, shales, sedimentary rocks such as sandstone, and alluvial deposits. Fey (2010) provides a summary of South African soil groups referenced to the FAO classification system. Soil groups include Oxisols, Alfisols, Vertisols, Mollisols, Lithosols and Ultisols.

USA: In Louisiana, soils are mainly of alluvial origin, classified mainly as Inceptisols and Ultisols. The pH is close to neutral, with medium soil textures and some soils are high in organic matter. Soils in Florida contain 40-50%

organic matter, have a high pH and up to 5% calcium oxide. They are commonly in the Histosol group. The dominant soils in the Texas industry are Alfisols and Ultisols.

Table 1.6. Interpretation of the chemical characteristics of Brazilian soils.

Element[1]	Low	Medium	Adequate or high
N (%)	<0.09	0.09-0.14	>0.14
pH (H_2O)	<5.0	5.0-6.0	6.1-6.5
P (mg kg^{-1})			
Mehlich 1	<5	5-10	11-20
Resin	<10	10-20	21-30
Exchangeable			
K (cmol(+)kg^{-1})	<0.10	0.10-0.24	0.25-0.30
% of CEC	<2	2-3.9	4-5
Ca (cmol(+)kg^{-1})	<1.5	1.5-4	4-5
% of CEC	<20	20-30	30-50
Mg (cmol(+)kg^{-1})	<0.5	0.5-1.0	1.0-1.5
% of CEC	<5	5-10	11-15
Al (cmol(+)kg^{-1})	<0.4	0.4-0.6	0.7-1.0
% Saturation	<20	20-40	>40
S-SO_4 (mg kg^{-1})	<5	5-10	11-15
B (mg kg^{-1})	<0.10	0.10-0.30	0.4-0.5
Cu (mg kg^{-1})	<0.4	0.4-0.7	0.8-1.2
Fe (mg $kg^{-1)}$	<20	20-30	31-40
Mn (mg kg^{-1})	<3	3-5	6-10
Zn (mg kg^{-1})	<0.5	0.5-1	1-2

[1]S-SO_4 in ammonium acetate+acetic acid; B in hot water; Cu, Fe, Mn and Zn in Mehlich.

Source: Modified from Malavolta and Kliemann, 1985.

2 Mineral Nutrition

2.1 Background

Sugarcane requires 17 elements to grow and function (Fig. 7). Carbon, hydrogen and oxygen come from water and the air and the remaining elements come from the soil and fertilizer inputs. Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg) and Sulfur (S) are commonly termed macro-nutrients and are taken up in larger amounts by sugarcane.

Silicon (Si) is also taken up in large amounts, and is considered beneficial rather than essential. Elements required in smaller amounts, termed micro-nutrients, include Copper (Cu), Zinc (Zn), Iron (Fe), Manganese (Mn), Molybdenum (Mo), Boron (B) and Chlorine (Cl).

Soil nutrients utilized by sugarcane are retained predominantly in the mineral and organic components of the surface soil. Labile nutrients are retained on the exchange complex and are accessed by cane roots from the soil solution. Various processes including weathering, mineralization, erosion, leaching, denitrification, volatilization, fixation, immobilization, additions in rainwater, crop nutrient uptake and removal, and fertilization/addition of ameliorants/ organic matter addition, determine the long term supply of nutrients for the crop.

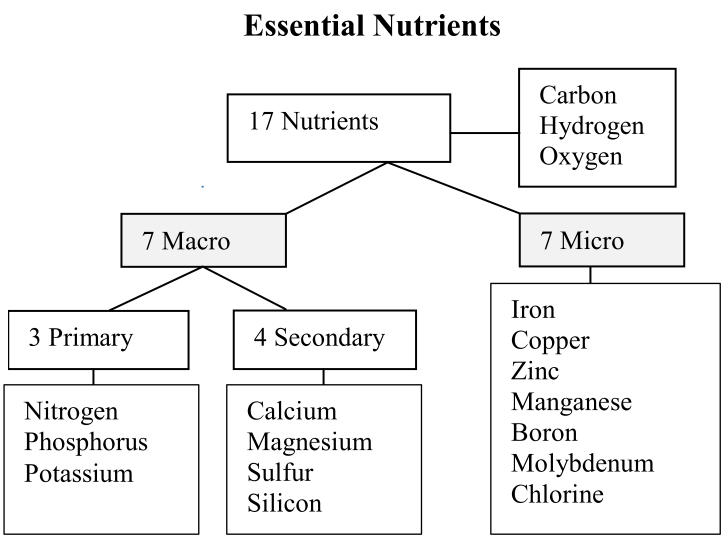


Fig. 7. Essential nutrients for sugarcane.

Soil pH has a strong influence on nutrient availability as indicated in Fig. 8, and loss of Ca, Mg and S from the soil is accentuated by strongly acid conditions in combination with leaching by rainfall.

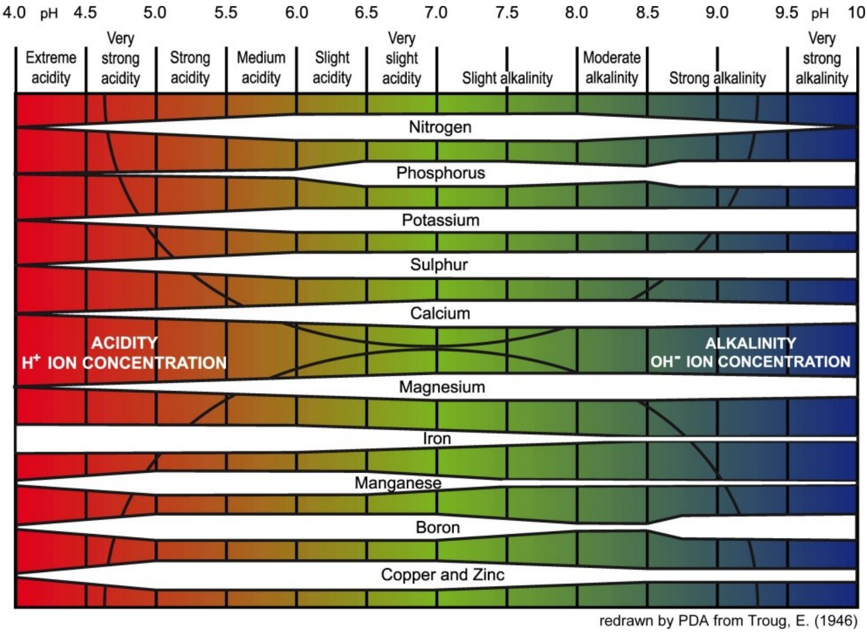


Fig. 8. Effect of soil pH on nutrient availability. *Source:* The Potash Development Association (PDA; http://www.pda.org.uk/leaflets/24/leaflet24-5.html).

2.2 Role of nutrients

The general role of the essential nutrients in plant growth is similar for most of the higher plants, but there are some differences for sugarcane, particularly in the effect on sugar accumulation and recovery during processing.

Nitrogen: N is one of the main building blocks of proteins in plants, and is responsible for the growth and expansion of leaves. It is essential for photosynthesis and sugar accumulation in sugarcane.

When N is deficient, the growth of the whole plant is affected; stalks will be thin and stunted and tillering and root mass will be reduced (Calcino *et al.*, 2000; Garside *et al.*, 1999). In most situations a greater cane and sugar yield response to nitrogen fertilizer application than for other nutrients can be expected (Chapman, 1994).

The response to nitrogen fertilizer is generally greatest in ratoon cane, and may be reduced significantly in plant cane after a legume crop in the fallow (Chapman, 1994).

Garside *et al.,* (1998) showed substantial N build up in the soil after fallow crops of soybeans, peanuts or mung beans.

While sugar yields may increase with increasing N supply to the sugarcane crop, research in several countries shows that excessive N application may cause decline in sugar content of cane (Garside *et al.*, 1999; Chapman, 1971 and 1994) and in juice purity. This is more evident in plant cane than ratoon cane (Chapman, 1971). It seems that this undesirable effect occurs only when the excess N delays maturation by stimulating new growth, including suckering (Salter and Bonnett, 2000).

It is also known that high fertilizer N rates increase amino acid levels in the cane stalk (Chapman *et al.*, 1996; Jackson *et al.*, 2004), particularly asparagine. Amino acids react with reducing sugars during milling to produce high molecular weight colorants in raw sugar (Paton, 1992).

Additional N applications near the end of the growing season lead to a higher incidence of eyespot disease (*Helminthosporium sacchari*), and high N rates may promote susceptibility to top rot disease caused by *Fusarium moniliforme* (Malavolta, 1994). It has also been reported that infestations with white top borer (*Sciropghaga auriflua*) and the stalk borer, *Eldana saccharena*, increase when too much N is applied.

Phosphorus: P is important in development of the spindle in sugarcane, and in early root formation and growth. It is essential for the formation of a vigorous root system, and plays an important role in photosynthesis and many other biochemical processes, such as cell division and growth. P also contributes to disease resistance in most plants (Calcino *et al.*, 2000). P deficient sugarcane will have thin, short stalks and internodes, and tillering will be poor. Severe P deficiency will reduce cane yields, and in Australia, South Africa and many other sugar producing countries there has been a substantial response to phosphate fertilizer on new land. In old land the response to P fertilizer is dependent on readily extractable levels of P in the soil, with cane yield responses from 0-40% at low soil P levels in historical Australian data (Schroeder *et al.*, 1998).

It is reported that application of P fertilizer gives better tolerance to brown stripe disease in sugarcane caused by *Cochliobolus stenospilus* (Whittle, 2000). High P levels in cane juice have been found to aid in clarification during processing at the mill (Steindl, 1998).

Potassium: K is taken up by sugarcane as potassium ions, and Calcino *et al.* (2000) report that it has many roles in sugarcane. It is essential for plant growth and photosynthesis due to its role in chlorophyll development in the leaves, helps the plant use other nutrients and water more efficiently, controls the movement of sugars in the plant, regulates stomatal opening and closing, promotes root development, assists in the uptake of water and nutrients by osmosis, helps prevent premature cell death, and controls starch formation.

The cane yield response to K fertilizer depends on soil reserves of K in exchangeable and non-exchangeable form, and in some situations the ratio (Ca+Mg):K (Schroeder *et al.*, 1998; Kingston *et al.*, 2009).

It has been reported in the literature that K applications can reduce the impact of moisture stress on crop growth, and data presented by Wood and Schroeder (2004) support this observation for sugarcane (Table 2.1). In some countries a consistent response in sugar content of cane to K applications is recorded (Perez and Melgar, 1998 for Guatemala; and Innes, 1960 for Jamaica).

Table 2.1. Effect of applied K fertilizer and moisture stress on sugarcane yield.

Water supply	Applied K (kg K ha^{-1})	
	0	120
	-----------------*mt ha^{-1}*-----------------	
Good	79.5	88.7
Poor	71.4	91.3

Source: Wood and Schroeder, 2004.

Sugarcane is a luxury user of K, and this can result in elevated ash levels in juice at the mill where high rates of K fertilizer are used (Kingston and Kirby, 1979).

Huber *et al.* (2012) report that K deficiency increases the susceptibility of plants to both obligate and facultative fungal parasites. These include Puccinia spp (Rusts), and Alternaria spp. (Leaf spots), respectively. These authors also report that application of chloride fertilizers may suppress various diseases.

Calcium: Ca is essential for the growth and development of the spindle, leaves and roots of sugarcane. It is a component of the plant cell walls, thus strengthening the plant, and has an important role in N metabolism (Calcino *et al.*, 2000). Ca is relatively immobile in the plant and is not transferred from older parts of the plant to new leaves. Ca deficiency has been shown to have a severe impact on sugarcane yield, and substantial yield responses to liming products or gypsum can be expected in deficient soils (Ridge *et al.*, 1980). Liming to correct Ca deficiency commonly has a negative impact on cane sucrose levels (Ridge *et al.*, 1980; Kingston *et al.*, 1996).

Huber *et al.* (2012) report that a higher Ca concentration in plant tissues reduces the incidence of parasitic diseases, mainly by improving the defence mechanisms of the plant against attack.

Magnesium: Mg is an essential constituent of chlorophyll, and therefore is important in photosynthesis, growth and sugar accumulation of sugarcane. It is needed for movement of phosphorus in the plant, and is involved in plant respiration and protein synthesis (Calcino *et al.*, 2000). Mg is mobile in the plant and deficiency symptoms occur first in the older leaves of sugarcane. Where soil Mg levels are low, a significant cane yield response to Mg applications can be expected (Ridge *et al.*, 1980). Mg applications also have a positive effect on sugar levels and reduce the negative impact of liming on sugar content.

Excessive levels of soil Mg may interfere with the uptake of K by sugarcane (Kingston *et al.*, 2009).

As for S there is evidence that Mg can affect disease incidence in plants (Huber *et al.*, 2012).

Sulfur: S is an important component of amino acids, and is essential for protein synthesis. It is also essential for chlorophyll formation, cell metabolism and plant growth (Calcino *et al.*, 2000).

S is a non- mobile element and deficiency symptoms occur first in young leaves of sugarcane. Soil S may be replenished from deposits of sulfur dioxide gas in rainfall, but deficiency is common in non-irrigated areas when no S is present in applied fertilizer (Chapman, 1996). There is limited information available on yield response to S applications on deficient soils, but symptoms of deficiency have been observed to disappear, together with visible growth responses (Chapman, 1996). A response in sugar content to S applications has also been noted.

Sulfate accumulation in the form of pyrite (iron sulfate) occurs under waterlogged conditions, in so called acid sulfate soils, and this can lead to severe acidity and toxicity to sugarcane when such soils are drained and exposed to oxidation of the pyrites. Huber *et al.* (2012) cite evidence that S can affect plant disease incidence.

Silicon: Si is not commonly considered an essential element for sugarcane, and all soils have high levels of Si, either in clay minerals or sand. However, Si is an important structural element of plants and improves resistance to certain fungal diseases, and to insect pests such as stem borers. Naidoo *et al*. (2011) reports that Si treatment significantly reduced the severity of infection with brown rust (*Puccinia melanocephala*). For the stalk borer, *Eldana saccharena*, Keeping *et al*. (2011) reported that Si amendments reduced severity of infestation and helped mitigate the effect of high N applications on damage. It also improves tolerance of salinity and assists with control of transpiration (Calcino *et al.*, 2000). In Australia, and elsewhere, yield responses to silicate applications have been measured on soils with low extractable Si levels (Hurney, 1973; Rudd and Berthelsen, 1998; McCray *et al.*, 2011 for Florida).

2.3 Uptake and accumulation of nutrients

The pattern of uptake of nutrients by sugarcane, and the corresponding increase in biomass, is dependent on a number of factors including timing of fertilizer applications, moisture conditions, other climatic factors and cane variety. Kingston *et al.* (1984) showed also that the rate of biomass accumulation by sugarcane, and the partitioning of biomass between cane stalks, tops and trash depended on time of crop establishment. Fig. 9a and 9b show selected data from Kingston *et al.,* for biomass and cane accumulation in typical plant and ratoon crops for the Bundaberg region of Australia.

Malavolta (1982) presents similar data obtained by Orlando Filho (1978) for the variety CB 41-76 in Brazil. This data also includes corresponding uptake of macronutrients in cane biomass (Fig. 10a and 10b).

This data represents the above ground component of nutrient uptake over time, and there would be additional nutrients in the root system. It is evident from Fig. 10a and 10b that the pattern of uptake of N and K is similar in both plant and ratoon cane and corresponds approximately to the pattern of biomass accumulation. These elements are key to biomass development, and both should be supplied early in crop growth to optimize yields. However, both will be taken up in excess of requirements for optimum cane and sugar yield if supplied in excess amounts to the crop.

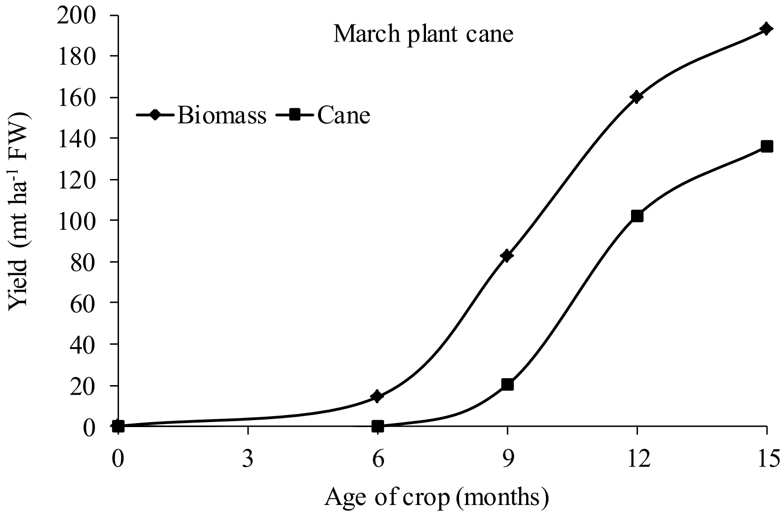


Fig. 9a. Pattern of biomass and cane accumulation in plant cane at Bundaberg, Australia for two varieties (Kingston *et al*., 1984).

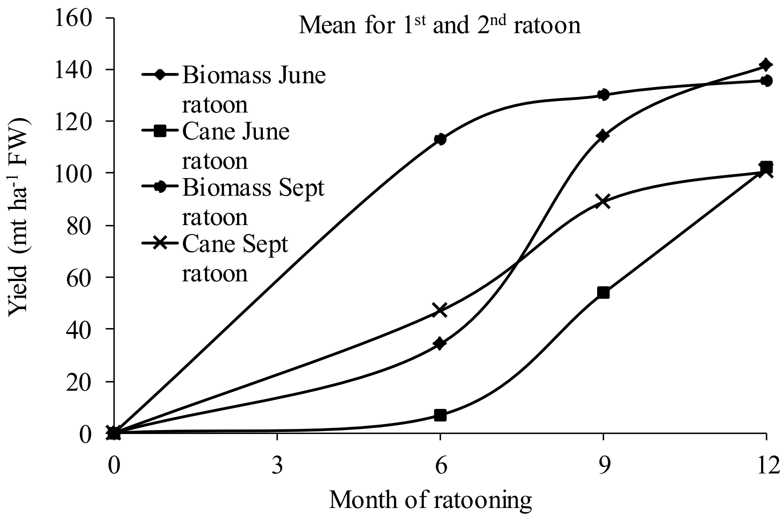


Fig. 9b. Pattern of biomass and cane accumulation in ratoon cane at Bundaberg, Australia for two varieties (Kingston *et al*., 1984).

