IPI
Bulletin 14

Fertilizing for High Yield
SUGARCANE

International Potash Institute
Basel/Switzerland

1994

IPI-Bulletin No. 14

Nutrient and Fertilizer Management in Sugarcane

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1994

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1. Introduction

Sugarcane, *Saccharum officinarum* L., an old energy source for human beings and, more recently, a replacement of fossil fuel for motor vehicles, was first grown in South East Asia and Western India. 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 was extended to nearly all tropical and subtropical regions. Portuguese and Spaniards took it to the New World early in the XVI century. It was introduced to the United States of America (Louisiana) around 1741. This historical summary is due to Aranha and Yahn (1987).

Botanically, sugarcane belongs to the *Andropogonae* tribe of the family *Gramineae*, order *Glumiflorae*, class *Monocotyledoneae*, subdivision *Angiospermae*, division *Embryophita siphonogama.* The subtribe is *Sacharae* and the genus, of course, *Saccharum*, derived from the Sanskrit "sarkara = white sugar", a reminder that the plant reached the Mediterranean region from India.

Most of the sugarcane which is grown today are hybrids of *S. officinarum* and other species with more rustic characteristics. According to Bacchi (1983), the sugarcane cultivars receive a designation which corresponds to the country wherein they were obtained. A few examples could be given: Argentina - NA; South Africa - N; Australia - Q; Brazil - CB, IAC, PB, RB and SP; Colombia - ICA; Cuba - C; USA - CP; Formosa - F; Philippines - Phil; India - Co; Indonesia - POJ; Peru - PCG; Egypt - E; Puerto Rico - PR; and Mauritius - M. The sigla is usually followed by three or more digits.

As shown in Table I, the total area harvested in the year 1992 according to FAO (1992) amounted to nearly 18 million hectares which yielded 1.1 billion metric tons with a productivity of 61 tons per ha, this is 5 tons higher than the average yield in the period 1979-81. Leading producers of sugarcane are Brazil, India and China, in this order. With respect to productivity comparison is difficult since the number of ratoons could vary from one region to another. Another factor to consider is irrigation which is practiced in certain countries, Colombia for instance. Sugar production (centrifugal plus non centrifugal) is higher in India than in Brazil due to the fact that in the latter a large proportion of cane is diverted to alcohol to be used extensively in motor vehicles instead of gasoline.

Table 1. World production of sugarcane.

Country or region	1000 ha 1979-81	 1992	MT/ha 1979-81	 1992	1000 MT 1979-81	 1992
World	13570	17934	56	61	769365	1104580
Africa	955	1243	64	57	61758	71369
Egypt	105	112	83	103	8738	11624
Mauritius	79	78	68	82	5393	6400
South Africa	229	260	75	71	17345	187500
N.C. America	2906	2901	58	57	170487	166281
Cuba	1305	1200	53	48	69322	58000
Mexico	535	576	66	69	35234	39955
USA	300	356	81	75	24465	26703
S. America	3681	5251	58	66	215013	347649
Argentina	325	280	48	66	15607	18500
Brazil	2657	45207	55	66	147824	270672
Colombia	284	315	86	92	24667	28930
Asia	5666	8110	52	60	294547	485854
China	624	1263	54	61	33848	77548
India	2788	3882	52	64	144912	249300
Philippines	425	330	74	82	31511	27300
Europe	6	2	57	85	324	174
Portugal	2	-	21	80	23	4
Spain	4	2	67	85	301	170
Oceania	356	428	76	78	27236	33253
Australia	290	348	80	84	23407	29300
Fiji	65	73	58	48	3785	3500
Papua N. Guinea	1	7	40	66	41	450

FAO (1992).

2. Botany and physiology

Sugarcane is a perennial grass very efficient in "harvesting the sun", that is, in converting sun's energy into sugar and fiber.

The books by Dillewijn (1952) and Alexander (1972) and the review by Burr *et al.* (1957) are classical sources of information on various aspects of the botany and physiology of the sugarcane plant.

Propagation: Sugarcane is propagated by cuttings or sections of the stalks called sets, points or seed pieces. Each set contains one or more buds and a circle of small dots above the node which are the root primordia. The buds, when germinating, give rise to the primary shoots whereas from the primordia the set roots originate. Secondary shoots and new roots are formed from the primary shoot. Later on tertiary shoots are produced. During nearly one month after germination, that is, sprouting of the buds, the young plant lives at the expense of the reserves present in the seed piece, and partially using water and nutrients provided for by the first roots.

Roots: The roots formed from the set die off when the roots from the shoots start to develop and take over their functions of absorption and anchorage. In the adult plant there are three classes of roots. The superficial roots come from primordia far from the base of the shoot, are 0.5 to 2.5 m long and branch abundantly. They are capable of supplying large quantities both of water and nutrients. The buttress roots originate near the base of the shoot grow at angles of 45-60 degrees to a length of 0.5 to 1.5 m. Their chief function is anchorage. Finally the rope system is characterized by growing downwards to depth of 5-6 m and for branching in the lower soil profile (Halliday, 1956). Root distribution is discussed by Casagrande (1991). Results obtained in Brazil and other regions point to the fact that the upper 30 cm contain 40 to 60% of the total root weight; 20-30% are present between 30 and 60 cm. Root development is influenced by moisture, pore distribution, soil density and presence of nutrients particularly P and Ca; it seems that sugarcane is relatively tolerant to toxic Al, although varietal differences are known.

Stubble or root stock: Stubble or root stock is the part of the shoot below the soil surface being composed of a number of sections or internodes. Stool designates the group of shoots which develop from a bud on a set. When the plant is harvested usually by cutting the stems or stalks close to the soil surface, the buds in the shoots underground begin to sprout thereby giving rise to primary, secondary and tertiary shoots as before. When the plant is cut the root system remains functional for some time and then is gradually replaced by the roots from the new shoots of the next crop (the ratoon).

Tillering: The process of stool formation through successive production of shoots is called tillering. It is influenced by several factors such as light, temperature, water and nutrients, density of planting (distance between rows), depth of planting, pests and diseases and time of planting. According to Bull and Glasziou (1978) as many as 144 stalks have been recorded in a stool arising from a one bud set. In practice, however, the number is smaller. The stalk or stem is cylindrical in shape with an average length of about 4 m.

Its fiber content varies from 9 to 17% depending upon variety and growth conditions. The sucrose content, in its turn also influenced by variety, growth conditions and age, can vary from 7 to 13%, as a rule although varieties exist which are even richer. The number of stalks per unit area is the single factor most closely related to yield (Nickell, 1977).