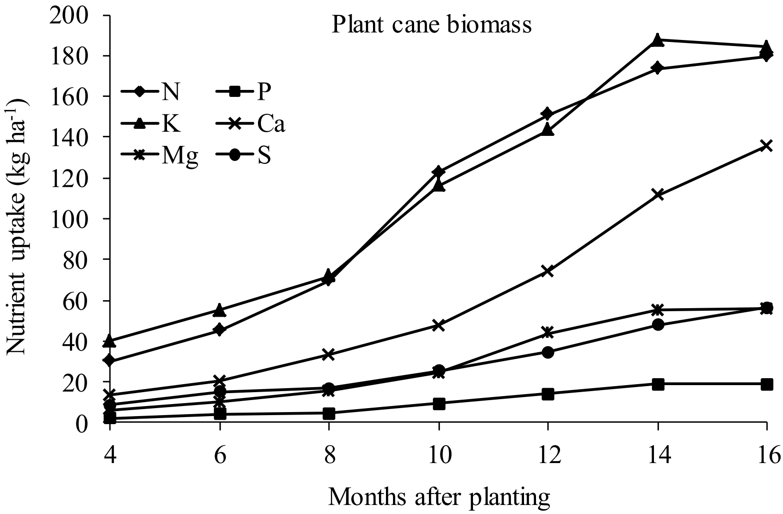


Fig. 10a. Pattern of nutrient uptake by plant cane in Brazil (after Malavolta, 1982).

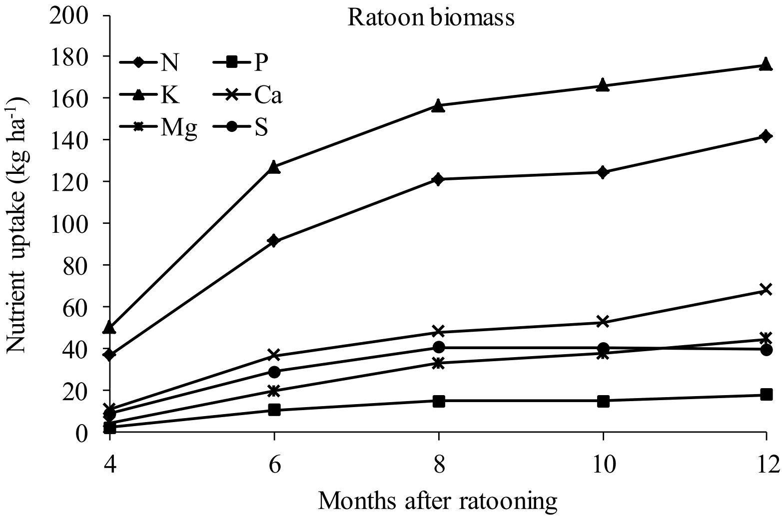
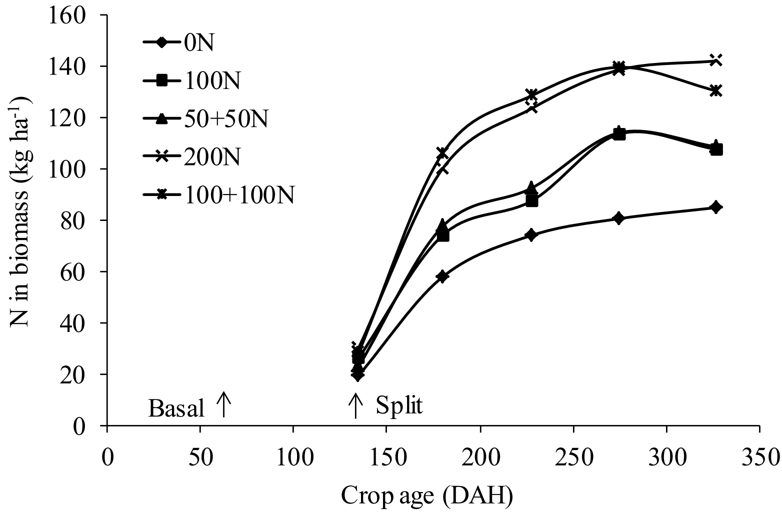


Fig. 10b. Pattern of nutrient uptake by ratoon cane in Brazil (after Malavolta, 1982).

There is limited information available on the benefit of splitting applications of N and K to minimize losses, or replace fertilizer lost by leaching or other means, and most field trials have been inconclusive.

Kingston *et al.* (2008) applied two rates of N in a single application and as split applications, together with artificial waterlogging to accentuate N losses. There was no benefit of splitting to cane yield, and a similar pattern of N accumulation in biomass with single and split applications occurred (Fig. 11). When the uptake of N in the zero N treatment is taken into account it is evident that the N fertilizer has been poorly utilized by the crop at both N rates.



DAH = days after harvest

Fig. 11. Uptake of N by biomass, mean for 3R and 4R crops, with single and split N applications (redrawn from Kingston *et al.*, 2008).

Malvolta (1994) presents data on the pattern of micronutrient uptake in stalks and leaves of two varieties drawn from Gloria *et al.* (1964) and Sobral and Weber (1983) in Brazil (Table 2.2). As for the macronutrients there is progressive uptake of the micronutrients, with Fe and Mn present in higher amounts than other micronutrients, and Mo in very small amounts.

Table 2.2. Accumulation of micronutrients in stalks and leaves of sugarcane in Brazil.

Age	B		Cu		Fe		Mn		Mo(1)		Zn	
(months)	stalk	leaves	stalk	leaves	stalk	leaves	stalk	leaves	stalk	leaves	stalk	leaves
	----------------$g\ ha^{-1}$----------------											
Plant cane												
4	1.8	31	3.1	29	62	2,145	30	363			10	71
6	11	51	11	59	283	4,006	64	642			27	107
8	28	66	36	75	604	2,682	196	907	0.4	0.8	77	181
10	79	81	60	65	1,114	5,023	416	1,173	21.3	1.9	155	204
12	147	116	119	121	1,719	8,218	618	1,526	1.9	0.6	278	310
14	235	129	194	167	3,242	13,394	1,212	1,741	1.3	4.0	381	396
16	249	139	243	98	3,130	7,018	1,331	1,915			573	352
1st Ratoon												
4	1.0	23	3.5	52	125	4,774	415	415			6	60
6	35	54	57	105	2,979	13,714	978	978			117	153
8	96	73	170	181	1,770	9,816	933	933			212	217
10	87	56	237	107	929	8,458	1,496	1,496			270	202
12	116	61	307	145	1,350	3,521	1,315	1,315			341	179

(1)Estimated from Gloria *et al.*, 1964; remainder from Sobral and Weber, 1983.

Source: Malavolta, 1994.

Further data on macro- and micronutrient uptake by sugarcane for different climatic conditions, soil fertility, and fertilizer applications is provided by Chapman *et al.*, 1981 (Tables 2.3 and 2.4). This data summarises 240 monitoring sites in different regions of the Australian sugar industry. It indicates differences in fertilizer utilization under different climatic conditions, and the large uptake of P and K in fertile soil of the Burdekin region relative to fertilizer application. It also shows that there is similar uptake of nutrients in millable cane and tops and trash for N, P and K in most districts.

Table 2.3. Mean nutrient uptake in sugarcane biomass for a range of Australian conditions.

Nutrient	Mossman Cairns	Babinda Tully	Ingham	Burdekin	Mackay	Bundaberg	Maryborough Rocky Point
Cane	100	93	740	119	84	92	85
mt ha^{-1}				*kg ha^{-1}*			
N	143	122	128	154	123	150	134
P	18	17	15	37	18	23	20
K	217	208	139	276	203	260	234
Ca	39	27	30	55	41	51	31
Mg	26	18	29	57	35	52	36
S	35	25	25	47	25	48	34
Cu	0.09	0.07	0.09	0.11	0.09	0.09	0.12
Zn	0.68	0.46	0.43	0.59	0.38	0.37	0.39
Fe	6.4	7.3	7.5	5.7	6.9	8.61	6.6
Mn	6.8	3.9	4.9	1.9	3.6	2.66	2.9

Table 2.4. Mean nutrient uptake by cane (c) and tops and trash (t) as a percentage of fertilizer applied.

Nutrient	Mossman Cairns		Babinda Tully		Ingham		Burdekin		Mackay		Bundaberg		Maryborough Rocky Point	
	c	t	c	t	c	t	c	t	c	t	c	t	c	t
							%							
N	38	41	37	38	31	34	34	36	36	27	34	52	39	38
P	20	20	28	23	22	26	272	196	33	19	38	38	36	27
K	79	88	74	79	88	121	974	1,145	115	73	99	83	131	98

Source: Chapman *et al.*, 1981.

Similar data for plant cane in Brazil (Table 2.5) is presented by Malavolta (1994). Plant cane data is derived from Catani *et al*. (1959), Orlando Filho (1978), Haag *et al*. (1987), Sampaio *et al.* (1987) and Korndorfer (1989). Ratoon cane data derived from Orlando Filho *et al.* (1980) is given in Table 2.6. The Australian and Brazilian data show similar proportions of the different nutrients in millable stalks and non- stalk material, and similar total levels of each nutrient in biomass.

Table 2.5. Macro- and micronutrient content in the above and below ground parts of plant cane.

Plant part	Roots	Millable stalk	Leaves	Total
FW (mt ha^{-1})	1.5	102	27	130.5
Element		*kg ha^{-1}*		
N	8	83	77	168
P	1	15	8	24
K	4	109	105	218
Ca	2	30	45	77
Mg	1	29	18	48
S	2	25	22	49
Cl	-	-	1	1
Si	-	98	150	248
Fe	4.93	3.80	7.90	16.6
Mn	0.084	1.17	1.98	3.24
		g ha^{-1}		
B	34	214	144	392
Cu	13	201	105	711
Mo	-	4	10	14
Zn	72	437	336	845

Source: Malavolta, 1994.

Table 2.6. Macro- and micronutrients in the above ground parts of first ratoon cane.

Plant part	Millable stalk	Leaves	Total
FW (mt ha^{-1})	114	30	144
Element		*kg ha^{-1}*	
N	77	63	140
P	16	9	25
K	72	120	192
Ca	40	32	72
Mg	33	18	51
S	27	18	45
Fe	1.35	3.52	4.87
Mn	0.96	1.32	2.27
		g ha^{-1}	
B	116	61	177
Cu	307	145	452
Zn	343	179	520

Source: Malavolta, 1994.

The potential for mining of soil nutrient reserves by sugarcane is significant for all nutrients, but in particular for K. Trial data from Kingston *et al*. (2009) on a soil with moderately high K reserves shows that at lower fertilizer rates crop uptake exceeds the application of K in fertilizer (Fig. 12). This is also evident in Table 2.4 from Chapman *et al.* (1981). In Fig. 12 it is also apparent that the proportion of biomass K in stalks increases with increasing fertilizer rate.

Nutrients in cane will be taken to the mill, and some will be returned to fields as filter press and mill ash; and nutrients in tops and trash will be retained in the field and potentially recycled into the soil.

Nutrients available for recycling are significantly reduced by burning the standing crop and post-harvest residues (Mitchell *et al.*, 2000). In field trials 79% of residue K was lost in pre- and post- harvest burning, and losses of other macronutrients ranged from 86 to 97%, with N showing the highest losses (Table 2.7).

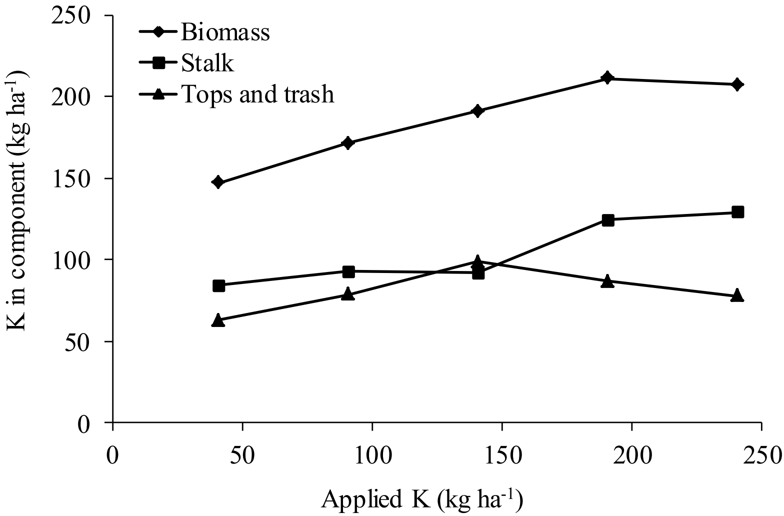


Fig. 12. K uptake in different sugarcane components with increasing K fertilizer rates in two field trials (redrawn from Kingston *et al.*, 2009).

Table 2.7. Losses of nutrients in top and trash residues as a result of pre- and post-harvest burning.

Treatment	Residue[1]	Nutrients					
		N	P	K	Ca	Mg	S
	mt ha^{-1}	----------------*kg ha^{-1}*----------------					
Initial	12.7	65	9	70	39	22	9
After pre-harvest burning	2.9	15	2	21	5	4	2
After burning residues	0.7	2	1	15	4	3	1
		---------------*Loss (%)*---------------					
After pre-harvest burning	77	77	78	70	87	82	78
After burning residues	95	97	89	79	90	86	89

[1]Tops and trash

Source: Mitchell *et al.*, 2000.

Three factors come into play when determining the nutrient value to subsequent crops of the residue from green cane harvesting: the rate of release of nutrients from the residues, crop uptake efficiency, and losses by leaching and other mechanisms. De Oliveira *et al.* (2002) studied changes in nutrient content of green cane trash residues in irrigated and non-irrigated environments in Brazil. The release of P, Ca, Mg and S was greatest in the irrigated environment, ranging from 61 to 66%. N release was 18% and the greatest change in nutrient levels was 94% for K. For tropical conditions in Australia, Klok *et al.* (2003) found that K was released rapidly from trash, Ca, Mg, P and S was released at similar but slower rates, and N was released at the slowest rate (Fig. 13). It appeared that a significant proportion of N and K released from trash was taken up by the crop.

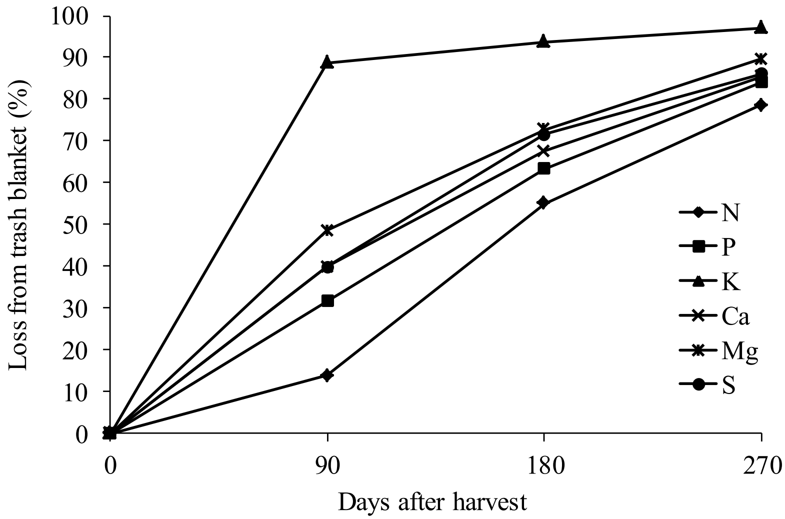


Fig. 13. Rate of loss of nutrients from trash blanket (Klok *et al.*, 2003).

2.4 Symptoms of deficiency and their causes

When sugarcane is unable to take up sufficient quantities of a particular nutrient to maintain normal growth processes, some visual symptoms of deficiency may be evident. Before symptoms develop there may already be restriction of growth, or a hidden hunger, and yield of cane may be restricted. However it is useful to be familiar with deficiency symptoms, particularly for elements which are not normally applied in fertilizer programs, so that remedial measures may be taken. When interpreting symptoms the mobility of different nutrients in sugarcane (and other plants) should be taken into account. For less mobile elements deficiency symptoms are most likely to appear in new leaves, and for mobile elements in the older or lower leaves. However, for certain elements, less obvious changes may occur in the stalks and/or roots (e.g. poor tillering, thin stalks, poor root system or stubbing of roots). The shortage of nutrients, which translates into symptoms of deficiency, can be due to several causes as shown in Table 2.8 (modified from Malavolta 1994).

Table 2.8. Causes of nutrient deficiency.

Element	Cause
Any	Low soil reserve
	Low availability in soil
	Absence or inadequate application in fertilizer
N	Low organic matter content in soil
	High acidity (lack of mineralisation)
	Low rainfall (same)
	High rainfall (leaching or waterlogging)
P	High acidity and high sesquioxides, allophane (fixation)
	Excess liming or native high pH soils
K	Excess liming (competition for uptake)
	Very high native Ca and/or Mg in soil
	High rainfall (sandy soils, leaching)
Ca and Mg	Excess K fertilizer (competition)
	Excess rainfall (leaching)
S	Low organic matter in soil
	High acidity, low rainfall (lack of mineralisation)
	Leaching on sandy soils
	Lack of input in irrigation water
B	As for N
	Excess N (dilution or inhibition of uptake)
	Excess liming (loss of availability)
Cu	Excess P fertilizer (inhibition of uptake)
	Excess liming (loss of availability)
Zn	Excess liming (loss in availability)
	High P fertilizer application (inhibition of uptake)
Fe	High organic matter and moisture (low availability)
	Excess liming (loss in availability)
Mn	High organic matter, excess liming (loss in availability)
Mo	High acidity (lower availability)
	Excess sulphate (inhibition of uptake)

Source: Modified from Malavolta, 1994.

The following description of symptoms of deficiency are based on Malavolta (1994) and Calcino *et al.* (2000). The main nutrients are separated according to the appearance of symptoms first on older leaves, or first on newer leaves. Symptoms for most nutrients are given in the Appendix.

2.4.1 Symptoms first on older leaves

Phosphorus: Leaves initially dark or blue green, with length and width reduced, often with red or purple tips and margins. Older leaves may turn yellow and die back from the tips and along the margins. Leaves may stand abnormally upright. Stalks are usually thin with shorter internodes. Tillering and root growth are poor.

Nitrogen: Stalks are thin and stunted and leaves turn light green to yellow, often with necrosis on the tips and edges of older leaves. Symptoms usually spread to the whole stool and are clearly evident in the crop. Both stooling and root mass will be reduced.

Potassium: On the older leaves, dead areas or dark red stripes may occur between the leaf veins and along the edges and tips. The upper surface of the midrib usually has reddish discoloration. In young crops lower leaves often turn deep yellow, with fired margins and tips, before the whole leaf undergoes premature senescence. The young leaves usually stay dark green and the spindle may have a fan appearance. Stalks will be thin and stools will be stunted.

Calcium: Older leaves are often pale green or yellow and may die prematurely. Leaves have small yellow spots which turn reddish brown and dry in their centre giving the leaf a rusty appearance. In severe cases, the young leaves become hooked and the spindle dies off at the tip and edges. Leaf margins may be serrated and the primary shoot may die.

Magnesium: Older leaf blades are pale green, with small yellow spots developing and turning brown, giving a rusted appearance, similar to Ca deficiency. The symptoms will gradually increase to cover the leaf sheaths, the symptoms often being termed orange freckle.

Silicon: Leaves develop circular white or yellow spots which eventually coalesce to form a bronze freckle on the surface of older leaves that are exposed to the sun. This is often termed sunny side up syndrome.

Molybdenum: Yellowish streaks develop between veins, more concentrated towards the leaf tip. With time the central part of the streaks may become purplish. Older leaves die prematurely from middle to top. Symptoms are similar to mild Pokkah Boeng disease.

2.4.2 Symptoms localised first in young leaves

Sulfur: Symptoms of S deficiency are similar to those for N, but symptoms appear first in the young or upper leaves. New leaves appear light green to yellowish, often with purple margins, but do not die back from the tips as for N deficiency. Stalks and leaves are thin, and stalks are more flexible at the tip than normal.

Copper: Leaves become droopy and the stalks become rubbery and flexible. Leaves may become chlorotic, and develop small dark green patches, or islands. Tillering and vigour will be reduced.

Zinc: Zn deficiency symptoms develop on the third or older leaves with broad bands of yellowish striping, but the midrib and leaf margins remain green. In some cases the yellow stripes are inter-veinal. The stool may suffer stunted growth, and root growth can be poor. Stalks may be thin and elastic. Some cane varieties become susceptible to infection by a red fungus, *Curvularia brachyspora*, and red fungal lesions may develop in the yellowish band between the midrib and leaf margin.

Iron: Longitudinal pale stripes develop between the veins of the leaves extending from the leaf base to the tip of the leaf. The entire leaf may become bleached (pale yellow to white) and this may extend to the whole plant. Young stubble roots have no new root development. Symptoms may be temporary and very patchy in a field, but are very obvious.

Boron: Symptoms are similar to Fiji disease, and the fungal disease Pokkah Boeng, caused by *Fusarium moniloforme*. The growing points may be distorted, or may die and leaves are distorted. Translucent lesions or water sacks form between the veins and water droplets may exude from the lesions on the upper surface of the leaf. Young plants are bunched with an excessive number of tillers. Leaves tend to be brittle and leaf tips can be severely burned and may split.

Manganese: Longitudinal pale stripes appear between the leaf veins, the stripes generally running from the middle of the leaf to the tip. The blades may split, and the entire leaf may become chlorotic under severe deficiency. Necrotic spots which coalesce in long streaks may also develop in severe cases.

Chlorine: Leaves wilt during the day and recover at night. Leaves may become chlorotic, roots may be shorter, and there may be an increased number of lateral roots.

Aluminium: Aluminium (Al) toxicity symptoms may develop in acid sulphate soils. Roots are shorter with thickened tips, resembling damage from nematodes or pre-emergent herbicides. Stalks may die and produce tillers from the base. Leaves may show symptoms of P and K deficiency.

3 Fertilization

3.1 Soil and plant analysis

Both soil and plant analysis are widely used in different sugar industries of the world as a guide to likely deficiencies of different elements in the crop, to determine fertilizer requirements, to assess the effectiveness of fertilizer programs, and to detect trends in nutrient reserves over time. When assessing possible deficiencies, soil and plant analysis are often used in combination. Plant analysis is of particular value in assessing the adequacy of fertilizer programs, and soil analysis for assessing long term trends in soil fertility. Soil analysis is also used for assessing non-nutritional problems such as soil salinity, sodicity and the acid sulphate potential.

3.1.1 Soil tests

Researchers in different sugar producing countries have developed and calibrated a range of chemical extractants for assessing the availability of specific nutrients to the sugarcane crop, and the reserves in the soil. For some nutrients such as Ca, Mg, and K the extractants usually assess exchangeable reserves in the soil, and values obtained in different countries will be comparable. For other nutrients the analyses may vary according to the extractant used. For both exchangeable cations and extractants used for other nutrients, calibrations against crop responses may vary between different sugar producing areas according to local soil types.

Available P in particular is extracted by a range of solutions. These include various acid extracts such as Mehlich (0.05M HCl + 0.0125M H_2SO4; Bray I and II (0.025M HCl + 0.03M NH_4F; 0.1M HCl + 0.03M NH_4F) and 0.005M H_2SO4 (Australia), and alkaline extracts such as Olsen (0.5M $NaHCO_3$). In general the acid extracts are favored for neutral to acid soils, and the Olsen extractant for neutral to alkaline soils. In Brazil, Raiij *et al*. (1986) introduced a mixture of anion and cation exchange resins for the simultaneous extraction of P, K, Ca and Mg. Fig. 14 gives a calibration curve for relative yield of sugarcane versus P in the Mehlich1 soil extract, derived in Guatemala (Perez *et al*., 2003).

Similar curves have been derived for P in other countries using other reagents (Kerr and von Steiglitz, 1938 (Australia); Orlando Filho and Rodella, 1983, (Brazil)), and these form the basis for P recommendations.

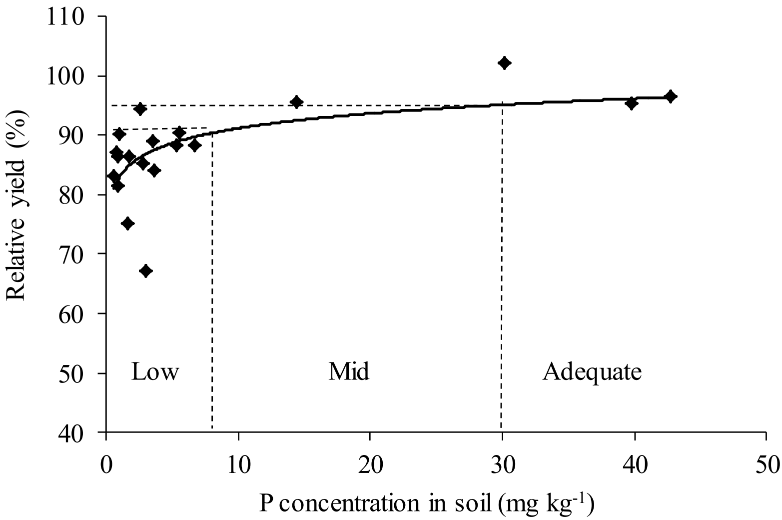


Fig. 14. Response curve for relative yield of cane as a function of Mehlich 1 soil P (after Perez *et al*., 2003).

In P fixing soils, recent research in Australia suggests that the Phosphate Buffer Index (PBI) of soils should be taken into account in determining P fertilizer rates (Hurney *et al*., 2010). Responses to P were obtained in a soil with a high PBI despite high extractable P values. Another approach has been adopted in Cuba, where P fertilization in Ferralsols with high P fixation is determined from the level of P in the soil solution as shown in Table 3.1.

Table 3.1. Recommended P rate in Cuban ferralsols according to P concentration in soil solution.

Soil category	P concentration in soil solution	Recommended P fertilization
	mg kg^{-1}	*kg ha^{-1}*
High fixation	<0.016	44
Medium fixation	0.016-0.025	22
Low fixation	0.025-0.038	11
Very low fixation	>0.038	0

Source: Cabrera, 1994.

In South Africa, higher P rate recommendations are made on soils with high P sorption (Wood and Myer, 1989).

Malavolta (1994) presented a calibration curve for soil K extracted by Mehlich's solution in Brazilian soils. This is redrawn in Fig. 15, and indicates 90% yield with 0.23 cmol(+)kg^{-1} extractable K. In Australia exchangeable K extracted by either 0.02M HCl or 1M NH_4Ac is used as a guide to K fertilizer applications in conjunction with an estimate of non-exchangeable available K (nitric acid extract - Haysom, 1971).

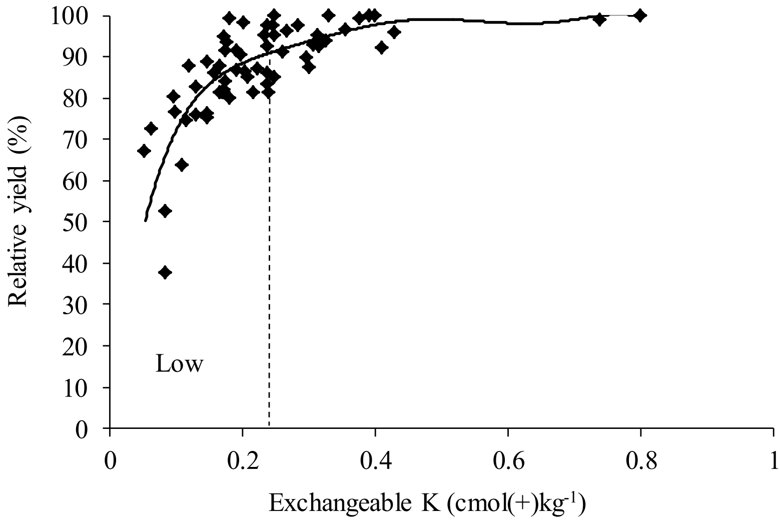


Fig. 15. Calibration of soil K extracted by Mehlich's solution against relative yield (Malavolta, 1994).

More recently Moody *et al.* (2007) have suggested that K extracted by tetraphenyl borate (TB-K) may be a better index of soil K reserves utilized by the crop, but this requires further research. In South Africa, K recommendations are based on four different critical values which reflect clay content, location and base saturation of soils (Donaldson *et al.*, 1990).

There have been many attempts to develop a soil test to assist with N fertilizer recommendations. These include extraction of nitrate-N from soil, and anaerobic and aerobic incubation of soil to assess soil N reserves.

These tests have been largely unsuccessful due to the dynamic nature of N supply to a long term crop like sugarcane. In South Africa, N recommendations are based on indirect assessment of the mineralising potential of soils, using soil color, texture, structure and organic matter content (Myer *et al*., 1986). Recent research in Australia also suggests that soil organic matter levels can be used to estimate N contributed from mineralization in a soil, and to fine tune N applications to sugarcane (Schroeder *et al*., 2005). These authors suggest adjustment of a base N application designed to produce district yield potential to allow for the soil mineralization index (Table 3.2). In this table, the base N rate to produce district yield potential is determined using a N use efficiency factor of 1.4 kg N per tonne of cane per ha up to 100 tonnes per ha, and 1 kg N per tonne of cane above 100 tonnes per ha (Keating *et al.*, 1997).

Table 3.2. N guidelines based on N mineralization index with a target district yield potential of 120 mt ha^{-1}.

N mineralisation index	Organic carbon	Aerobic N mineralisation[(1)]	N rate ratoons
	%	*kg ha^{-1}*	*kg ha^{-1}*
VL	<0.4	<20	160
L	0.41-0.8	20-30	150
ML	0.81-1.2	30-40	140
M	1.21-1.6	40-50	130
MH	1.61-2.0	50-60	120
H	2.01-2.4	60-70	110
VH	>2.4	>70	100

VL=very low; L=low; ML=Medium low; M=medium; MH=Medium high; H=high; VH=very high

[(1)]After Schroeder and Wood, 2001.

Source: Schroeder *et al.*, 2005.

Research in Australia (Ridge *et al*., 1980; Haysom *et al*., 1986) found that exchangeable Ca levels in soil are the most reliable guide to liming requirements in sugarcane, and liming to correct apparently high exchangeable Al levels could not be justified in most circumstances. Similarly, exchangeable Mg levels were found to be a reliable indicator of Mg fertilizer requirements.

For nutrients other than N, P, K, Ca and Mg, similar procedures have been used to calibrate soil analytical values against crop responses in the field. The critical values obtained for soil tests have varying reliability in indicating crop responses, and some are indicative only of high or low values of a particular property or component in the soil. Other tests used to identify problems, such as salinity and high exchangeable sodium (Na) levels are indicative of non-nutritional problems. In Australia the range of soil tests has been rated in terms of their reliability (modified from Calcino *et al*., 2000), as presented in Table 3.3.

Table 3.3. Reliability of soil analysis for guiding sugarcane nutrition in Australia.

Soil assay	Reliability	Extractant
Ca	A	0.02M HCl; 1M NH_4Ac
Mg	A	0.02M HCl; 1M NH_4Ac
P	A	0.005M H_2SO4
K (after harvest)	A	0.02M HCl; 1M NH_4Ac
Zn	A	0.1M HCl
pH (water)	Ap	
Al	Ap	0.01M $CaCl_2$
Na	Ap	0.02MHCl
Conductivity (SEC)	Ap	1:5 Water
K (after fallow)	B	0.02M HCl; 1M NH_4Ac
K (nitric)	B	1M HNO_3
Cation exchange capacity (pH7)	B	0.1M $BaCl_2$
Sulfate-Sulfur	B	0.01M Ca orthophosphate
Cu	B	Buffered DTPA
Si	B	0.01M $CaCl_2$
Organic carbon	B	Dichromate/H_2SO_4
FR	C	Buffered DTPA
Mn	C	Buffered DTPA
B	C	Hot water
Nitrate-Nitrogen	C	Water/PMA
Cl	D	Water
Exchange acidity	D	1M KCl
Al saturation	D	

A=most reliable; B=average reliability; C=unreliable, indicates high or low only; Ap=problem areas; D=not yet used.

Source: Modified from Calcino *et al*., 2000.

Critical values for soil assays used in Australia and Brazil are compared in Table 3.4 (Calcino *et al.,* 2000; Malavolta, 1994).

Table 3.4. Soil assay critical and marginal levels for Australia and Brazil.

Soil assay	Unit	Deficient (low)		Marginal	
		Australia	Brazil	Australia	Brazil
N	Cmol(+)kg^{-1}	-	<0.09	-	0.09-0.14
Ca	Cmol(+)kg^{-1}	<0.65	<1.5	0.65-1.50	1.5-4.0
Mg	Cmol(+)kg^{-1}	<0.10	<0.5	0.10-0.30	0.5-1.0
P	mg kg^{-1}	<10	<10 (resin)	10-20	10-20 (resin)
K (after harvest)	Cmol(+)kg^{-1}	<0.2	<0.1	-	0.1-0.24
K (after fallow)	Cmol(+)kg^{-1}	<0.25	-	-	-
K (nitric)	Cmol(+)kg^{-1}	<0.2	-	0.2-0.6	-
Sulfate-sulfur	mg kg^{-1}	<3	<5	3-7	5-10
Cu	mg kg^{-1}	<0.30	<0.40	-	0.4-0.7
Zn (HCl)	mg kg^{-1}	<0.60	<0.50	-	0.5-1
Nitrate-N	mg kg^{-1}	<5		-	-
Fe	mg kg^{-1}	<5	<20	-	20-30
Mn	mg kg^{-1}	<5.9	<3	-	3-5
B	mg kg^{-1}	<0.15	<.010	-	0.10-0.30
Si ($CaCl_2$)	mg kg^{-1}	<10	-	-	-
Si (P extract)	mg kg^{-1}	<100	-	-	-

Sources: Calcino *et al*., 2000; Malavolta, 1994.

3.1.2 Plant tissue analysis

Tissue analysis evaluates the soil supply of nutrients to the sugarcane crop using the plant as the extracting agent. The most common tissue analyzed is the leaf, but internodes and juice from millable stalks have also been analyzed as a guide to nutrient deficiencies and fertilizer recommendations.

Third leaf analysis

The most commonly used plant index of sugarcane nutritional status used in different sugar industries is the top visible dewlap (TVD), as defined by Clements and Glotb (1968), or the third leaf. This is identified as indicated in Fig. 16.

Fig. 16. Location of the third leaf on the sugarcane plant, where the partially unfurled spindle is taken as zero.