Leaves: The leaf of the sugarcane plant consists of a blade (2-10 cm wide, 1-2 m long) with a distinct midrib and a sheath joined by a portion of tissue called dewlap, "collar" or leaf triangle. The leaves are numbered by Kuijper's system, as quoted by Casagrande (1991). The first leaf from top to bottom of the stalk with clearly visible dewlap is designated as +1. Downwards they receive, in succession, the numbers +2, and +3. Usually leaf +3 is considered recently mature, being used in the evaluation of the nutritional status (see Figures 1 and 2, redrawn from Casagrande, 1991).

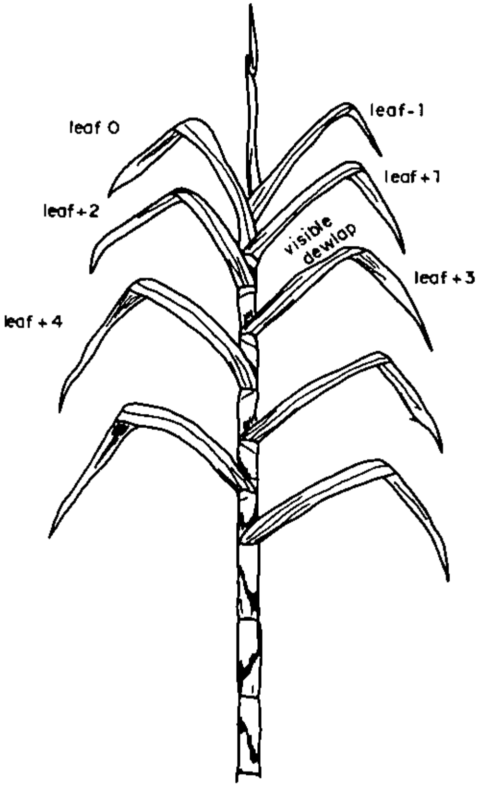

Fig. 1. System of numbering the leaves of sugarcane according to Kuijper.

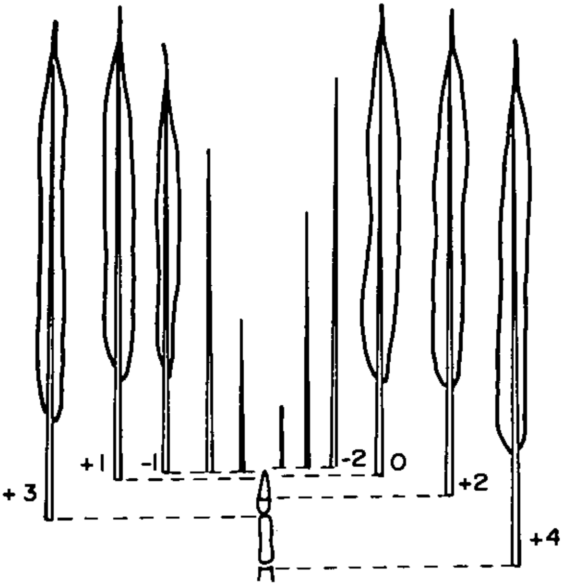

Fig. 2. Detail of the system of numbering the leaves.

Inflorescence: The inflorescence (arrow or tassel) has many spikelets which contain complete flowers. Flowering, which depends largely on the relative length of days and nights, leads to a consumption of stored sugar and therefore, to a decrease in the sucrose yield.

Photosynthesis and sugar storage: The pioneer work carried out in the late 1940s by the Hawaiian Sugar Cane Planters Experiment Station, using $^{14}CO_2$ to study photosynthesis, revealed that malate was the main labelled compound, instead of 3-phosphoglyceric, as was the case of other plants which fix carbon according to the Calvin cycle. It was also found that with time, the label from malate was transferred into 3-phosphoglyceric acid. The sugarcane pathway - C_4 or dicarboxylic acid pathway - operates in other species as well and seems to have some unique anatomical features. Sugarcane and other C_4 plants have their chloroplasts located in a layer of mesophyll and an adjacent layer of bundle sheath cells which surrounds the vascular bundle. The chloroplasts in the mesophyll cells do not usually accumulate starch, whereas those of the bundle sheath cells have either no or very reduced grana and accumulate starch (Bull and Glasziou, 1978). The mesophyll cells first fix CO_2 as oxaloacetate which is then reduced to malate.

Malate is transported to the bundle sheath cells wherein it undergoes decarboxylation giving CO_2 and pyruvate, CO_2 enters into the Calvin cycle generating 3-phosphoglyceric acid. The transfer of sucrose, the end product of photosynthesis, from the mesophyll cells to the phloem vascular system involves the movement through the plasmalemma and the cell wall. This transport depends upon the supply of metabolic energy, and takes place thanks to a sucrose carrier which is associated with the transport of potassium (Mascarenhas, 1987). While photosynthesis takes place, part of the sucrose goes from the chloroplast into the cytosol and is exported to other regions of the plant. Part is temporarily stored in the leaves, especially in the vacuoles. Both the starch and the sucrose which were stored can be mobilized and transported or consumed in respiration. The movement of sucrose from the leaf into the stalks has been studied by Hartt *et al.* (1963) who used $^{14}CO_2$. They observed that the label was dispersed in the leaf blade tending, however, to funnel into the direction of the sheath. Since the leaf sheath surrounds the stalk, distribution is uniform over the whole circumference. The labelled ^{14}C next reaches the node wherein the sheath was fixed and afterwards continues to move via xylem and phloem to the upper parts and to the roots. Sugarcane is considered a highly efficient plant in the conversion of light into chemical energy. Photosynthetic rates of 100 mg CO_2 fixed per square dm of leaf per hour have been estimated. High biomass production, however, seems to be more dependent on other factors: large photosynthesis per unit area which is influenced by the leaf area index (LAI) and long cycle of production.

Growth habit, maturation and yields: The growth habits of sugarcane show differences due to the variety. Usually, however, stalks 2-4 m long are produced per year, at the rate of 3 nodes per month. As a rule, the first harvest of the plant cane is done after 12 or 18 months. There are variations among regions: in parts of Thailand for instance, the first harvest takes place after 10 months only whereas in Hawaii it occurs after 24 months (Cavalcante Jr., 1994, private communication). The successive ratoons are harvested after 12 months of growth. The number of economical ratoons depends upon variety, climatic, soil and management conditions, including how harvesting is done. Two ratoons are common. Under favourable conditions up to 6-7 could be obtained. Burning leaves, sometimes with a flame thrower (Texas, Louisiana, for example), is a routine to make harvesting (either mechanical or manual) easier. This of course, means loss of nutrients particularly N and S. According to Casagrande (1991), dry matter production of the top as a function of time obeys a sigmoidal curve.