The sampling procedure for third leaves used in most countries is to take about 30-40 leaf blades from sound stalks diagonally across the cane block of interest (or from sections of the block with and without apparent deficiency symptoms). The middle 200 mm section of each leaf is retained, the midribs removed, and the remainder is used for analysis (Calcino *et al.*, 2000). Samples are kept fresh in a paper bag in a cooler, before being dried as soon as is practical, at or below 70°C, and ground for analysis. The timing of third leaves sampling varies between different countries, but it is generally agreed that samples should be taken when the crop is actively growing, and preferably at least six weeks after fertilizer application. The most common age for sampling is three to five months in plant and ratoon crops, with slightly later sampling in cool climates where crop development may be slower.

Third leaf analysis is used for several different purposes, including:

- Diagnosis of existing problems (nutrient deficiencies, toxicities and imbalances).
- Prediction of nutrient problems in current or succeeding crops.
- Monitoring of crop nutritional status (comparing districts, varieties, soil types, assessing crop nutrient removal and evaluating fertilizer practices) (Schroeder *et al.*, 1999).

Malavolta (1994) points out that there is also a relationship between leaf nutrient levels and yield, with a zone of restriction or adjustment until the lower critical level is reached, a zone of luxury consumption where yield does not increase with increasing leaf nutrient levels, and at very high levels, a zone where yields may decrease due to nutrient imbalance (or toxicity).

A range of leaf nutrient values (adequate, marginal, critical) has been established for diagnostic purposes in different countries, and for brevity critical values are compared in Table 3.5. For N, P and K, where a range of values is given (South Africa and Guyana), this allows for different crop ages, varietal differences, and differences between plant and ratoon crops, where relevant (Schroeder *et al*., 1999).

It is also widely accepted that moisture stress affects leaf nutrient values and restricts interpretation of data. Table 3.6 (Schroeder *et al*., 1993) shows that nutrient levels in third leaves from commercial cane blocks in South Africa improved dramatically after moisture stress was relieved. This observation supports the recommendation for leaf sampling when plants are actively growing.

Table 3.5. Critical values used in different countries for third leaf samples.

Nutrient	Australia	South Africa	Mauritius	Guyana	Florida
			Element concentration (%)		
N	1.8	1.6-1.9	1.95	1.9-2.4	1.80
P	0.19	0.16-0.19	0.21	0.18-0.21	0.19
K	1.1	0.7-1.05	1.25	1.25	0.90
Ca	0.2	0.15	0.2	0.13-0.15	0.2
Mg	0.08	0.08	0.1	0.08	0.12
S	0.13(1)	0.12	-	-	0.13
Si	0.7	-	0.7	-	0.5
			mg kg^{-1}		
Cu	2	3	5	3.5	3
Zn	10	15	20	15	15
Fe	50	-	-	-	50
Mn	15	15	15	15	16
B	1	1	1	1	4
Mo	0.08	-	0.1	0.08	0.05

(1)In Australia an N:S ratio >17 is also used as an index of S deficiency.

Sources: Calcino *et al*., 2000 (Australia); Schroeder *et al*., 1992, Meyer *et al*., 1971 (South Africa); Basserau, 1988 (Mauritius); Evans, 1965 (Guyana); McCray *et al*., 2009 (Florida).

Table 3.6. Influence of moisture stress and cane variety on third leaf nutrient levels.

Variety	Age	N	P	K
	Months		%	
			Crop moisture stressed	
NCo376	4.5	1.39	0.12	0.87
Mixed	4.5	1.38	0.14	1.07
			After rainfall	
NCo376	6.5	1.66	0.185	1.45
Mixed	6.5	1.82	0.195	1.47

Source: Modified from Schroeder *et al*., 1993.

Where third leaf analysis has been used for guiding routine fertilizer applications, it is also recognized that critical values may vary between varieties (Schroeder *et al.*, 1992 (South Africa); Farquhar, 1965 (Australia); Bassereau, 1988 (Mauritius)). In Brazil, Orlando Filho (1976) analyzed macronutrients in third leaves for 16 varieties grown on the same soil. The range of third leaf values for each nutrient for the 16 varieties is shown in Table 3.7.

Table 3.7. Variation in nutrient levels in third leaves between 16 varieties in Brazil.

Element	Range	LSD
	-----%-----	
N	1.94-2.29	0.20
P	0.26-0.35	0.06
K	0.96-1.72	0.29
Ca	0.94-1.30	0.31
Mg	0.08-0.23	0.08
S	0.22-0.50	0.14

Source: Orlando Filho, 1976.

Data from Brazil provided by Orlando (1978) shows the influence of rainfall and crop age on third leaf N, P and K levels, and a similar increase in levels following rainfall (Fig. 17, after Malavolta, 1994).

Beaufils (1973) questioned the use of single-value critical levels for different nutrients as he considered the optimum concentration of a particular nutrient to be dependent on the concentration of other nutrients. He developed Diagnosis and Recommendation Integrated System (DRIS) indices. Evaluations of the DRIS system for sugarcane have indicated that the calculated indices, based on leaf nutrient ratios, are probably more efficient in detecting nutrient imbalances and deficiencies than conventional critical values in young cane (Meyer, 1981; Ng Kee Kwong and Deville, 1983). In order to use DRIS it is necessary to have a body of data (nutrient levels and yields) which allows the calculation of means and variances of element ratios for comparison of high and low yielding populations. A formula is used to calculate the relative indices for elements which may be higher (positive) or lower (negative) or equal to zero. The more negative the value is the more deficient a nutrient is, and the greater the need for adjusted fertilizer applications. When all the indices are added, irrespective of sign, the Nutritional Balance Index (NBI) is obtained. The higher the NBI, the greater the imbalance of nutrients. In the mid-1980s, a DRIS application was developed for Florida (Elwali and Gascho, 1983; 1984) and their data is shown in Table 3.8.

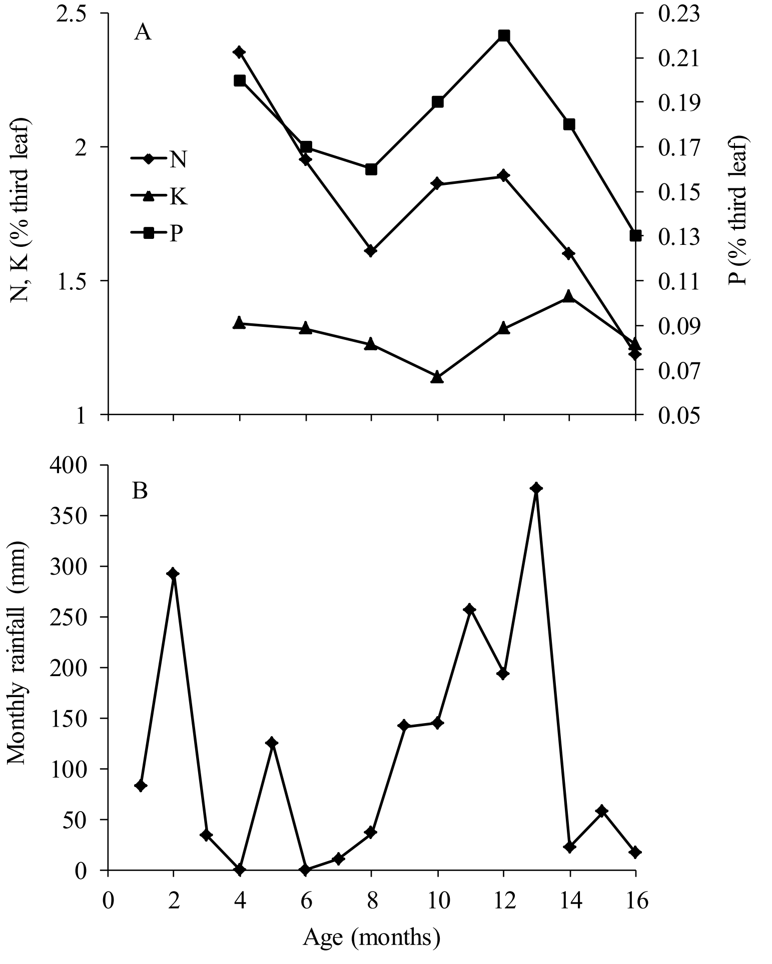


Fig. 17. Variation in third leaf N, P, and K (A) with age of crop and rainfall (B) for plant cane in Brazil (after Malavolta, 1994).

The useful role of third leaf analysis in monitoring crop responses to fertilizer applications is demonstrated in Fig. 18 drawn from the data of Salter *et al.*

(2010). Similar data for Brazil is shown in Table 3.9 where the DRIS approach was used to show the influence of nutrient deficiency and interaction between nutrients in an NPK trial (Orlando Filho and Zambello Jr., 1983). In the control plot (0-0-0) P was limiting, becoming more limiting when N and K were applied. When P and K were added, N was limiting. The negative index with respect to K appeared only when N and P were applied. Despite this data the DRIS system is not widely used, as the NBI sensitivity appears to diminish with crop age, and there is limited published information relating fertilizer recommendations to DRIS indices.

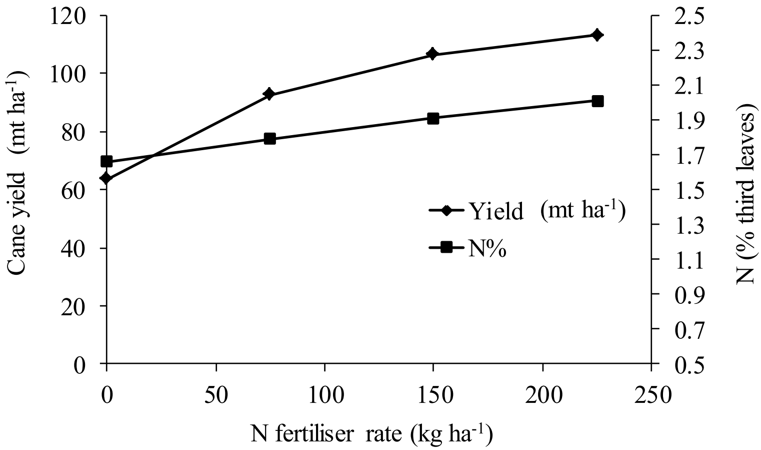


Fig. 18. Relationship between third leaf N, yield and N fertilizer rate (Salter *et al.*, 2010).

Table 3.8. Concentration of elements and DRIS indices for eight fields in Florida.

Field	N	P	K	Ca	Mg	N	P	K	Ca	Mg	NBI[(1)]
	--------------------------------	---	%	---	--------------------------------	-------------------------	---	*DRIS indices*	---	-------------------------	
1	2.89	0.33	1.61	0.50	0.28	2.9	0.0	-6.4	6.0	-2.5	17.8
2	3.10	0.26	1.37	0.42	0.18	22.7	-2.5	-10.2	9.3	-19.3	64.0
3	2.30	0.20	0.70	0.57	0.31	14.6	-13.4	-62.3	45.5	15.6	151.4
4	3.01	0.36	1.54	0.53	0.31	3.9	4.2	-13.1	4.9	0.0	26.2
5	2.45	0.26	1.44	0.57	0.26	-6.1	-6.1	-6.8	24.2	-5.2	48.4
6	2.66	0.27	1.37	0.42	0.21	8.1	0.0	-7.1	7.2	-8.2	30.6
7	2.01	0.32	1.19	0.32	0.20	-7.3	19.8	-7.2	0.0	-5.3	39.6
8	2.78	0.34	1.45	0.39	0.22	7.9	9.1	-8.1	0.0	-8.9	34.0

[(1)]Nutritinal Balance Index. *Source:* Elwali and Gascho, 1984.

Table 3.9. Utilization of DRIS indices in interpretation of a fertilizer trial in Brazil.

Treatment			Yield	N	P	K	N	P	K	NBI[(1)]
N	P	K								
---------------	*kg ha^{-1}*	--------------	*mt ha^{-1}*	------------------	%	------------------	------------	*DRIS indices*	-----------	
0	0	0	81	1.66	0.13	1.30	21	-32	32	85
0	131	249	97	1.71	0.16	1.42	-41	-12	14	67
180	131	249	168	1.86	0.17	1.42	3	-3	3	9
160	0	249	106	1.73	0.11	1.32	74	-74	72	220
160	131	0	126	1.90	0.18	1.32	9	19	-19	47

[(1)]Nutritinal Balance Index. *Source:* Orlando Filho and Zambello Jr., 1983.

Other plant indices

The sugarcane crop log system was developed by Clements (1959) in Hawaii, aimed at detecting and correcting any nutrient (and/or water) deficiencies in the established crop. With this system, samples (leaves 3-6 for N analysis and their sheaths for fresh weight, moisture, total sugars, P, K, Ca and Mg) were collected every 35 days. The resulting nutrient indices (N, Ca and Mg as a percentage of dry matter, and P and K as percentages of sugar-free dry matter) were charted for the life of the crop. Fertilizer was applied to alleviate any deficiencies identified. This system requires very intense sampling and expensive analysis and has not been widely accepted (Schroeder *et al.*, 1999).

Burr *et al.* (1957) proposed the use of stalk samples from the 8-10 internodes of cane as a more sensitive index of N nutrition than the leaf. Data from Brazil obtained by Santos *et al.* (1977) confirmed this, with a closer relation of N content of 8-10 internodes to N fertilizer rates (R=0.58), than for N content of third leaves (R=0.22). The 8-10 internode analysis has been tested elsewhere (e.g. Australia), but has not been widely used, possibly due to the more destructive and difficult sampling procedure relative to third leaves.

Keating *et al.* (1999) found that approximately 60-70% of N in cane stalks was recovered by measurement of N in first expressed juice at the sugar mill. Previous research by Catchpoole and Keating (1995) had shown that cane stalk N levels gave a more sensitive indication of the response in N uptake to fertilizer application than third leaf samples. High amino-N levels in juice were found in fertile soils, with high N fertilizer rates, and in plant cane relative to ratoon cane. Moisture stress also inflated amino-N levels. Preliminary evaluation of Near Infrared Spectrometry (NIR) for amino-N analysis showed that NIR may provide rapid and cost effective evaluation of the N status of cane, by on-line juice monitoring at the mill.

Miphokasap *et al.* (2012) investigated Field Imaging Spectroscopy for estimating the N status of the sugarcane canopy. Using a stepwise multiple linear regression model they found that spectral readings gave a high correlation coefficient with measured N levels in the field (R=0.86) and a low root mean square error of estimate of 0.033% N. They consider that this technique is promising for non-destructive surveying of crop N status in the field.

3.2 Fertilization techniques in the sugar industry

Fertilizer techniques used in different sugar producing countries depend on the degree of mechanization of cultural practices, cost and availability of chemical fertilizers, the availability of alternative fertilizers such as sugar mill by-products, and the availability of irrigation.

In most countries fertilizer rates are determined from historical fertilizer rate trials, soil analysis, and in some cases, leaf analysis of cane to monitor nutrient uptake or detect potential deficiencies.

The most common chemical fertilizers used are urea, as the primary source of N (based on cost), muriate of potash for K, and various products to supply P, including single superphosphate, mono ammonium phosphate (MAP), di-ammonium phosphate (DAP) and triple superphosphate. In the more mechanized countries, fertilizer is usually applied as mixtures formulated specifically for use in plant or ratoon cane, using single or multi-row fertilizer applicators. The mixtures may include S and micronutrients where responses to these nutrients are expected. In less mechanized countries fertilizers, including micronutrients, may be applied separately by hand and covered by hand.

Green manure legume crops, sometimes as inter-row plantings, are used in most industries as a general soil improver, and to supply N for the sugarcane plant crop.

Similarly, mill by- products such as filter cake and filter cake/ash mixes are recycled to the field mainly in the fallow, acting as a general soil ameliorant, and a substantial supplier of N, P and Ca. In India, Pakistan and some African countries, manures are also used as fertilizers, mainly in the plant crop. In countries with distilleries, waste products such as vinasse, provide an important means of recycling K removed by the cane crop.

The preferred placement of fertilizer in most countries is below ground on either side of the cane row, but surface placement has been used in trash blanketed fields in some countries to reduce application costs.

It is common to apply P as a single application, often only in plant cane, but N and K applications may be split, particularly in plant cane. In ratoon, cane splitting of N and K applications is more common in countries such as India, where split applications can be made by hand, but there is a good case for split applications of both K and N in sandy soils. Where drip irrigation is available, N and K may be split to meet demand by the developing crop, and this provides more efficient use of these fertilizers.

Sugarcane soils in most producing countries are subject to acidification, and the use of liming products is becoming more common. With the recognition of Si as an essential nutrient for sugarcane there is also increasing use of calcium silicates as a liming material.

In all countries there is an emphasis on achieving the most economic returns from fertilizer application, and when cane prices fall, there is some reduction in fertilizer applications. Where there are reserves of K and P in soils it is more common to continue N applications at the expense of K and P fertilizer applications.

3.3 Use of by-products of the industry for fertilization

In most sugar producing countries the waste products of mills and alcohol distilleries are returned to the field as fertilizer, and this serves two purposes:

- it returns at least some of the nutrients removed from the field at harvesting
- and, provides a valuable source of organic matter and nutrients to rehabilitate soils.

3.3.1 Filter cake, filter mud, or mill mud

Filtercake is the material removed at the filters following clarification of juice in the mill. It is a high moisture product, and very bulky, limiting the distance that it can be economically transported from the mill. It is usually rich in Ca and P, where lime and P are used in clarification, but is relatively low in K. For this reason some countries blend filter cake and mill ash, or filter press and vinasse (dunder) from the distillery. There is also composting of filter press with additives such as vinasse, bagasse and cane trash. Typical analyses of filter cake and filter cake/ash mixtures are given in Table 3.10. Barry *et al.* (1998) found considerable variability in filter cake nutrient percentages in different districts of Australia, according to soil types and milling practices, and also recorded the heavy metal content of both filter cake and mill ash. They concluded that the heavy metal return to fields in these products does not pose a significant environmental problem.

Filter cake is usually applied at relatively high rates due to difficulty in metering the wet material at low rates, but countries such as Australia and Brazil have developed equipment that controls rates more accurately and allows direction into the row or cane furrow where required. Malavolta (1994) reports broadcast rates of 50 to 100 mt ha^{-1} pre-planting, and rates from 5-20 mt ha^{-1} in the plant cane row, or beside ratoon rows in Brazil. Typical broadcast rates in Australia are reported as 100-150 mt ha^{-1}. Newly developed equipment allows accurate applications of 50 mt ha^{-1} in the cane row, or broadcast across the interspace (Markley and Refalo, 2011).

Table 3.10. Composition of filter press or mud[(1)], ash, and filter mud/ash blends expressed in relation to dry matter.

Component	Filter press			Ash	Filter press/ash
	Brazil	Australia	Range		
pH	-	7.2	6.4-7.9	8.7	7.8
	---------------------------------		*%*		---------------------------------
N	1.4	1.48	0.84-2.24	0.15	0.61
P	1.3	0.91	0.51-1.41	0.17	0.41
K	0.3	0.38	0.12-0.92	0.92	0.79
Ca	3.0	2.34	1.37-3.31	0.91	1.51
Mg	0.4	0.63	0.35-1.1	0.68	0.64
S	1.3	0.27	0.12-0.43	0.07	0.13
Si	3.0	-	-	-	-
C	40.0	30.0	-	-	22.8
	---------------------------------		*mg kg^{-1}*		---------------------------------
Cu	65	34	22-56	35	30
Zn	89	136	84-230	92	110
Fe	2,500	-	-	-	-
Mn	624	1,281	666-2,039	959	1,183
Mo	0.6	-	-	-	-

[(1)]Moisture 78% Brazil; 79.5% Australia (limited data).

Source: Sobr, 1958; Gloria *et al.*, 1974; Barry *et al.*, 1998; Purcell *et al.*, 2012; and Markley and Refalo, 2011.

In Brazil there is some blending of filter cake with vinasse, the resultant slurry being diluted and pumped to the field (Gloria *et al.*, 1973). The composition of the mixture is given in Table 3.11.

Yield increases due to the application of filter cake have been recorded in various countries such as Brazil (Rodella *et al.*, 1990), Colombia (Quintero, 1986), Costa Rica (Berrocal, 1988), and Florida in the US (Gilbert *et al.*, 2008). The effects are explained in terms of improvements in soil physical conditions, and the supply of nutrients, particularly N, P Ca and S.

In Australia, significant improvement in soil fertility has been reported as a result of around two applications of filter cake or filter cake/ash mixture over a 10-15 year period at 100-150 mt ha^{-1} (Table 3.12, Barry *et al.*, 2001). Changes were more significant with filter cake alone than combined filter cake/ash applications.

Table 3.11. Composition of the vinasse and filter cake mixture.

Component	kg m^{-3}
N	0.4
P	0.04
K	0.29
Ca	0.42
Mg	0.05
S	0.11
C/N	19.0
pH	5.3

Source: Gloria *et al.*, 1973.

Table 3.12. Effect of filter cake and filter cake/ash applications[(1)] on soil properties.

Soil test	Filte cake		Filter cake/ash	
	added	not added	added	not added
pH	5.6	5.3	5.8	5.6
Acid P (mg kg^{-1})	304	70	180	28
Total P (%)	0.12	0.04	0.07	0.03
Exch. Ca (cmol(+)kg^{-1})	4.9	1.9	4.9	4.7
Total Ca (%)	0.48	0.23	0.43	0.44
Exch. Mg (cmol(+)kg^{-1})	1.7	0.9	2.4	2.4
Exch. K (cmol(+)kg^{-1})	0.75	0.23	0.31	0.18
Total K (%)	1.26	0.91	0.9	0.8
DTPA Cu (mg kg^{-1})	1.23	0.84	1.7	1.5
DTPA Zn (mg kg^{-1})	2.81	1.25	1.7	0.8
Organic C (%)	2.6	1.7	1.3	1.2
Exch. Acidity (cmol(+)kg^{-1})	0.67	1.1	0.3	0.6

[(1)]The paired sites differ in location for filter cake and filter cake/ash treatments.

Source: Barry *et al.*, 2001.

Schroeder *et al.* (2005) estimate that following filter cake application at 150 mt ha^{-1}, N rates can be reduced by 80 kg ha^{-1} in the plant crop, 40 kg ha^{-1} in the first ratoon crop and 20 kg ha^{-1} in the second ratoon crop, and by 50, 20 and 10 kg ha^{-1} in corresponding crops following application of filter cake/ash mixture.

3.3.2 Distillery waste (vinasse, dunder)

In the factory process for extracting raw sugar, more than three quarters of the K in the millable stalks is concentrated in the molasses. When the molasses is used to make rum or industrial alcohol, the K remains in the waste vinasse or dunder (Halliday, 1956). Similarly, where alcohol is produced from cane juice, the majority of the K is contained in the vinasse. According to Orlando Filho (1994) the following situations occur:

- One tonne of cane will give approximately 100 kg sugar, 35 kg of filter cake, and 40 kg molasses or 12 liters of alcohol and 156 liters of vinasse.
- One tonne of cane will generate 80 liters of alcohol and 1,040 liters of vinasse.

The composition of vinasse may vary depending on the substrate for fermentation as seen in Table 3.13 (Gloria *et al*., 1973). The vinasse produced in all cases is low in P and high in K.

The method of application of vinasse varies between and within countries, with three techniques reported for Brazil (Malavolta, 1994):

- Vinasse, diluted in the proportions 1:8 to 1:10 with waste water or other sources, is applied in the furrows.
- Vinasse with or without supplements of N and P is applied to plant and ratoon cane using tanker trucks (Lima, 1953).
- Vinasse is brought to the field and, after dilution, is sprayed on the field by big gun irrigators (Leme *et al*., 1979).

Rates of application are usually between 50 and 100 m^3 ha^{-1}.

In the Mackay district of Australia, a more concentrated product called Biodunder is produced by the distillery (Chapman *et al*., 1995). This can be applied at 4 m^3 ha^{-1}, supplying 120 kg ha^{-1} K, 36 kg ha^{-1} N, 1 kg ha^{-1} P, 38 kg ha^{-1} Ca, 23 kg ha^{-1} Mg, and 25 kg ha^{-1} S. The concentrated nature of the product allows economic transporting to distances of up to 80 km from the distillery. Chapman *et al.* (1995) carried out experiments to demonstrate that urea could be added to the dunder, and surface applied on or beside the cane row, without excessive N losses by volatilization. Today there are a number of

Biodunder blends available with varying levels of added N, and where required, P, at appropriate rates for plant and ratoon cane.

Table 3.13. Chemical composition of vinasse from different fermentation substrates.

Element	Molasses	Blend	Juice
		kg m^{-3}	
N	1.2	0.7	0.3
P	0.09	0.09	0.09
K	6.5	3.8	1.0
Ca	2.6	1.2	0.5
Mg	0.6	0.4	0.1
S	2.1	1.2	0.2
Org. matter	19.2	11.5	5.9
		g m^{-3}	
Cu	3	4	1
Fe	67	57	51
Mn	6	6	6
Zn	3	4	2
pH	4.8	4.6	4.1

Source: Gloria *et al.*, 1973.

The main yield benefit from application of vinasse or Biodunder would be expected on K deficient soils, and four trials conducted by Chapman *et al.* (1995) gave no yield response to Biodunder without added N (Table 3.14). Biodunder with or without added N was applied to the inter row at a rate of 2.5 m^3 ha^{-1}, supplying 95 kg ha^{-1} K, and 160 kg N ha^{-1}. Biodunder was also supplemented with urea or nitram applied to the cane row.

With the application of vinasse at much higher rates than Biodunder, Ranzani (1956) found an increase in water holding capacity in treated soils, and an increase in the cation exchange capacity, and exchangeable cations, particularly of K. Nunes *et al.* (1981) had similar findings. Large cane yield responses to vinasse application have been observed in Brazil, with additional responses where P fertilizer was also applied (Malavolta, 1994).

High dosages (more than 100 m^3 ha^{-1}) of vinasse can delay maturation, increase ash in juice, and lower cane sucrose content (Stupiello *et al.*, 1977; Magro *et al.*, 1980). They may also create environmental problems.

Table 3.14. Sugar yield in four Biodunder ratoon cane trials.

Treatment	Sugar yield
	-----*mt ha*$^{-1}$-----
Control	9.7
Biodunder	9.8
Biodunder with dissolved urea	11.2
Biodunder with granular N on row	12.7

Source: Chapman *et al.*, 1995.

3.3.3 Molasses as fertilizer

In the past molasses has been used as fertilizer in Australia, South Africa and other countries, with benefits from the K supplied to the crop, and other possible benefits due to increase in microbial activity in the soil (Cleasby, 1959). Because of the high value of molasses it is no longer used as a fertilizer despite its nutritional value (Table 3.15. Wythes *et al.,* 1978).

Table 3.15. Molasses composition on dry weight basis (Australia).

Nutrient/component	Unit	Value
N	%	0.90
P	%	0.07
K	%	5.2
Ca	%	1.2
Mg	%	0.6
S	%	0.7
Cu	mg kg^{-1}	11
Zn	mg kg^{-1}	12
Fe	mg kg^{-1}	247
Mn	mg kg^{-1}	82
Total sugar	%	65.3
Dry matter	%	76.4

Source: Wythes *et al.*, 1978.

3.4 Fertigation of sugarcane crops

Where sugarcane is irrigated there is the opportunity to supply nutrients through the irrigation system at regular intervals during crop growth. The term 'fertigation' is typically used for the application of fertilizers using drip irrigation, but there is also the opportunity to add nutrients through other systems such as centre pivot or lateral move irrigators.

Fertigation using drip systems offers potential advantages by:

- Allowing correction of any deficiencies noted after establishment of the crop, particularly in advanced cane where mechanical application is no longer feasible.
- A more even application of fertilizer directly in the rootzone, eliminating the wind effects that may occur with overhead irrigation systems, and minimizing stimulation of weed growth in the interspace.
- Saving fertilizer through reduced losses by leaching or surface runoff.
- Low labor requirements for fertilizer application.
- Reduced compaction by mechanical equipment.

Typically N and K are the main nutrients applied through the drip system, with P applied mechanically at planting or ratooning. The most suitable fertilizers for fertigation are soluble products with minimal impurities (Table 3.16). There is also a range of soluble micronutrient products that can be applied through drip irrigation.

In Mauritius ^{15}N labelled fertilizer was used to compare uptake of N applied through drip irrigation and N applied conventionally by burying. It was found that with drip irrigation, 80 kg N ha^{-1} gave similar sugarcane yields and N recovery by the plant to 120 kg N ha^{-1} applied conventionally (Ng Kee Kwong *et al.*, 1999.

Similar results were obtained by Ridge and Hewson (1995) in Australia, with four splits of N through drip irrigation compared to a single conventional N application over plant and two ratoon crops (some N was also applied at planting). Similar cane yield and sugar content was obtained with a 75% N rate applied through drip irrigation, and the full rate applied conventionally. The full N rate applied through drip irrigation gave some depression of sugar content of cane. Dart *et al*. (2000) also concluded that drip irrigation allowed a reduction in N rates to approximately 75% of conventional fertilizer rates. They also observed that N losses by leaching were higher with conventional fertilizer placement, and that drip irrigation allowed replacement of lost N, if required, following wet periods.

Table 3.16. Fertilizers suitable for use in fertigation.

Nutrient	Water soluble fertilizers	Nutrient content N-P-K
		-----------%-----------
N	Urea	46-0-0
	Ammonium nitrate	34-0-0
	Ammonium sulphate	21-0-0 (24 S)
	Calcium nitrate	16-0-0 (23 Ca)
	Magnesium nitrate	11-0-0 (9.7 Mg)
	Urea ammonium nitrate	32-0-0
	Potassium nitrate	13-0-38.3
P	Monoammonium phosphate	12-27-0
	Monopotassium phosphate	0-22.7-28.6
	Phosphoric aci	0-35.8-0
K	Potassium chloride	0-0-51
	Potassium sulphate	0-0-41.5 (16.5 S)
	Potassium nitrate	13-0-38
	Monopotassium phosphate	0-22.7-28.6

Source: Netafim, 2012.

3.5 Use of manures and crop residues

The use of manures and crop residues in sugarcane fields serves a similar function to the return of mill by-products to the soil by adding nutrients and organic matter to the soil, and promoting improved soil physical properties.

3.5.1 Manures

In India there is widespread use of manures and composted material for fertilizing sugarcane. Kauer *et al.* (2005) analyzed soils receiving manures for a period of seven years for chemical and biological properties. They found that application of farmyard manure, poultry manure, and sugarcane filter cake, with or without chemical fertilizers, improved soil organic carbon, and total N, P and K. They also found increased microbial activity in soils receiving organic manures.

There are conflicting results about the yield benefit from farmyard manures compared to conventional fertilizers. Mahar *et al.* (2008) compared cane yields with chemical fertilizer application (225-112-168 NPK kg ha^{-1}) and farm yard manure and filter cake application at 25 mt ha^{-1}. The most effective treatment was chemical fertilizers (Table 3.17). Gana (2008) in Nigeria found that cane yields were highest with cowdung (10 mt ha^{-1}) plus 120-26-75 NPK kg ha^{-1}, followed by NPK alone and then cowdung or legume incorporation. All treatments gave a significant yield response compared to cane receiving no treatment.

Farmyard manure is usually applied at 12-15 mt ha^{-1} just prior to planting in India, and incorporated when plowed for the last time. A typical analysis for this material is 0.5% N, 0.09% P and 0.4% K (Advance Agricultural Practice, 2012). The manure application is usually supplemented with chemical fertilizer.

Table 3.17. Comparison of cane yields in Pakistan with conventional fertilizer application, farmyard manure and filter cake.

Treatment	Cane yield	Sugar
	-----*mt ha^{-1}*-----	-----*%*-----
225-112-168 NPK (kg ha^{-1})	106.7	10.6
FYM (25 mt ha^{-1})	85.1	8.9
Filter cake (25 mt ha^{-1})	87.7	9.3
LSD (5%)	2.9	0.3

Source: Mahar *et al.*, 2008.

Moberly and Stevenson (1971) compared yields between poultry manure and conventional fertilizers in South Africa. They recorded similar cane yield responses for the two nutrient sources, but there was some benefit in nematode control with poultry manure at high application rates. They concluded that the use of poultry manure could only be justified if it was obtained at a very low cost.

3.5.2 Green manures

Green manures produce fresh plant material that is turned into the soil with the purpose of adding nutrients (mainly N) and organic matter. According to Pimentel Gomes and Cardoso (1958) the desirable characteristics of plants used as green manures are as follows:

- They should belong to the *Leguminosae* family in order to fix N in symbiosis with *Rhizobium* bacteria.
- Growth should be fast so they compete well with weeds.
- They should produce substantial dry matter with a low C/N ratio that promotes rapid decomposition.
- There should be a strong root system to promote improved soil structure.

Malavolta (1994) gives some typical fresh matter yields for a range of green manure crops. These are compared with dry matter yields obtained by Garside *et al.* (1996, 1998) in Australia in Table 3.18. In tropical regions of Australia Garside *et al.* (1996) found that planting on ridges, and use of herbicides for weed control, gave significant improvements in dry matter yields.

In Brazil and Australia it is common to plant legumes after destruction of the cane stubble at the end of the crop cycle, and before the commencement of the wet season. Seed is inoculated and, where necessary, P and lime is applied prior to planting.

Seed may be broadcast and cultivated in, but generally planting as a row crop gives superior yields.

When the legumes begin to bloom they are plowed in and the green material breaks down rapidly, allowing establishment of the next cane crop.

Table 3.18. Production of fresh and dry matter by green manure crops.

Species	Fresh matter	Dry matter[1]
	--------------*mt ha*$^{-1}$--------------	
Arachis hypogaea (peanut)	-	5.5-6.5
Crotalaria spp.	16-54	-
Dolichos lab-lab	10-40	3
Styzolobium spp.	16-43	-
Cajanus cajan	15-35	-
Canavalia ensiformis	22-33	-
Glycine max (soybean)	15-19	5.0-8.5
Sesbania spp	5-24	-
Vigna spp (cowpea, mungbean)	18	2-5
Lupinus sp	6	-
Tephrosia candida	20	-

Source: Malavolta, 1994; [1]Garside *et al.,* 1996 and 1998.

Soybeans, beans and peanuts may also be harvested as a cash crop and the residue after harvesting incorporated before planting of cane.

In India and Pakistan it is common to grow green manure crops between the rows of cane and incorporate green material about 45 days after planting. Ramesh *et al.* (2003) concluded that leguminous crops grown in the interspace can save up to 25% in N requirements.

The N contribution from legume green manure crops to sugarcane nutrition was measured more precisely by Umrit *et al.* (2009) using ^{15}N. They showed that N returns to the soil from green manures ranged from 100 to 267 kg N ha^{-1}, of which 50-70% was obtained from biological fixation. The legume crop contributed between 21 and 44 kg N ha^{-1} to the following cane crop. They concluded that the plant cane N fertilizer rate could be reduced by half following the incorporation of a legume crop. Garside *et al*. (1998) measured N levels in various legume crops between 30 and 248 kg ha^{-1}, the highest levels being for soybeans (*Glycine max*). In plant crop following the different legume crops there was no significant response to N fertilizer, but in the first ratoon crop there was a significant yield response to 140 kg N ha^{-1}.

Malavolta (1994) lists nutrient levels for two common green manure crops in Brazil (Table 3.19).

With the move to reduced tillage practices in Australia, Garside and Berthelsen (2004) compared traditional incorporation of green material with various reduced tillage approaches. They found that incorporation of either green material or mature soybeans resulted in more rapid loss of nitrate from the soil by leaching, than where crop residues were left on the soil surface. This had a negative impact on the yield of the following cane crop (Table 3.20). Where mature soybeans were harvested and the stubble removed from the field there was also a negative impact on cane yield.