There is an initial phase of slow growth of about 6-7 months followed by a fast one which lasts for another 6-7 months.

There is an initial phase of slow growth of about 6-7 months, followed by a fast one which lasts for another 6-7 months. In this second phase, about 75% of the dry matter of the top is accumulated. Finally in the last 3 months or so, growth slows down and 11% of the biomass is produced. Dry matter formation rates of 7, 14 and 18 g m^{-2} per day have been recorded in Brazil and in the USA (Louisiana).

Yields vary from region to region and within a region due to variety soil and climatic conditions as chief factors. Usually plant cane yields more than the ratoons. Humbert and Ulrich (1969) quote yields in the extreme range from 36 to 240 tons per hectare.

In most sugarcane growing regions, the harvest time coincides with a period of drought (or much less rain) and lower temperature which favours the accumulation of sucrose in the stalks. Even when such conditions prevail ripening can be induced by chemicals such as "Polaris" (Nickell, 1977). The ripener causes vegetative growth to stop and sugar to build up.

3. Soil and climate

Sugarcane is grown in the belt 35°N and 35°S, from sea level to 1000 m of altitude or a little more, on a wide diversity of soil types (see Figure 3).

Chemical constraints in the soils, such as acidity and low fertility, are relatively easy to correct or control. Poor physical conditions, however, when limiting, are much more difficult to ameliorate. For this reason, Humbert (1968) in his discussion of soil as a factor in sugarcane growth, gives much emphasis to the physical properties. This is undoubtedly due to a large extent, to the fact that the intense mechanization, involving traffic of heavy machinery from planting to harvesting and transporting to the sugar mill or distillery, can cause the deterioration of soil physical conditions. This translates into compaction with a cohort of harmful side effects: reduction in storage and movement of air and water, mechanical difficulty for root growth, difficulty in the absorption of nutrients from the soil itself and from the fertilizer.

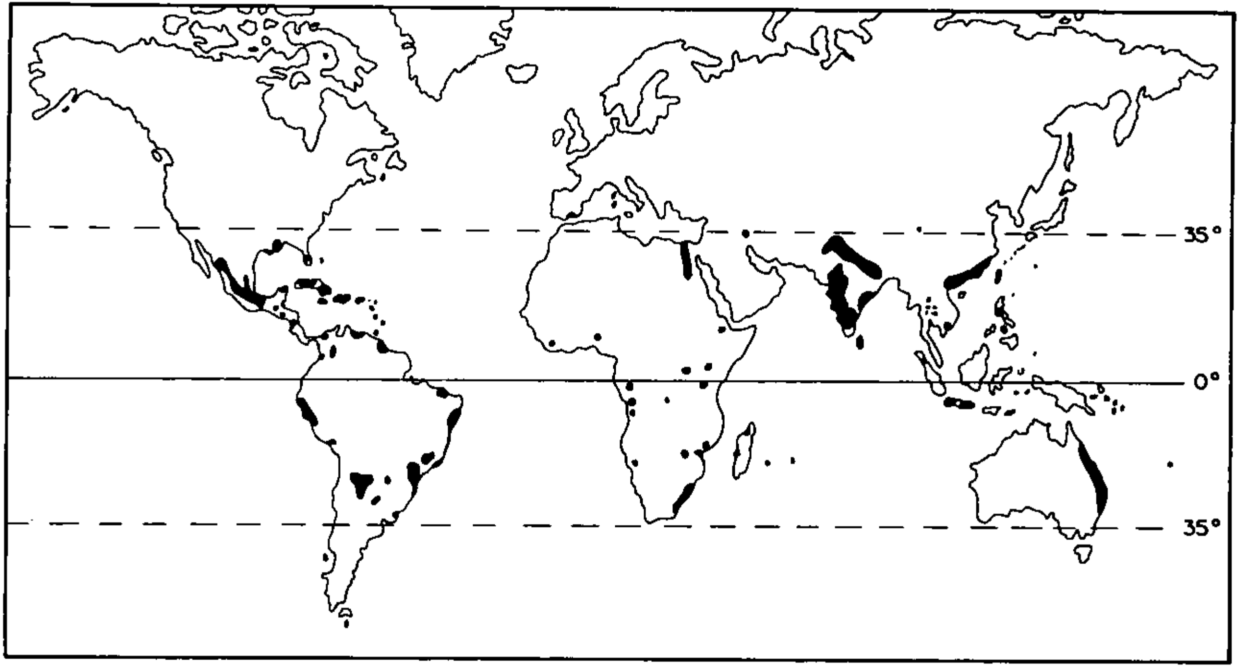

Fig. 3. The main sugarcane growing areas (redrawn from Fauconnier and Bassereau, 1975).

Eventually mechanical methods (subsoiling or chiseling or deep plowing) or biological means (green manuring between last ratoon harvest and start of a new crop) have to be used to destroy the compacted layer and allow roots to develop normally. It seems that good physical conditions exist when bulk density is between 1.1 - 1.2 (1.3 in sandy soils) and total porosity, with an adequate balance between pores of various sizes, is higher than 50%. When the volume of pores is lower, root degradation takes place. Based on the experience gained in Brazil, Kofeler and Bonzelli (1987) suggested a few criteria to define soils which are apt for sugarcane growing.

As seen in Table 2, several physical features have to be considered. Shallow soils subject to the invasion by the rising water table can sometimes be planted as long as drainage and mounds are provided. A soil depth of less than 1.5 m or so can restrict growth making the plant more susceptible to drought and less efficient in the use of nutrients. The restriction to mechanization, one of the criteria in Table 2 does not apply in case of small holdings in which all operations are manual or by animal power.

Table 2. Criteria to classify the aptitude of soils for growing sugarcane.

Characteristics	Classes			
	Good	Average	Restricted	Unfit
Effective depth	Deep	Medium	Shallow	Too shallow
Texture	Clayey	Medium too clayey	Sandy	Too sandy
Relief	Flat	Rolling	Too rolling	Hilly
Fertility	High	Medium or low	Too low	-
Drainage	Good	Medium to accentuated or incomplete	Incomplete	Excessive, Deficient
Restraints to mechanization	Absent	Medium	Strong	Too strong
Susceptibility to erosion	Low	Medium	High	Too high

The diversity of soils whereon sugarcane is grown can be illustrated with examples of a few selected regions, presented in alphabetical order. Information on Australia, Cuba, India, South Africa and the U.S.A. were taken from Halliday (1956). An attempt was made to give the classification of the soils by the U.S. Taxonomy using the maps published by Aubert and Tavernier (1975) and by Sanchez (1976).

Australia: The soils consist of residuals and alluvials granite and schist and red volcanic loams (Ultisols and Vertisols).

Brazil: There are three main sugarcane regions, two located in the Southeast (São Paulo and Rio de Janeiro) and one in the Northeast (the states of Alagoas and Pernambuco). In the State of São Paulo almost half of the area (47%) is represented by the Great Group Latosol Roxo (Eutrustox or Eutrorthox), soils derived from basic eruptive rocks, very deep and well drained with 40-60% clay and with large variation in exchangeable bases. Next comes the Red Yellow Latosol (Ustox or Orthox), with a participation of 13%, derived from sandstone with 15-30% clay, well drained and deep. Sandy Red Yellow Podzolic (Ultisols and Alfisols) represents about 10%. In the other Southern region, the State of Rio de Janeiro, closer to the Atlantic Ocean Ustox or Orthox and Ultisols contributes with 53% of the total area. Hydromorphic soils cover 38%; since water is present during part of the year, drainage is essential. Finally in the Northeast, Ustox or Orthox, Ultisols and Alfisols put together constitute three fourths of the area. Both in the Northeast and in the region of the State of São Paulo, which is the leader in sugar and alcohol production in Brazil, Red and Yellow Sands (Psamments) of exceedingly low cation exchange capacity (CEC) and fertility, are also cultivated. Table 3, slightly modified from Malavolta and Kliemann (1985; p. 13) presents on interpretation of the fertility level of Brazilian soils, in the arable layer. As a rule, sugarcane soils when first cultivated fall within the low or medium category. By the use of lime, fertilizers and residues such as filter press cake, vinasse, composted bagasse, and green manuring, fertility level is raised up to the adequate class. Further details on sugarcane soils of Brazil are given by Orlando and Zambello Jr. (1983).

Colombia: Data on soils from Colombia are supplied by Guerrero (1991) and by Garcia Ocampo (1991). The main sugarcane growing region is the Valle del Cauca. Mollisols, soils with base saturation above 50%, deep and well drained, with good fertility occupy around 1/3 of the total area. Vertisols, very rich in montmorillonite come next; these soils show cracks when dry and expand when moist. Inceptisols with fine to medium texture, CEC from medium to high, occupy about the same area as the Mollisols. Other soil types, on smaller areas, are Alfisols, Entisols and Ultisols.

Cuba: The chief features of the soils in Middle and Eastern Cuba are their depth and high clay content. The red Matanzas clay, although having more than 90% clay drains easily from the surface down to the limestone rock underlying sometimes 7 m or more below. In the Oriente region friable clay soils cover a serpentine deposit 15 m deep. In Western Cuba sandy soils represent a sharp contrast with the others. Most of the Cuba soils are Mollisols.

Table 3. Interpretation of chemical characteristics of Brazilian soils (1).

Element	Low	Medium	Adequate or high
N%	< 0.09	0.09 -0.14	> 0.14
pH (in H_2O)	< 5.0	5.0 - 6.0	6.1 - 6.5
P μg/cm^3			
Mehlich 1	< 5	5 - 10	11 - 20
Resin	< 10	10 - 20	21 - 30
Exchangeable			
K meq/100 cm^3	< 0.10	0.10 -0.24	0.25 -0.30
% CEC	< 2	2 - 3.9	4 - 5
Ca meq/100 cm^3	< 1.5	1.5 - 4	4 - 5
% CEC	< 20	20 - 30	30 - 50
Mg meq/100 cm^3	< 0.5	0.5 - 1.0	1.0 - 1.5
% CEC	< 5	5 - 10	11 - 15
Al meq/100 cm^3	< 0.4	0.4 - 0.6	0.7 - 1.0
Saturation (m)	< 20	20 - 40	> 40
V%	< 25	25 - 49	50- 60
S-SO_4 μg/cm^3	< 5	5 - 10	11 - 15
B ppm	< 0.10	0.10 -0.30	0.4 - 0.5
Cu	< 0.4	0.4 - 0.7	0.8 - 1.2
Fe	< 20	20 - 30	31 - 40
Mn	< 3	3 - 5	6 - 10
Zn	< 0.5	0.5 - 1	1 - 2

(1) S-SO_4 in ammonium acetate +acetic acid;
B on hot water; Cu, Fe, Mn and Mg in Mehlich.

India: Sugarcane is grown in two belts. The first is situated on the Indo-Gangetic alluvium, a tract of "drift soil". The second belt lies on the "residual soils" of the peninsula. The soils of the northern belt are more fertile. In the first region the following orders prevail: Alfisols and Ultisols. In the peninsula Vertisols, Inceptisols and Alfisols are found.

South Africa: The soils of the sugar belt were originally classified as follows: (a) recent sands, reddish or grey low in organic matter; (b) alluvial soils, acid to alkaline, often with high water table; (c) derived from conglomerate, shallow and with iron gravel layer on top of clay; (d) derived from shales; (e) derived from basalts and dolerites, fertile, deep, with 30-40% clay, acid; (f) derived from sandstone, depth and fertility variable; (g) derived from granite, shallow to deep, infertile; (h) derived from sandstone or dolorite, acid, rich in organic matter. Alfisols, Ultisols and Oxisols are the main soil orders.

USA: In Louisiana the soils are largely of alluvial origin (Mississippi alluvium and Red River sediments) and the coastal prairie soils. They are Inceptisols and Ultisols. The pH is usually near neutrality, with medium texture, sometimes organic. The soils of Florida contain 40-50% organic matter, high pH and as much as 5% calcium oxide. They commonly belong to the Histosols order. In the Hawaiian islands Ultisols and Inceptisols are the main orders. Alfisols and Ultisols support the crop in Texas.

Humbert (1968) characterizes the *"ideal" climate* to grow sugarcane for sugar production as follows: (1) a long, warm summer growing season with adequate rainfall - the plant uses from 148 to 300 g of water to produce 1 g of dry substance (Burr *et al.*, 1957). (2) a fairly sunny and cool but frost free season for ripening and harvesting - moisture percentage drops steadily throughout the life of the sugarcane plant, from 83% in very young cane to 71% in mature cane, meanwhile sucrose grows from less than 10 to more than 45% of the dry weight (Burr *et al.*, 1957). (3) typhoon and hurricane free. The subject is detailed by Fauconnier and Bassereau (1975) and by Alfonsi (1987). Quantitative aspects of ecological factors as related to growth and yield are discussed by Clements (1980).