The effect of Crotalaria juncea on yields and the response to liming by a low fertility soil is shown in Table 3.21 (Wutke *et al.*, 1960). In Australia it was noted that legume crops (*Vigna sp.*) may fail completely in Ca deficient soils (Ridge, unpublished data).

Table 3.19. Quantities of nutrients accumulated by green manures.

Element	Crotalaria[1]			Lab lab[2]		
	Roots	Tops	Total	Roots	Tops	Total
	kg ha^{-1}					
N	13.6	151.2	165	13.4	69.1	82
P	1.7	11.9	13	1.9	4.2	6
K	20.8	85.3	106	8.6	42.4	51
Ca	6.6	74.5	81	8.2	31.9	40
Mg	4.1	19.4	23	2.9	5.9	9
S	3.8	12.9	17	4.4	3.3	8
	g ha^{-1}					
B	107	497	604	52	112	164
Cu	26	54	80	36	11	47
Fe	8,650	24,807	33,457	6,944	1,635	8,579
Mn	487	982	1,469	764	299	1,063
Zn	38	97	135	48	36	84

Fresh weight in tonnes: [(1)]Roots 6, Tops 32; [2)]Roots 4, Tops 13.

Source: Malavolta, Kronka and Caceres, 1994 (unpublished).

Table 3.20. Plant cane stalk and sugar yields with various methods of handling soybean residues.

Soybean residue treatment	Cane yield	Sugar yield
	mt ha^{-1}	
Green incorporated	81	6.9
Green cut and left on surface	92	8.8
Mature crop incorporated	82	7.4
Mature crop harvested/res. incorp.	75	6.8
Mature crop cut and left on surface	92	8.3
Mature crop left standing	88	8.3

Source: Garside and Berthelsen, 2004.

Table 3.21. Sugarcane yield response to mineral fertilizers, liming and green manure.

Treatment	Cane yield			
	Plant	1st ratoon	2nd ratoon	Mean
	----------------------*mt ha*$^{-1}$----------------------			
Control	52	31	30	38
PK + crotalaria	88	75	67	77
PK + crotalaria + liming	86	100	90	92
NPK	80	69	63	71
NPK + liming	88	95	97	93

Source: Wutke *et al*., 1960.

3.6 Recommended fertilizer application practices

Fertilizer best practices for a particular sugar producing country take into account a number of factors including: available fertilizers, responses to particular nutrients and fertilizer rates obtained under local conditions, local fertilizer application techniques, optimum timing of fertilizer applications, economics of responses to fertilizer, and possible environmental implications of fertilizer practices.

3.6.1 Types of fertilizer

The most common fertilizers supplying N, P and K for sugarcane production and their characteristics are listed in Table 3.22. In this table a high Salt Index indicates those fertilizers which may cause root burn by themselves, or as a main component of fertilizer mixtures, if they are placed too close to setts at planting. Similarly, a negative $CaCO_3$ equivalent indicates those fertilizers that may have an acidifying effect in the field. In general ammonium sulfate and MAP are considered to have the highest acidifying effect; and DAP, ammonium nitrate and urea a moderate effect. The acidifying effect is increased if there is significant leaching of these fertilizers.

In many countries phosphate fertilizers are still described in terms of their content of P_2O_5, K fertilizers in terms of the content of K_2O, and lime as their content of CaO. For simplicity, analyses are expressed here as content of the particular elements P, K, and Ca. Common sources of Ca, Mg, Si and S (apart from Table 3.22) are listed in Table 3.23. The main sources of micronutrients are given in Table 3.24.

All mineral sources of N are considered to be equally effective according to Srivastava *et al.* (1992), and in most sugarcane industries the N source is selected on the basis of price per unit of N and convenience of application. In some situations, apparent advantages of products such as ammonium sulfate may be due to a correction of S deficiency (Malavolta, 1994).

Where N is applied on the soil surface in trash blanket situations, fertilizer mixtures based on ammonium nitrate, calcium ammonium nitrate and sulfate of ammonia, are sometimes used in Australia in place of urea blends to reduce N losses by volatilization. Chapman (1990) found some yield advantage of surface applied ammonium nitrate or sulfate of ammonia over surface applied urea. Freney *et al.* (1992) reported that losses of N by volatilization ranged from 17-39% for surface applied urea, compared to less than 1.8% for sulfate of ammonia. Ammonium nitrate and calcium ammonium nitrate are security sensitive products, and in Australia, for example, the content in fertilizer mixtures is limited to 45 and 55%, respectively. Special licenses are required to store, transport and use these products as straight fertilizers or more concentrated blends.

Newly available blends based on humus coated urea and DAP (so called black urea and black DAP) are claimed to reduce N losses by volatilization and leaching. The choice to use such products depends on relative costs per unit of 'effective N', and environmental considerations.

The short term effectiveness of P fertilizers is assessed by the percentage of P present in water and citrate soluble form, but the insoluble components may become available to the crop in the longer term (Calcino *et al.*, 2000). Products such as superphosphate and ammonium phosphates are preferable where P levels are low, but larger dressings of inexpensive, low solubility products such as rock phosphate have been used in Australia on acidic soils to build up P reserves. Rock phosphate is not effective in alkaline soils due to its low solubility in these soils (Malavolta, 1994). When high P sorption soils are first brought into production, broadcast applications of superphosphate or rock phosphate give long term benefits by blocking P sorption sites (Calcino *et al.*, 2000). As for ammonium sulfate, P sources such as single superphosphate which contain significant levels of other nutrients (Ca and S) may give comparatively better yield than ammonium phosphates in soils with low S or Calevels (Ferreira *et al.*, 1989).

Potassium chloride and potassium sulfate are equally effective, except where soils are deficient in S.

Table 3.22. Some common fertilizers used in routine nutrition of sugarcane.

Fertilizer	Nutrient content						$CaCO_3$ equivalent	Salt index
	N	P	K	Ca	Mg	S		
	----------------------------------			%		----------------------------------		
Anhydrous ammonia	82	-	-	-	-	-	1.5	47
Aqua ammonia	16-25	-	-	-	-	-	-0.3-0.5	-
Ammonium nitrate	34	-	-	-	-	-	-0.6	105
Ammonium sulfate	21	-	-	-	-	24	-1.1	69
Calcium nitrate	15	-	-	26	-	-	+0.2	65
Calcium ammonium nitrate	27	-	-	8	-	-	-	78
Nitrochalk	27	-	-	3	2	-	-0.3	61
Sodium nitrate (Chilean)	16	-	-	-	-	-	+0.3	100
Urea	46	-	-	-	-	-	-0.8	75
Diammonium phosphate (DAP)	18	20	-	-	-	1.7	-0.7	34
Monoammonium phosphate (MAP)	10	22	-	-	-	2.0	-0.6	30
Single superphosphate	-	10	-	20	-	12	0	8
Triple superhosphate	-	21	-	14	-	1.4	0	10
Rock phosphate	-	11-16	-	25-28	-	-	-	-
Potassium chloride	-	-	50	-	-	-	0	116
Potassium sulfate	-	-	41	-	-	18	0	46
Potassium nitrate	13	-	38	-	-	-	0.26	76

Source: Modified from Malavolta, 1994.

Table.3.23. Other fertilizers supplying Ca, Mg, Si and S.

Product	Content				NV[1]
	Ca	Mg	Si	S	
	---------------------%---------------------				
Lime ($CaCO_3$)	38-40	-	-	-	95-100
Burnt lime (CaO)	70	-	-	-	160
Earth Lime ($CaCO_3$)	20-30	-	-	-	50-70
Dolomite CaMg $(CO_3)_2$	24	12	-	-	109
Magnesite ($MgCO_3$)	-	26	-	-	95-105
Granomag (MgO)	-	54	-	-	180-220
Magnesium sulfate ($MgSO_4.7H_2O$)	-	9.6	-	13	nil
Gypsum ($CaSO_4.2H_2O$)	19	-	-	15	nil
Phosphogypsum	18	-	-	14	nil
Calcium silicate ($CaSiO_3$)-slag	26	-	20	-	65-90

[1]Neutralising value; % of pure lime.
Source: Various commercial suppliers.

Table 3.24. Main sources of micronutrients.

Micronutrient	Product	Content
		----%----
B	Borax ($Na_2B_4O_7$. $10H_2O$	11
	Solubor ($Na_2B_4O_7$.5H2O + $Na_2B_{10}O_{16}.10H_2O$)	20
	Boric acid (H_3BO_3)	17
Cu	Cupric sulfate ($CuSO_4.5H_2O$)	25
	Cupric oxide (CuO)	75
	Cu chelates	5-13
Fe	Ferrous sulfate ($FeSO_4.7H_2O$)	25
	Fe-chelates	5-14
Mn	Manganous sulfate ($MnSO_4.H_2O$)	26-28
	Manganous oxide (MnO)	41-68
	Mn-chelates	8-12
Mo	Sodium molybdate ($Na_2MoO_4.2H_2O$)	39
	Ammonium molybdate $(NH_4)_6Mo_7O_{24}.4H_2O$	54
	Molybdenum oxide	66
Zn	Zinc sulfate ($ZnSO_4$.7H2O)	23
	Zinc oxide (ZnO)	30-78
	Zn-chelates	5-13

Source: Malavolta, 1994.

Liming products are generally assessed in terms of their nutrient content (% Ca and/or Mg), neutralizing value and fineness. Most are relatively insoluble, and finer products (>90% passing a 250µ sieve) will give a faster crop response than coarser materials. Similarly, products with a high neutralizing value will give a more rapid rise in soil pH and soil effective cation exchange capacity. Where burnt lime (CaO) is available it will give a more rapid reaction than lime ($CaCO_3$), but it is a more difficult product to handle because of its caustic properties (Ridge *et al.*, 1980).

In general available calcium silicate products are relatively insoluble and fineness of the product is important. There has also been some research to improve the solubility of slag materials used as Si sources in sugarcane and other crops (Crooks and Prentice, 2011).

In most countries the major elements are applied in solid form, but there is increasing use of liquid formulations in Brazil where blends are often formulated by the mills which buy in the raw materials (Malavolta, 1994).

3.6.2 Placement of fertilizer

The optimum placement of fertilizer in sugarcane is dependent on a number of factors including cost and convenience of application, susceptibility of a nutrient to losses, the solubility or mobility of the particular nutrient, and soil properties.

Prior to planting, broadcast applications of single superphosphate, rock phosphate dust, liming products or calcium silicate are usually made to allow thorough incorporation of these products, and allow reaction time in the soil. This is because of low solubility, or in the case of superphosphate, to promote sorption onto P fixation sites. Similarly, mill by products such as filter cake were traditionally broadcast and incorporated, but it is becoming more common to apply lower rates in the row at planting.

In India it is common to apply superphosphate and any necessary micronutrients in the row before planting, and N and K beside the cane setts after planting (Advance Agricultural Practice, 2012). In Australia and other more mechanized countries part of the N and all of the P is usually applied at planting, generally on either side of the planting material, but preferably not in contact with the cane setts. In some cases K at relatively low rates may be included in the planting mixture, and micronutrients such as Cu and Zn, if required. Separation of the fertilizer from the cane setts, and minimizing the use of high salt index K fertilizer, is critical in minimizing root burn from fertilizer.

After planting, N and K is usually placed beside the cane row so that it is covered by soil.

In ratoon cane, fertilizer mixtures were traditionally applied below the soil surface, usually on either side of the cane row, and issues such as high losses of N by volatilization or denitrification were not considered to be critical. With the move to green cane harvesting and trash blanketing in many countries several alternative placement methods have been developed, including: broadcast application, surface application on the cane row, application below ground in the cane row behind a coulter, and application in the center of the interspace behind a coulter and tine. Some of the reasons for these developments are:

- reduced application costs;
- the desire to reduce tillage and preserve an undisturbed trash blanket for weed control;
- difficulties in certain soil types with placing fertilizer below the surface beside the row;
- and, the combination of fertilizer placement with disturbance of compaction in the center of the interspace.

Research in Australia and elsewhere has shown significant losses of N (up to 35%) by volatilization as ammonia where urea, or urea based mixtures, are applied on the soil surface (Prammanee *et al*., 1989; Denmead *et al*., 1990; Kong *et al*., 1991). Freney *et al*. (1992) found that losses were accentuated by heavy dew on the trash, but reduced where there was sufficient rain to wash urea into the soil. Significant losses of N by denitrification have also been observed where waterlogging occurs soon after N application in ratoons (Prammanee *et al.,* 1989; Chapman, 1990), particularly where fertilizer was placed in the center of the interspace.

As a result of these and similar observations, Calcino *et al.* (2000) gives the following recommendations for N (urea) placement in trash blanketed fields:

- Where possible urea or urea based mixtures should be placed beside the row, and below ground, using specialized equipment.
- If urea is placed on the soil surface, application should be delayed until there is sufficient leaf canopy development (0.5 m high) to give some protection. It is preferable to place the urea on the cane row and, where possible, urea should be applied just before rain, or 15-20 mm of irrigation should be applied. Depending on economics, products such as sulfate of ammonia or ammonium nitrate and calcium ammonium nitrate blends should be considered.

Where liquid N formulations such as anhydrous ammonia and aqua ammonia are used, these are usually injected beside the row, and it is important that applicators and soil conditions allow a good seal of the soil to minimize losses (Innes, 1960).

Generally, liming products and mill by-products such as filter press and vinasse are applied on the soil surface, and liming products in particular are generally cultivated into the soil. Where lime was applied on the surface in trash blanket situations Schroeder and Wood (2004) found that there was more rapid breakdown of trash, and lime still produced significant pH change in underlying soil. Filter press applied on the surface gave similar results with more enhancement of trash breakdown.

With micronutrients Calcino *et al.* (2000) indicates that foliar sprays offer an alternative for more rapid correction of deficiencies, but care should be taken that nutrient solutions are sufficiently dilute to prevent leaf burn. Most micronutrients can also be applied through drip irrigation.

3.6.3 Timing of applications

The timing of fertilizer applications should ideally be dependent on crop requirements, and in Fig. 10a and 10b it is evident that initial uptake of N and K is slower in plant cane than in ratoon cane, due to slower development of cane biomass. Both N and K fertilizers also have a relatively high salt index (Table 3.22), and there is potential for serious root burn if high rates are applied when cane setts are germinating. For N fertilizers, timing of applications should also take into account minimizing losses by leaching or volatilization as discussed earlier. For K fertilizers, losses by leaching may be important on sandy soils. Practices developed in different countries take these factors, and the practicality of splitting fertilizer applications, into account.

Since P losses are minimized by sorption of P in the soil, most countries apply P as a single application, mainly at planting and, where required, prior to the 'out of hand' stage in ratoons. This ensures that P is available at an early stage of crop growth to support root development.

For N in plant cane, it is common practice in Australia to apply some N at planting (20-40 kg ha^{-1}), and the remainder with K around the time of the final cultivation to fill in the planting furrow. Malavolta (1994) reports that in high production areas of Colombia a single application of N and K is made approximately three months after planting, and in ratoons 120 to 140 kg ha^{-1} N and 50 kg ha^{-1} K are applied one month after cutting, followed by 50-60 kg ha^{-1} N three months after cutting. In India it is reported that N and K are applied in three equal splits of 90 and 30 kg ha^{-1}, respectively, at 30, 60 and 90 days after planting (Advance Agricultural Practice, 2012).

In ratoon cane, which develops biomass more rapidly than plant cane in most situations, it is more common to apply all the N and K (and where required P) as a single application within two months of harvest. As discussed earlier, applications may be delayed in trash blanketed fields for urea applied on the surface, in order to give some protection by the leaf canopy, and reduce losses from volatilization.

With conventional fertilizer application there is limited evidence of the benefit from split applications of N in ratoons, but it has been demonstrated that split applications through drip irrigation may allow reduction of N rates by 25-30% (Ridge and Hewson, 1995; Ng Kee Kwong *et al*., 1999; Dart *et al.,* 2000).

Dart *et al.* (2000) also pointed out that progressive N through drip irrigation reduced NO_3-N losses by leaching, and offered the opportunity to replace N lost following abnormally high rainfall events. It should be kept in mind that late applications of N, particularly at high rates, may depress sugar levels due to promotion of vegetative growth (Ridge and Hewson, 1995).

For a sandy soil with very low K reserves, Alvarez and Freire (1962) demonstrated the benefit of splitting K fertilizer into two applications - half at planting and half two months later - compared to a single application at planting. Splitting K into three applications (planting, two and nine months later) was less efficient (Fig. 19).

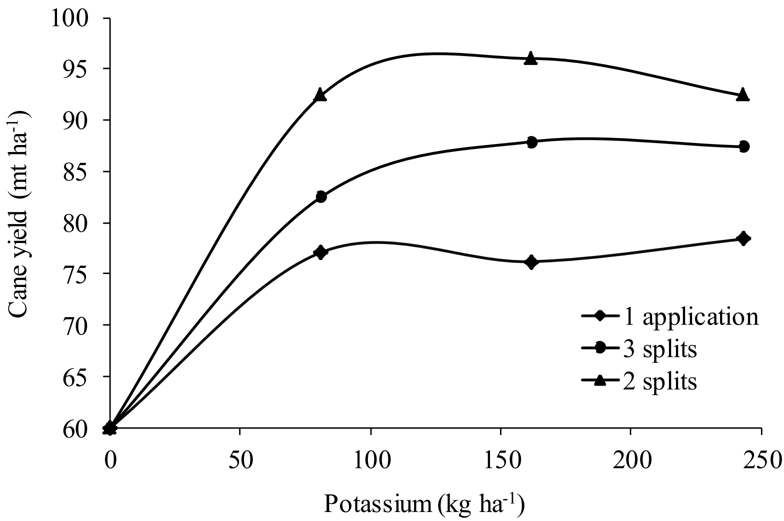


Fig. 19. Effect of rates and split applications of K in plant cane (Alvarez and Freire, 1962).