Growth is closely related to temperature. It slows down below 25°C, reaches a plateau between 30-34°C, is reduced above 35°C and practically stops when the temperature is higher than 38°C. Temperatures lower than 0° induces freezing of less protected parts such as young leaves and lateral buds. The damage depends upon the length of the cold period. Being a C_4 plant, sugarcane is capable of high photosynthetic rates and the process shows a high saturation range with regards to light. Stalk growth increases when daylight is within the range of 10-14 h. A total rainfall between 1100 and 1500 mm is usually sufficient provided the distribution is right: abundant in the months of vegetative growth followed by a dry period for ripening. When temperatures and rainfall are high during the year vegetative growth continues at the expense of the sugar yield. This seems to be the case in regions of South America and South East Asia.

4. Mineral nutrition

The soil-plant-atmosphere system can be represented as shown in Figure 4 in which the place of the fertilizer and amendment is indicated.

M stands for a macronutrient, that is, nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulphur (S) or for a micronutrient, namely boron (B), chlorine (Cl), cobalt (Co), copper (Cu), iron

(Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), silicon (Si), zinc (Zn), and possibly (since sugarcane is a C_4 plant), sodium (Na).

Solid phase means organic matter and the mineral fraction which are sources or reservoirs of M. Labile phase corresponds to the exchange complex. Soil solution is the immediate supplier of nutrients to the plant. M (atmosphere) in the particular case of sugarcane represents principally N and S from burning of trash as a preliminary operation to cutting the stalks.

The meaning of the various digits in the transfer reactions is the following:

1. weathering, mineralization
-1. fixation, immobilization
2. desorption
-2. adsorption
3. uptake
-3. excretion, loss
4. long distance transport
-4. translocation, circulation
5. erosion
6. leaching
-6. capillary ascent
7. addition of limestone or phosphogypsum
8. fertilization
9. burning
-9. deposition (rainfall or other)

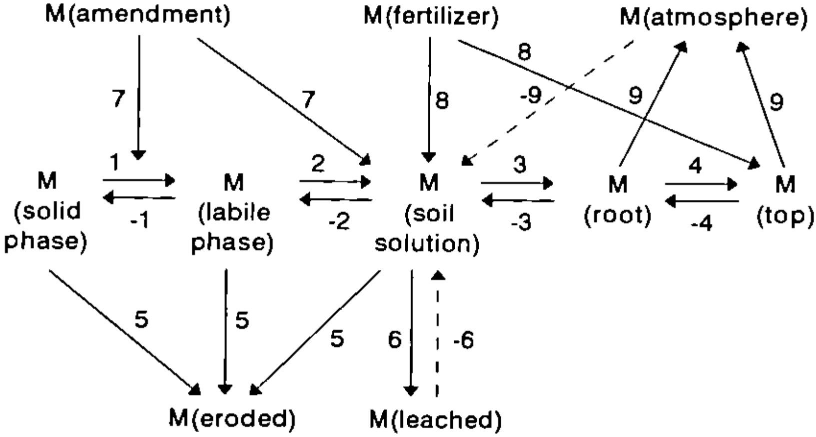

Fig. 4. The soil-plant-atmosphere system-compartments and transfer reactions.

As shown in Figure 4, the addition of amendments, usually to correct surface and subsurface acidity, also influences transfer reactions related to availability (1,2) and adds nutrients to the soil solution (Ca, Mg, S).

Fertilization practice consists simply in adding an element to the soil solution whenever the demand by the plant exceeds the soil supplying capacity, that is:

M (fertilizer) = M (demand - supply) × F

wherein F is a factor greater than one, variable with M and local conditions, destined to compensate for the various losses indicated in the scheme.

4.1. Accumulation of nutrients

The patterns of uptake of nutrients and build up of biomass as a function of time are described by parallel, sigmoid curves. Dillewijn (1952) gave one of the first examples showing the amounts of N, P, K, Ca and Mg removed by the entire stool (tops and roots) in a 10 month cycle. Similar studies were made in other regions usually however measuring and analysing only the above ground portion (stems and leaves). The same pattern holds.

Data obtained by Orlando Filho (1978) were used by Malavolta (1982) to prepare Figs. 5 and 6 which describe, respectively, accumulation of biomass and of macronutrients by the variety CB 41-76 under Brazilian conditions.

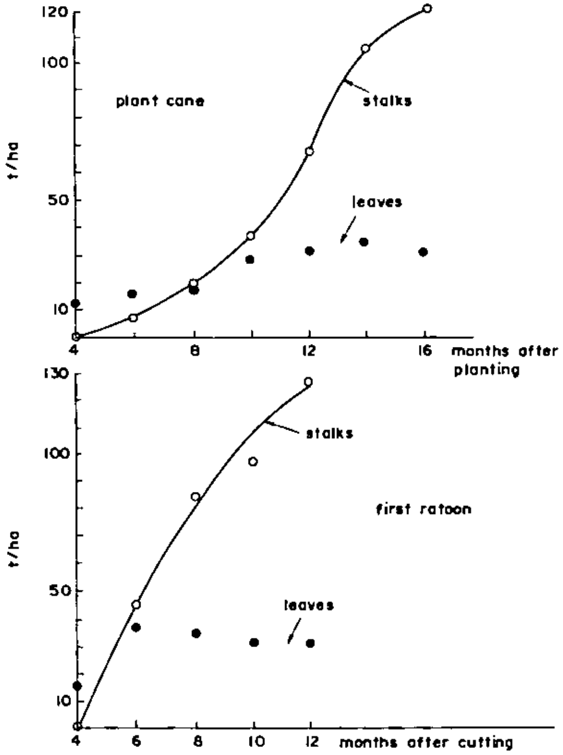

Fig. 5. Growth curves of variety CB 41-76 (fresh weight).

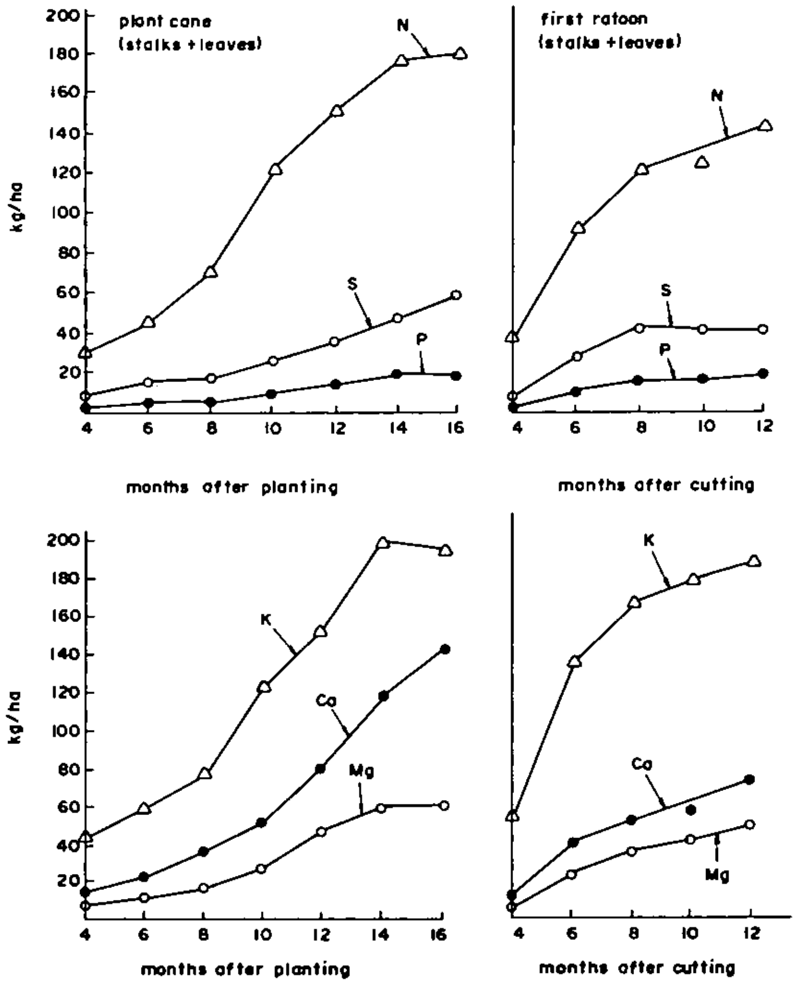

Fig. 6. Absorption of macronutrients by the variety CB 41-76.

A comparison of the two figures shows that both for plant cane and first ratoon there is a close relationship between increase in stalk production and accumulation of N and K which suggests that these two elements "go together" in the nutrition and fertilization of the sugarcane plant.

The maximum velocity of uptake in the period of higher growth rate is given in Table 4.

Table 4. Maximum rate of uptake of macronutrients by plant cane and first ratoon.

Element	Plant cane 8-14 months (180 days)	First ratoon 4-8 months (120 days)
	kg ha^{-1} day^{-1}	
N	0.59	0.73
P	0.08	0.11
K	0.71	0.95
Ca	0.45	0.33
Mg	0.24	0.26
S	0.16	0.31

Actually the soil reservoir has to supply even larger quantities since the amounts contained in the roots were not included. In case this cannot take place the fertilizers have to compensate. It should be noted that absorption by the ratoon crop per unit time is greater than that by plant cane. A comparison of the curves of the two crops indicated that plant cane should receive part of the required N after planting in order to reduce leaching losses and to meet the need which is higher at a later stage. The same should be done with respect to K on sandy soils whereon leaching could be appreciable. The fertilization of the ratoon with regard to both N and K has to be made shortly after harvesting the plant cane so that the plant could reform its root system more rapidly and have the elements in quantities sufficient to meet the demand of the stalks and leaves.

Table 5 gives the accumulation of micronutrients. As a rule the same pattern observed with the macronutrients prevails, that is small quantities are taken up in the beginning of the cycle. This is followed by a period of greater absorption and, finally, there is a tendency to level off. In the case of the variety Co 419 the final fresh weights of stalks and leaves were, respectively, 101 and 30 metric tons per hectare.

4.2. Extraction, export and losses of nutrients

Clements (1980) wrote that "To become well acquainted with any element in the nutrition of a crop plant, it is necessary to start by analyzing all the various parts of the plant from several crops, throughout the full growing period under field conditions". It seems that such complete information is not available in the case of the particular crop the late Dr. Clements was talking about, that is, sugarcane.

Table 5. Accumulation of micronutrients in stalks + leaves of the variety CB 41-76 (1).

Age (months)	B		Cu		Fe		Mn		Mo		Zn	
	st	le	st	le	st	le	st	le	st	le	st	le
	g ha^{-1}											
4 plant cane	1.8	31	3.1	29	62	2145	30	363	-	-	10	71
4 1st ratoon	1.0	23	3.5	52	125	4774	18	415	-	-	6	60
6 plant cane	11	51	11	59	283	4006	64	642	-	-	27	107
6 1st ratoon	35	54	57	105	2979	13714	166	978	-	-	117	153
8 plant cane	28	66	36	75	604	2682	196	907	0.4	0.8	77	181
8 1st ratoon	96	73	170	181	1770	9816	831	933	-	-	212	217
10 plant cane	79	81	60	65	1114	5023	416	1173	21.3	1.9	155	204
10 1st ratoon	87	56	237	107	929	8458	891	1496	-	-	270	202
12 plant cane	147	116	119	121	1719	8218	618	1526	1.9	0.6	278	310
12 1st ratoon	116	61	307	145	1350	3521	957	1315	-	-	341	179
14 plant cane	235	129	194	167	3242	13394	1212	1741	1.3	4.0	381	396
16 plant cane	249	139	243	98	3130	7018	1331	1915	-	-	573	352

(1) Data for Mo refer to variety Co 419, estimated from Gloria *et al.* (1964). Data for variety CB 41-76 taken from Sobral and Weber (1983).

st = stalks; le = leaves

Table 6. The nutrient content of sugarcane plant parts (1).

Part	% dry matter							ppm dry matter					
	N	P	K	Ca	Mg	S	Cl	B	Cu	Fe	Mn	Mo	Zn
Meristem	1.77	0.51	4.48	0.42	0.26	0.34	0.240	7	11	78	23	1.6	153
Spindle cluster	1.30	0.14	2.14	0.17	0.06	0.12	0.100	2	4	54	9	1.8	30
Young blades	1.18	0.10	1.67	0.24	0.05	0.11	0.036	6	4	68	11	2.0	17
Old blades	0.89	0.07	1.33	0.20	0.09	0.13	0.004	4	5	80	16	2.7	17
Young sheaths	0.45	0.06	2.66	0.18	0.07	0.24	0.076	1.5	3	35	6	2.1	14
Old sheaths	0.31	0.04	1.95	1.17	0.07	0.35	-	2	5	52	15	3.3	12
Green leaf cane	0.42	0.06	2.00	0.09	0.07	0.08	0.008	1.5	4	27	2	0.5	19
Top internode	0.20	0.03	1.15	0.04	-	-	-	-	-	-	-	-	-
Middle internodes	0.14	0.03	0.77	0.03	-	-	-	-	-	-	-	-	-
Bottomost internodes	0.19	-	0.36	-	-	-	-	-	-	-	-	-	-

(1) Plant cane about 12 months old, cycle of 24 months, in the case of N, P, K, and Ca.
Plants from sand culture in the case of all other elements.