For liming products and mill by-products, such as filter cake, applications are usually made on fallow land to allow incorporation prior to planting, but Schroeder and Wood (2004) found that applications on top of the trash blanket after harvest were effective in non-deficiency situations.

Similarly, products such as vinasse are usually applied soon after harvest, and the work of Chapman *et al*. (1995) suggests that where more concentrated products such as *Biodunder* are fortified with urea, application should be delayed until there is some canopy development to minimize volatilization losses.

3.6.4 Rates to apply

The fertilizer rates used in different sugar producing countries depend largely on trial and commercial results obtained over a number of years. The recommended rates are refined using soil and leaf analyses as discussed earlier; for irrigated (or high rainfall) conditions versus dryland production; and, for plant cane versus ratoon cane to take into account the effect of fallow practices on nutrient availability. Table 3.25 adapted from Malavolta (1994) gives a broad indication of N, P, and K fertilizer recommendations in selected countries.

In both Australia and South Africa N rates are reduced on soils with high organic carbon levels (Table 3.2), and in Australia plant cane N rates are adjusted for the N contribution made by fallow legume crops. Schroeder *et al.* (2005) indicate that no N is required following a good legume crop, and N rates should be reduced by 70 to 90 kg ha^{-1} following a poor legume crop, or where a legume crop such as soybean has been harvested for grain. For replant crops, where there is no significant fallow period, N rates are as for ratoon cane.

It is evident from Table 3.25 that N applications for optimum production differ significantly between countries, and Australia, India and South Africa appear to have lower N fertilizer use efficiency than South American producers. For sugarcane in Australia, Chapman *et al*. (1991) found that the maximum recovery of labeled ^{15}N fertilizer in the crop and surrounding soil was just over 60%. Robinson *et al.* (2011) found that commercial cultivars in Australia were inefficient in utilizing NO_3-N compared to NH_4-N, and postulated that this may contribute to the low efficiency in using N fertilizer. There is currently a breeding program in Australia aimed at improving the N use efficiency of commercial varieties.

Table 3.25. General indication of fertilizer recommendations in selected countries.

Country/region	Crop	N	P	K
		----------------*kg ha^{-1}*----------------		
Australia[1]				
Burdekin	Plant	140-160	20	nil
	Ratoon	210-250	nil	0-50
Central	Plant	150	20-50	50-80
	Ratoon	170	0-30	70-100
Other	Plant	140	20-50	50-100
	Ratoon	160	0-30	100-120
Brazil				
North East	Plant	60-80	35-79	25-100
	Ratoon	60-80	9-44	33-116
South East	Plant	50-90	22-48	17-100
	Ratoon	50-90	11-22	8-66
Central West	Plant	30-40	13-52	25-100
	Ratoon	40-60	7-26	17-75
South	Plant	40-100	0-52	25-100
	Ratoon	20-40	9-26	0-50
Colombia	Plant	50-70	22-44	50-125
	Ratoon	50-100	26-44	50-125
India				
Subtropics	Plant	100-250	26	66
Tropics	Ratoon	150-300	35-52	90
South Africa[2]	Plant	60-140	20-80	75-250
	Ratoon	100-200	20-40	125-250

[1]From Schroeder *et al*., 2006; [2]From Schroeder *et al*., 1998.

Note: N rates exclude legume fallow and P and K rates vary with soil analyses. Higher P applications recommended on new land and high P sorption soils (South Africa, Australia). Higher K rates correspond with soils with high base status (South Africa).

Source: Modified from Malavolta, 1994;

The apparent lower N fertilizer requirement in South America may in part be due to substantial biological fixation of N in association with sugarcane roots, as identified in Brazil (Dobereiner, 1992). Fertilizer rates are reduced by up to 60 kg ha^{-1} to allow for N fixation by diazotrophic bacteria such as Glucanacetobacter diazotrophicus (Wood *et al*., 2010). While similar bacteria have been isolated from sugarcane in Australia (Chapman *et al*., 1992), no significant N fixation has been observed using current management practices of high N fertilizer applications relative to Brazil.

The adjustment of phosphorus rates to take into account soil P levels in Australia is shown in Table 3.26 from Calcino *et al.* (2000).

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The adjustment of phosphorus rates to take into account soil P levels in Australia is shown in Table 3.26 from Calcino *et al.* (2000).

Table 3.26. Recommended phosphorus rates according to soil P levels (Australia).

Soil P level	Recommended P rate	
	Plant and replant	Ratoon
----*mg kg^{-1}*----	------------------*kg ha^{-1}*------------------	
<6[(1)]	80	25
6-10[(1)]	40	25
11-20[(1)]	25	25
21-40	20	20
>40	20	0

[(1)]On high P sorption soils an initial broadcast application of superphosphate at 1.25 mt ha-^{1} is recommended followed by 40 kg ha-^{1} P at planting.

Source: Calcino *et al.*, 2000.

The adjustment of K rates for soil reserves of P in Australia is shown in Table 3.27 from Calcino *et al.* (2000).

Table 3.27. Recommended K rates according to soil reserves.

Soil K level		Crop	K
			kg ha^{-1}
Low:	Exch. K <0.2 cmol(+)kg^{-1}	Plant	100
	Nitric K <0.2 cmol(+)kg^{-1}	Ratoon, replant	120
Intermediate:	Exch. K <0.2 cmol(+)kg^{-1}	Plant	80
	Nitric K 0.2-0.6 cmol(+)kg^{-1}	Ratoon, replant	100
High:	Exch. K <0.2 cmol(+)kg^{-1}	Plant	50
	Nitric K >0.6 cmol(+)kg^{-1}	Ratoon, replant	70
	Exch. K >0.2 cmol(+)kg^{-1}	Plant	50
	Nitric K <0.6 cmol(+)kg^{-1}	Ratoon, replant	50
	Exch. K >0.2 cmol(+)kg^{-1}	Plant	0
	Nitric K >0.6 cmol(+)kg^{-1}	Ratoon, replant	0-50

Source: Calcino *et al.*, 2000.

Rates of liming products used for correction of Ca and/or Mg deficiency are determined primarily from soil Ca analyses. Calcino *et al.* (2000) indicate that for Australian soils, where soil Ca is less than the critical value of 0.65 cmol(+)kg^{-1}, responses to lime are expected up to a soil Ca level of 1.0 cmol(+)kg^{-1}, and applications should be targeted at achieving soil levels of 1.5 cmol(+)kg^{-1} or above. Fig. 20 from Calcino *et al*. (2000) shows computed rates of different liming products to bring soil Ca levels to 1.5 cmol(+)kg^{-1} or above. In this figure, blends with 29 and 33% Ca represent blends of lime and Mg products supplying 5 and 3% Mg, respectively.

For Mg deficiency a similar strategy is adopted in Australia, as indicated in Table 3.28 from Calcino *et al.* (2000).Where more rapid correction of deficiency symptoms is required in an established crop, magnesium sulfate application at 300 kg ha^{-1} is recommended.

S applications may be warranted where soil or leaf analyses indicate marginal levels, where there is no significant addition of S in the usual fertilizer program or in irrigation water, and more commonly, on sandy soils. Recommended applications are 25 kg ha^{-1} S for deficient soils, and 10 kg ha^{-1} S for marginal levels of S in soil. This is typically supplied in special blends for such situations containing sulfate of ammonia. Other S sources include single superphosphate and gypsum (Calcino *et al.*, 2000).

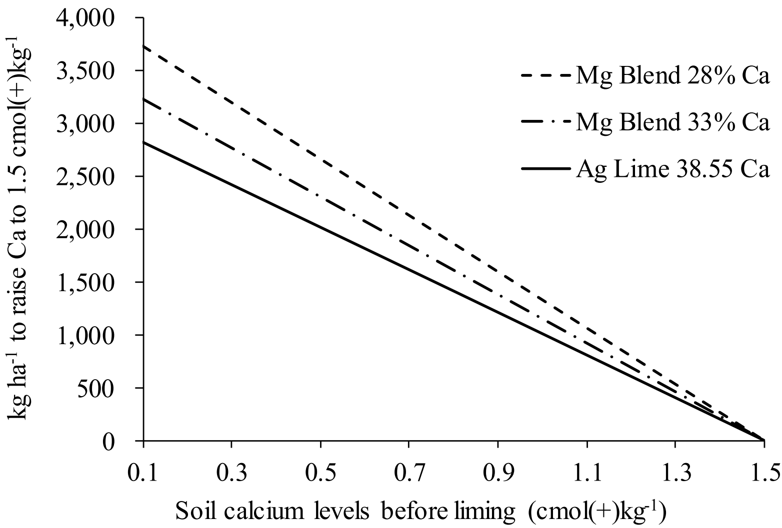


Fig. 20. Estimation of liming rates from soil Ca analyses.

Table 3.28. Mg rates for correction of deficiency.

Soil Mg	Situation	Product rate	Mg
cmol(+)kg^{-1}			*kg ha^{-1}*
<0.09	Likely response	MgO 300 kg ha^{-1}or Lime blend (5% Mg) @ 3.2 mt ha^{-1}	160
0.09-0.25	Possible response	MgO 150 kg ha^{-1} or Lime blend (3% Ca) @ 2.6 mt ha^{-1}	80
>0.25	Adequate Mg	No application	0

Source: Calcino *et al.*, 2000.

Where soil Si levels are low, and sunny side up symptoms were evident in previous crops, applications of 3-4 mt ha^{-1} calcium silicate or 3 mt ha^{-1} of cement are recommended (Calcino *et al.*, 2000). Sugar mill ash and filter cake/ash mixtures have also provided good yield responses on Si deficient soils.

Typical micronutrient application rates for deficient soils are summarized in Table 3.29. In Australia the only micronutrients applied routinely are Cu and Zn (Calcino *et al.*, 2000).

Table 3.29. Application rates and most common sources for micronutrients.

Micronutrient	Situation	Product	Nutrient rate
Cu	Low soil and/or leaf Cu, leaf symptoms, sandy soils	Cu fortified mixture or copper sulfate	10 kg ha^{-1} as Cu for crop cycle
Zn	Low soil and/or leaf Zn, leaf symptoms	Zn fortified mixture or zinc sulfate	10 kg ha^{-1} as Zn for crop cycle
Fn	Temporary leaf symptoms, treatment rarely warranted	Iron sulfate or iron chelate	5 kg ha^{-1} as Fe
Mn	Low leaf Mn, leaf symptoms	Manganese sulfate 20-30 kg ha^{-1}	5-8 kg ha^{-1} as Mn
B	Low leaf B, leaf symptoms	Borax 10 kg ha^{-1}	1.1 kg ha^{-1} as B
Mo	Low leaf Mo, leaf symptoms	Sodium molybdate 1 kg ha^{-1}	390 g ha^{-1} as Mo

Source: Calcino *et al.*, 2000.

3.6.5 Economics

The main objective of sugarcane growers in all countries is not to obtain maximum yields from fertilizer, but to obtain the maximum economic yield, bearing in mind preservation of soil fertility in the long term. Economic returns are a function of the incremental cane and sugar yield response to fertilizer, the cost of fertilizer, and the price paid for cane and its sucrose content. In Brazil rates of N, P and K are adjusted according to the ratio of price of cane (P) to cost per unit of fertilizer (C), taking into account the expected commercial yield response to N, P or K. Typical recommendations taking into account the P/C ratio are given in Tables 3.30, 3.31 and 3.32 (Orlando *et al.*, 1981; Martinho and Albuquerque, 1978).

Table 3.30. Recommendations for N fertilizer in ratoons according to the P/C ratio.

P/C ratio	N kg ha^{-1}
13	128
15	141
17	151
19	162
21	171

Source: Orlando *et al*., 1981; Marinho and Albuquerque, 1978.

Table 3.31. Recommendations for K fertilizer in plant cane according to the P/C ratio and soil test data.

P/C ratio	Soil test K (cmol(+)kg^{-1})(1)				
	<0.12	0.12-0.23	0.24-0.40	0.41-0.80	>0.80
	-------------------------*K applied kg* ha^{-1}-------------------------				
30	133	116	83	58	0-42
40	141	125	91	66	0-42
50	149	133	100	75	0-42

(1)Extracted by 0.5 N H_2SO_4

Source: Orlando *et al*., 1981; Marinho and Albuquerque, 1978.

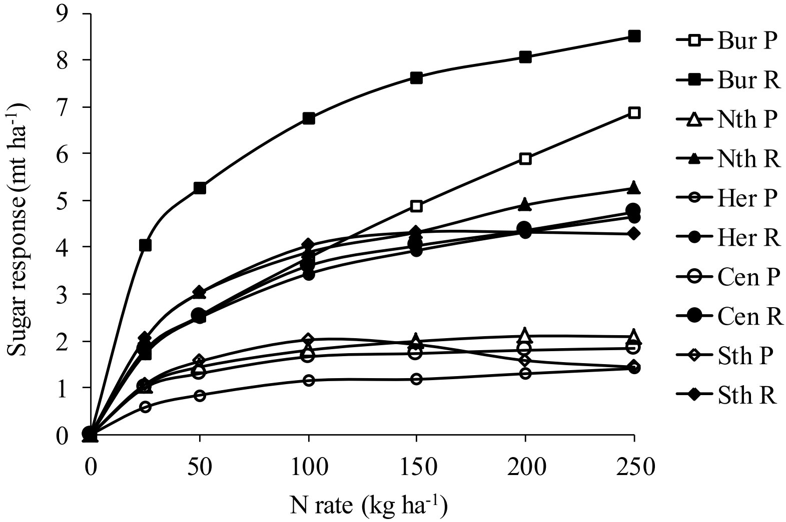
Table 3.32. Recommendations for P applications on plant cane according to P/C ratio and P soil test data.

P/C ratio	Soil test P (mg kg^{-1})(1)				
	<5	6-9	10-16	17-34	>34
	-------------------------*P applied kg* ha^{-1}-------------------------				
8	52	22	4	-	-
14	65	35	17	4	-
20	74	44	26	13	4
26	79	52	35	22	13
32	83	61	44	31	17

(1)Extracted by Mehlich 1.

Source: Orlando *et al*., 1981; Marinho and Albuquerque, 1978.

In general, N responses are lower in plant cane than ratoon cane and commercial N rates reflect this difference. Chapman (1994) presents data from five regions of the Australian sugar industry comparing responses to N in plant and ratoon crops (Fig. 21).



Note: P=plant; R=ratoon;
Bur=Burdekin, Nth=North Queensland, Her=Herbert, Cen=Central Queensland, Sth=South Queensland

Fig. 21. Mean sugar yield responses to N for plant and ratoon cane in five regions of Australia (Chapman, 1994).

Using the response curves in Fig. 21, Chapman derived nitrogen fertilizer rates for two different sugar prices, allowing for harvesting and fertilizer costs and a 15% return on the farmer's investment in fertilizer (Table 3.33).

In Australia the most reliable economic responses to P are obtained on new land as indicated in Fig. 22 (Bramley *et al.*, 1995). In the two trials soil P levels were approximately 11 mg kg^{-1}, and the standard P recommendation on new land would be 80 kg P ha^{-1}. There is a clear difference in the optimum P rate at the two sites, but responses at the recommended P rate are economically viable at both sites.

Malavolta (1994) quotes responses to P ranging from 4 to 89 mt ha^{-1} for a number of trials conducted in Brazil with a greater proportion of responses in plant cane than ratoon cane. In a significant proportion of cases responses would not be economic, and where there are moderate P reserves in soil commercial P, applications are likely to be reduced when sugar prices fall.

Table 3.33. N fertilizer recommendations based on sugar yield response curves and economic returns.

Sugar price	Crop class	Location	
		Burdekin	Other regions
		-------------*kg ha*$^{-1}$-------------	
<AUD300 per tonne	Plant	135	120
	Ratoon and replant	210	160
>AUD300 per tonne	Plant	150	120-150
	Ratoon and replant	270	160-200

Source: Chapman, 1994.

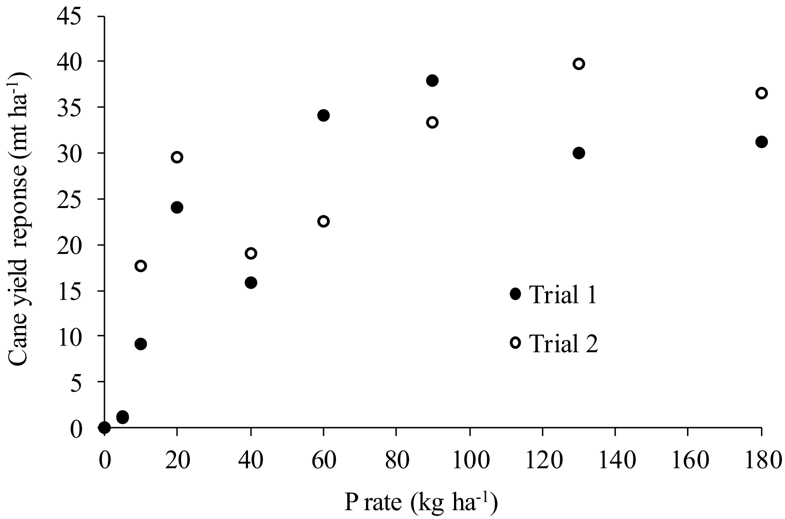


Fig. 22. Response of plant cane to P fertilizer on new land.

Fig. 23 shows the variable nature of responses to K fertiliser in historical Australian data. Malavolta (1994) quotes responses to K ranging from 1 to 38 mt ha^{-1} for a number of trials conducted in Brazil. At the lower end of the response range K application is likely to be uneconomic, and when cane prices are low, applications are likely to be reduced in soils with moderate K levels. This will result in some mining of K reserves in the soil.