Part of his contibution nevertheless is summarized in Table 6 as an example. All the elements, with the possible exception of Mo, are present in higher concentration at the meristems, the growing part. Potassium content exceeds that of any other element in all parts analyzed. Generally speaking, the content of the macro- and micronutrients in the plant obeys the following decreasing order:

K > N > P > Ca > S > Mg > Cl > Fe > Zn > Mn > Cu > B > Mo.

Most of the published data on the mineral requirements of sugarcane refer only to the above ground parts, that is stalks and leaves. Table 7 is an attempt to show the quantities of macro and micronutrients contained in the entire plant cane. Main sources of information were: Catani *et al.* (1959), Orlando Filho (1978), Haag *et al.* (1987), Sampaio *et al.* (1987), Korndorfer (1989).

Table 7. Quantities of macro and micronutrients in the below ground and aerial parts of plant cane.

Element	Roots (1)	Millable stalks (2)	Leaves (3)	Total
		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
		g ha^{-1}		
B	34	214	144	392
Cu	13	201	105	711
Fe	4900	3800	7900	16600
Mn	84	1170	1981	3235
Mo	-	4	10	14
Zn	72	437	336	845

(1) Average of 5 varieties; 1.5 tons dry weight.

(2) Average of 3 varieties grown in 3 soils, except Si and Mo; 102 tons fresh weight.

(3) Average of 3 soils, one variety, except Cl, Si and Mo data; 27 tons fresh weight.

The quantities taken up by the crop are influenced by several factors such as: variety, soil conditions, length of the cycle, type of crop (plant cane, ratoon). The requirements of nutrients obey the following decreasing order: Si > K > N > Ca > Mg = S > P > Fe > Mn > Cl > Zn > Cu > B > Mo. On the other hand, export in the millable stalks takes place according to this order: K > Si > N > Ca = Mg > S > P > Fe > Mn > Zn > B = Cu > Mo. Among the three primary macronutrients, therefore, K presents both the highest demand and removal in the stalks.

Information on the requirements of the ratoon crops is rather meager. Data from Orlando Filho *et al.* (1980) and from Table 5 were taken to prepare Table 8. The following decreasing orders are shown:

demand K > N > Ca > Mg > S > P
Fe > Mn > Zn > Cu > B
export N = K > Ca > Mg > S > P
Fe > Mn > Zn > Cu > B

as a rule the pattern is the same as observed in plant cane.

Table 8. Quantities of macro and micronutrients in the first ratoon crop.

Element	Millable stalk (1)	Leaves (2)	Total
		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
		g ha^{-1}	
B	116	61	177
Cu	307	145	452
Fe	1350	3521	4871
Mn	957	1315	2272
Zn	341	179	520

(1) 114 tons/ha; (2) 30 tons fresh weight/ha.

For comparison Table 9 was prepared. It gives the quantities of macro and micronutrients per metric ton of millable stalks using plant cane and ratoon data. It can be seen that the information summarized in this paper agrees with the world literature pooled by Srivastava *et al.* (1992) for plant cane and with the results obtained by Coale *et al.* (1993) for the ratoon crop (except in the case of K).

Table 9. Quantities of nutrients contained in 1 ton of millable stalks.

Element	Plant cane Srivastava *et al.* (1992)	 This paper	Ratoon Coale *et al.* (1993)	 This paper
	kg		kg	
N	0.80-1.75	0.81	0.76	0.67
P	0.13-0.20	0.15	0.22	0.14
K	1.01-4.61	1.06	3.33	0.63
Ca	0.30-0.50	0.29	0.34	0.36
Mg	0.29-0.39	0.28	0.25	0.29
S	0.25	0.24	-	0.23
	g		g	
B	1.20 - 2.00	2.1	-	1.0
Cu	0.50 - 2.00	1.9	-	2.7
Fe	31	37	-	12
Mn	11	11	-	8.4
Mo	0.01	0.04	-	-
Zn	2.50 - 4.50	4.3	-	3.0

As indicated in Figure 4, there are three other causes of loss of nutrients in sugarcane fields besides the export in the millable stalks: burning of trash, leaching and erosion. It is conceivable that when the field is burned prior to the harvest nearly all the N in the trash goes to the atmosphere, that is, about 70 kg ha^{-1} for a 100 ton crop (see Table 7). At least 75% of the total S would have the same fate giving a figure of about 16 kg per hectare. Part of the N and S could come back to the field either as particulates or as ammonia, nitrate or sulfate in the rainfall. Leaching losses of N from 14 to 21 kg per ha were measured by Salcedo and Sampaio (1984) when 60 kg N were added in split or single application, respectively.

4.3. Effects of the nutrients

Although the general functions of the macro and micronutrients are known to be the same for all higher plants, there are some aspects which are more particular to the sugarcane.

Nitrogen: Biological nitrogen fixation (BNF) has been known for some time to occur in the roots and in the rhizosphere of sugarcane. In the association with *Beijerinckia sp*, under field conditions, up to 50 kg N per ha per year were fixed (Dobereiner *et al.*, 1972, 1973). A figure even higher, 99.5 kg, was recorded by Ruschel (1975).

A new type of plant-bacteria association hitherto unknown for N fixing bacteria was described more recently (Urquiaga *et al.*, 1992; Dobereiner, 1992). Three new such bacteria, *Aceto-bacter diazotrophicus, Herbaspirillum seropedicae* and *H. rubrisubalbicans* were found to be obligatory, or predominantly endophytic; that means they do not occur in soil but are plentiful in stems or leaves of sugarcane. Spores of the vesicular mycorrhizal fungus *Glomous clarum* are the vehicle of *A. diazotrophicus* to the roots of sugarcane. Several varieties of sugarcane were grown in large pots filled with a poor soil fertilized with P, K and micronutrients, no N being added neither to the plant cane nor to two sucessive ratoons. Under these conditions yields were estimated to be higher than the Brazilian average. BNF was calculated to contribute about 60% of the N needs of the three crops.

Nitrogen taken up by the roots from the soil solution is transported to the top. In the leaves, meristems and roots the incorporation of N into organic compounds such as aminoacids, amides and proteins take place. As shown in Table 6, the highest percentage of N occurs in the meristematic tissue and, for this reason, there is a certain proportionality between growth and content of the element (Clements *et al.*, 1941). The work by Takahashi (1959) in Hawaii has shown the rapid absorption of leaf-applied N: 0,2 g of ^{15}N labelled urea were placed between the sheath and the stalk. By sampling and analysing the plants 24, 72 and 168 hours after the treatment it was verified that 45, 74 and 79% of the applied urea were absorbed. The isotope first concentrated in the sheaths, next in the blade and later was translocated to the upper parts. Although some tagged N moved to new tissues, most of it remained in the treated leaves. It seems that young plants take up more N than they actually need. This sort of luxury consumption, however, is beneficial because the accumulated N will be used for the new growth which causes a reduction in the content of the older tissues (leaves and nodes) (Sampaio *et al.*, 1988).