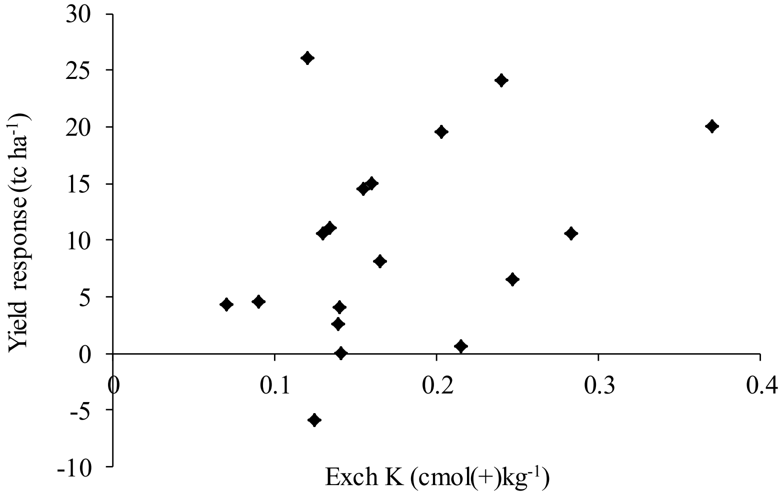


Fig. 23. Cane yield response versus exchangeable soil K (Schroeder *et al.*, 1998).

In many sugar producing countries soils are acidic, and without liming, there will be further acidification due to N fertilizer application in association with leaching. The impact of liming products and Mg on sugarcane yield and sugar content is shown in Table 3.34 for 12 sites in the North Queensland region of Australia (Ridge *et al.*, 1980).

Kingston *et al.* (1996) utilized data from the seven most responsive sites, and later trial results, to assess the economics of application of lime and related products to correct Ca deficiency, assuming, for example, that responses to a single application of lime would occur for five years. Relative net returns from different treatments, taking depression of sucrose percent into account, are summarised in Fig. 24. Relative net economic returns are expressed as a percentage of the maximum return from the cement treatment.

Table 3.34. Effect of liming products, Mg and micronutrients on cane yield and commercial cane sugar (CCS).

Soybean residue treatment	Cane yield	Sugar (CCS)
	------*mt ha^{-1}*------	--------*%*--------
Untreated	67.3	15.12
Magnesium sulphate	+10.3	+0.18
Lime	+14.4	-0.30
Lime plus magnesium sulphate	+25.8	-0.25
Lime+magnesium sulphate+Mn[(1)]	+27.8	-0.21
Cement	+28.4	-0.16
Cement+magnesium sulphate+Mn	+33.2	-0.21

[(1)]Mn represents a micronutrient mix.

Source: Ridge *et al.*, 1980.

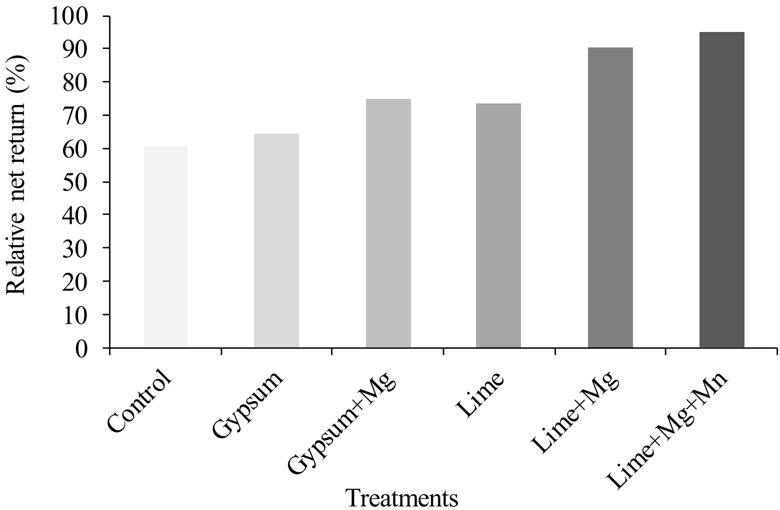


Fig. 24. Relative net returns from different liming products compared to maximum returns from cement where Mn refers to micronutrients (Kingston *et al.*, 1996).

Mallawaarachchi *et al.* (1998) reported on the long term benefits of liming in a trial in northern Australia where yields were monitored over an 18 year period. They calculated the net present value (NPV) of the income per ha for different liming strategies over a 15 year period (Table 3.35). It was concluded that the most economic liming program was an initial application of 5 mt ha^{-1} lime on Ca deficient soil, followed by 1.25 mt ha^{-1} each time the crop was replanted. For this treatment the sensitivity of NPV to percentage change in cane price and lime cost per tonne is given in Fig. 25.

Table 3.35. The NPV of income streams per ha for different liming strategies over a 15 year period.

		NPV (AUD)
T_1	Control, no liming	3,686
T_2	Lime 5 mt ha^{-1}; 1978	5,329
T_3	Lime 5 mt ha^{-1}; 1978 + 1.25 mt ha^{-1}; 1983, 1990	6,088
T_4	Lime 5 mt ha^{-1}; 1978 + 2.5 mt ha^{-1}; 1983, 1990	5,993
T_5	Lime 5 mt ha^{-1}; 1978, 1983, 1990	5,824

Source: Mallawaarachchi *et al.*, 1998.

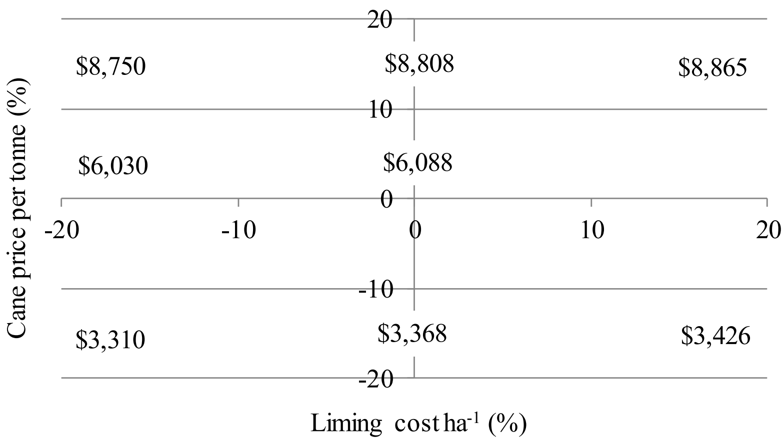


Fig. 25. Sensitivity of NPV to percentage change in cane price and lime cost (AUD) per tonne for the most economic treatment-T_3 (Mallawaarachchi *et al.*, 1998).

For soils with low S levels or where third leaf analysis showed low S levels, Chapman (1996) obtained variable yield responses to S applications in 16 trials throughout the Australian sugar industry. It was concluded that S should be included in fertilizer mixtures to supply 10-25 kg ha^{-1} S where there were low soil levels and no S was applied in irrigation water. It was noted that crop removal of S each year ranged from 25-48 mt ha^{-1}, and inclusion of S in the fertilizer program provided an insurance against yield losses and depletion of soil S.

The economics of micronutrient fertilizers is difficult to assess due to the localized nature of deficiency symptoms in most situations, but significant yield responses to Cu and Zn have been observed in Australia, Brazil and elsewhere. Isolated instances of responses to B and Mn have been recorded in Brazil (Malavolta, 1994). In India responses to foliar sprays of ferrous sulfate have been observed where lime induced iron chlorosis occurs. Again the economics of treatment are difficult to assess due to the temporary nature of iron chlorosis in many situations. Because of these uncertainties application of micronutrients in many cases is aimed at preventing yield losses in soils known to have marginal levels of particular micronutrients. In a survey of North Queensland soils in Australia, Reghenzani (1993) found that more than 15% had less than the critical value of 0.6 mg Zn kg^{-1} in a 0.1 M hydrochloric acid extract, with low values occurring mainly in metamorphic, beach sand ridge and granite derived soils.

In Australia historical commercial soil analysis databases also provide an index of the proportion of soils that are likely to be most responsive to different nutrients in the major districts (Cook *et al.*, 2002). Their findings, averaged for the period 1982 to 2002, are summarized in Table 3.36. In general the high fertility soils in the Burdekin region of Australia correspond to the lower end of the range for each nutrient. For B and Mn no deficiency symptoms have been observed despite the low soil values.

Table 3.36. Use of historical commercial soil analyses as an index of the areas giving the greatest economic response to different nutrients.

Nutrient	Critical level	Apparent deficiency
		----------%----------
N (% org. C)	<0.5%	4-10
P (H_2SO_4 extract)	<10 mg kg^{-1}	6-10
K (NH_4Ac extract)	<0.12 cmol(+)kg^{-1}	4-20
K (nitric acid extract)	<0.6 cmol(+)kg^{-1}	1-36
Ca (NH_4Ac)	<0.55 cmol(+)kg^{-1}	0.5-17
Mg (NH_4Ac)	<0.08 cmol(+)kg^{-1}	0.1-5
S (MCP)	<3 mg kg^{-1}	6-17
Zn (HCl)	<0.6 mg kg^{-1}	13-39
Cu (DTPA)	<0.22 mg kg^{-1}	1-22
Fe (DTPA)	<10 mg kg^{-1}	0.8-3.4
Mn (DTPA)	<5.9 mg kg^{-1}	12-41
B (hot water)	<0.15 mg kg^{-1}	3-19
Si ($CaCl_2$)	<10 mg kg^{-1}	2-37

Source: Cook *et al.*, 2002.

3.6.6 Environmental considerations

The proper management of sugarcane production should aim for high yields and economic returns while avoiding any detrimental impacts of fertilizers on the environment.

Potential concerns include off-farm movement of nutrients in runoff water, losses by leaching into the groundwater, and losses as greenhouse gases into the atmosphere. In all producing countries there is concern about such losses, and practices are aimed at achieving the most efficient use of applied fertilizer.

The adoption of green cane harvesting and trash blanketing is increasing, and this has a positive impact, due mainly to the reduction in soil erosion, but also due to the reduction in air pollution and greenhouse gas emissions from cane fires. The reduction in soil erosion is particularly important in reducing fertilizer movement attached to soil particles.

In Australia there is particular sensitivity to losses of fertilizer from cane farms due to the risk of discharge of nutrients into the Great Barrier Reef, and potential degradation of coral reefs and marine life. Farmers are now required to carry out regular soil testing to monitor and record nutrient levels in their soils, and to comply with recommended fertilizer practices. Larger farms are also required to have a fertilizer management plan to minimize off-site effects of fertilizer use.

Monitoring of nutrients in runoff from farms has shown typical figures of 3.5 kg ha^{-1} $year^{-1}$ of N, and 0.4 kg ha^{-1} $year^{-1}$ of P. The level of loss decreased from block to farm to catchment scale, reflecting the success of soil conservation measures and riparian vegetation in trapping nutrients and sediment (Hunter and Armour, 2001). The proportions of nutrients and amounts present in solution, or attached to sediment, change according to catchment slopes, soil conditions, fertilizer practices, and the level of trash blanketing (Reghenzani and Armour, 2002).

Research by Ham (2007) showed that surface placement of fertilizer, associated with furrow irrigation to wash in fertilizer, resulted in significant losses of N in runoff water, predominantly as NH_4-N, but including NO_3-N. Measures to combat this problem include a change back to sub-surface fertilizer placement, and the recycling of runoff water back to the fields.

Localised eutrophication effects have been observed in small streams adjacent to cane fields in Australia, particularly where there has been leaching of sugar and nutrients such as ammonium-N from trash blankets, and no doubt there are similar occurrences in other countries.

In green cane trash blanketed fields substantial losses of N as the greenhouse gas, nitrous oxide (N_2O), have been recorded under waterlogged conditions (Wang *et al.,* 2008). In soil with high organic matter annual N_20-N emissions were 12 kg ha^{-1} from unfertilized soil, and 28 kg ha^{-1} where 160 kg ha^{-1} of N was applied as urea. In soil with low organic matter levels, the loss was 3.6 kg ha^{-1} as N_20-N where 150 kg ha^{-1} N was applied as urea.

Where high nitrate levels are present in the soil in circumstances such as: following filter cake application; after incorporation of a good green manure crop; failure to adjust fertilizer N rates in high organic matter soils; or, where fertilizer N applications have been excessive, there is a risk of nitrate leaching to groundwater.

Thorburn *et al.* (2007) and researchers in Mauritius, propose the use of a ‘replacement strategy’ for N fertilizing to minimize such losses, and the potential environmental impact. N applications are adjusted to replace estimated removal at harvest of the previous crop, and environmental losses. They report that N reserves in the soil do not appear to have been ‘mined’ by this approach, and that N monitoring by NIR at the mill offers a promising technique for assessing crop N removal.

Ridge (2002) reported on voluntary guidelines for minimizing the off-site impact of fertilizer use in sugarcane. Some of the recommendations are:

- Timing of fertilizer applications to avoid periods where high runoff events are expected.
- Various measures to reduce soil erosion and to intercept nutrients and sediment in runoff before they reach streams.
- Adopting cultural practices to reduce losses of N by leaching, volatilization and denitrification, with particular emphasis on applying the minimum N rate to achieve yield objectives.

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Appendix: Visual Symptoms of Nutrient Deficiency

Nitrogen

Photo 1. Mature cane.
Source: Ridge, D.R., Australia.

Photo 2. Young cane.
Source: Calcino, D., BSES, Australia.

Poor plant growth, thin stalks. Pale green to yellow leaves, some dying back of old leaves.

Phosphorus

Photo 3. *Source:* http://advanceagricul-turalpractice, India.

Photo 4. *Source:* Ridge, D.R., Australia.

Tillering is poor, stalks are thin with short internodes. Leaves often have red or purple tips and margins, and may be otherwise dark green.

Potassium

Photo 5.
Source: Calcino, D., BSES, Australia.

Photo 6.
Source: Tiwari, K. IPRI, India.

In young crops lower leaves often turn yellow, with 'fired' margins and tips. Similar fired edges occur in more mature cane. There may also be dark red stripes between the leaf veins.

Sulfur

Photo 7 and 8. Vertisol soil. *Source:* Ridge, D.R., Australia.

Photo 9. Sandy soil.
Source: Hurney, A.P., BSES, Australia.

Leaves are narrower and shorter than normal, and stalks are slender and flexible. New leaves appear light green to yellow. Note comparison of healthy and deficient leaves

Calcium

Photo 10 and 11. Necrosis of leaf spindle. *Source:* Samuels, G; photo 10: Australia, photo 11: Florida/USA.

Photo 12. Typical Ca freckling in deficient soil where Mg was applied. Lime trial with untreated plot foreground.
Source: Ridge, D.R., Australia.

Spindles often become necrotic at the leaf tip, stalks are thin and taper at the growing point, tillering is poor and stalks are stunted, and typical leaf freckling develops, initially on younger leaves.

Magnesium

Photo 13 and 14.
Source: Hurney, A.P., BSES, Australia.

Photo 15.
Source: Anderson, D.L., Florida/USA.

Magnesium deficiency is first seen on older leaves, with red necrotic lesions developing and spreading to other leaves. This is often termed orange freckle.

Copper

Photo 16. Typical droopiness of leaves. *Source:* Kingston, G., BSES, Australia.

Photo 17. Typical green islands and leaf yellowing. *Source:* Ridge, D.R., Australia.

Leaves become droopy and stalks become rubbery. Small dark green patches or islands may develop on chlorotic leaves.

Zinc


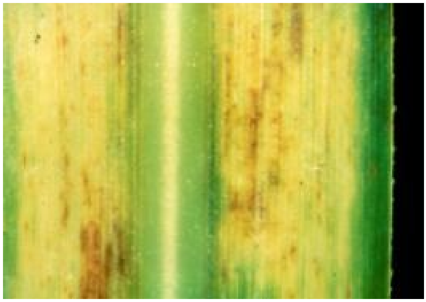

Photo 18 and 19. Interveinal yellowing, with midribs and leaf margins remaining green. Yellowing spreading and typical red fungal lesions on older leaves. *Source:* Reghenzani, J., Australia.

Photo 20. Leaf yellowing, and thin elastic stalks in mature cane. *Source:* Ridge, D.R., Australia.

Zinc deficiency symptoms typically become evident first on the third and older leaves. Broad bands of yellow stripes develop with midribs and leaf margins remaining green. Stalks become thin and elastic, and on some varieties there is infection by a red fungus, causing red lesions in the yellow bands. Symptoms are usually patchy in a field.

Iron

Photo 21. Typical patchiness of symptoms in the field.
Source: Ridge, D.R., Australia.

Photo 22. Typical iron deficiency on alkaline soil.
Source: Orlando Filho, J., Brazil.

Iron deficiency typically occurs first on younger leaves and symptoms are patchy. Young plants may overcome symptoms as the plant matures and the root system develops.

Silicon

Photo 23. *Source:* Bowen, J.E., Hawaii.

Young leaves develop yellow flecks which eventually coalesce to form a bronze freckle on the surface of older leaves that are exposed to the sun, termed sunny-side up. Symptoms appear on the edge of blocks in late summer-winter.

Manganese

Photo 24. *Source:* Bowen, J.E., Hawaii.

Photo 25. *Source:* Orlando Filho, J., Brazil.

Symptoms appear first on younger leaves as pale longitudinal stripes running from the middle of the leaf to the tip. The entire leaf may eventually become bleached.

Boron

Photo 26. *Source:* Gascho, G.J., Florida/USA.

Young plants tend to be brittle and bunched, with many tillers. Deficiency is uncommon, but may be induced by liming.

Molybdenum

Photo 27. *Source:* Bowen, J.E., Hawaii.

Short longitudinal streaks appear in the apical one third of the leaf. Similar to mild infections of Pokkah Boeng disease is rare but most likely to occur on acid soils.

Aluminium toxicity

Photo 28. *Source:* Ridge, D.R., Australia.

Occurs on acid sulfate soils, resulting in primary stalk death, and tillering from the base of the stalk. Tillers leaves become dark green, resembling P deficiency.