Tillering is improved by N. In nitrogen deficient soils (low in organic matter, usually) it seems that BNF is not sufficient, since there are positive responses to the application of nitrogenous fertilizers. But excess of N can be detrimental causing a decrease in the sucrose content of the stalks: Table 10, taken from Humbert (1963) shows that, despite the production increase due to the application of N, sugar yield per ha was decreased. It seems that this undesirable effect shows up only when the excess N delays maturation by stimulating new growth which would either use up accumulated sugar or prevent its accumulation within the stalks.

Table 10. Effect of the excess N on sugarcane yield and quality.

N kg ha^{-1}	Cane t ha^{-1}	Sugar %	 t/ha
177	245	9.5	23.0
277	267	9.0	23.7
377	260	8.5	22.2

Other effects of N were summarized by Dillewijn (1952). Cane which is amply supplied with N fertilizer is more juicy than cane grown under poor nitrogen nutrition. This means a dilution of juice and represents one of the ways in which N affects the quality: the effect of increasing N supply on fiber content is practically the reverse; there is a decrease when the nitrogen applications are increased. There is a depressing effect on tasseling. On the other hand, excess N promotes lodging, particularly if K is lacking. Heavy N dressings near the end of the growing period lead to higher incidence of the eyespot disease (*Helminthosporium sacchari*). Increasing N applications also promote the susceptibility to the top rot disease caused by *Fusarium moniliforme*. It has been reported that the occurrence of the pest white top borer (*Scirpophaga auriflua*) increases when too much N is applied.

Phosphorus: This is essential for cell division which accounts for stalk and root elongation, that is, the growth of the sugarcane plant. Actually Humbert (1963) writes that "phosphorus has a striking effect on root and shoot development". When P is deficient, therefore, the root system is poorly developed. Growth of secondary rootlets is restricted resulting in a minimum of root surface for contact with the soil and its solution. Poor root development means inadequate supplies of air (for respiration), water and nutrients for the growth of the entire plant. Lack of P causes less tillering, and reduction both in diameter and length of the internodes. Studies on the absorption of radioactive phosphate discussed by Burr *et al.* (1957) have shown that when ^{32}P is fed into culture solutions radioactivity could be detected up in the stalk within thirty minutes; after one hour the ^{32}P was distributed uniformly throughout the leaves. Two months later, new blades were more radioctive than old and recently formed stalks were as rich in ^{32}P as the parent plant. Other studies in which radioactive P was either injected into the stem or applied to a leaf proved that there is interstalk translocation.

Clements (1980) recalls that the synthesis of sugars in the photosynthetic process (see section on botany and physiology) the formation of sucrose from glucose and fructose, and their translocation are made possible by several types of phosphate compounds.

the stalks. This could be due to the reserve of the element in the seed piece and accumulation during the period the plants received Mg before the treatment started. The mobility of Mg is well known.

Sulphur: As Table 6 shows, the concentration of S is higher in the meristem as is the case with other nutrients. Nevertheless old sheaths contain just as much sulphur. When S is deficient the plants lack vigour, grow less, have stalks with small diameter tapering rapidly towards the growing point (Dillewijn, 1952). Humbert (1968) believed that sulphur deficiency could affect carbohydrate metabolism in sugarcane. Actually the omission of S from the nutrient solution caused a reduction of 50% in the sucrose content of the stalks (Haag, 1965).

5. Symptoms of deficiency and their causes

When a given nutrient is not present in the soil solution in a concentration sufficient for normal growth and differentiation visual symptoms of malnutrition may eventually show up. Since all nutrients play the same function or functions in all species a common denomination does exist. A few symptoms, however are more specific. Before the abnormality could be seen and identified - and hopefully corrective measures can be taken - yield could already be limited due to "hidden hunger". The deficiency symptom is in fact the end of a chain of events which begins with a change at the molecular level, is followed by modification in a part of the cell, then in the whole cell. When a number of cells or tissue is affected the symptom is observed.

The shortage of nutrients which translate into symptoms of deficiency could be due to several causes as shown in Table 11. It is clear that the three chief causes are low reserves to begin with, as it is the case of old weathered soils in the tropical regions, decrease in availability, and absence or lack of the element in the fertilizer program at the rates it is applied.

Usually the symptoms of deficiency either show up first or are more easily identified in the leaves. Other organs as the stalks and roots, however, can be also affected. Depending upon the element old or young leaves could be the first ones to show the symptons. This of course reflects the degree of translocation or redistribution - phloem mobility in fact - of the nutrient. The following key for the identification of deficiency symptoms takes into account the organ which is initially affected, whether old leaves, young leaves or the roots themselves.

Table 11. Main causes of deficiency symptoms in the sugarcane plant.

Element	Cause
Any :	Low soil reserve Absence or inadequate quantity in the fertilization or liming program
Nitrogen :	Low organic matter content High acidity (lack of mineralization) Low rainfall (same) High rainfall (leaching)
Phosphorus :	High acidity and high sexquioxides (fixation) Excess liming (lower availability)
Potassium :	Excess liming (competition for uptake) High rainfall (sandy soils, leaching)
Calcium and magnesium :	Excess potassium in the fertilizer program (competition)
Sulphur :	See Nitrogen Use of "concentrated" fertilizers
Boron :	See Nitrogen Excess nitrogen ("dilution" or inhibition in uptake) Excess liming (loss in availability)
Copper :	Excess phosphorus in the fertilization program (inhibition in uptake) Excess liming (loss in availability)
Iron :	High organic matter and moisture (lower availability) Excess liming (loss in availability)
Manganese :	High organic matter, excess liming (loss in availability)
Molybdenum:	High acidity (lower availability) Excess sulphate (inhibition in uptake)
Zinc :	Excess liming (loss in availability) High P in fertilizer program (inhibition uptake)

Before using the key, however, it is recommended to take a few steps destined to find out if the abnormality is actually a nutritional disorder. The following conditions should be fulfilled in case of deficiency symptoms or symptoms of excess for that matter:

(1) *generalized* - large tracts of the plantation should present the symptom, otherwise other causes could be responsible, such as pests, diseases, erosion, soil depth;

(2) *symmetry* - a given leaf and the next one should show the abnormality;

(3) *gradient* - the symptom of deficiency has its intensity increased from older to younger leaves or vice versa, depending upon the element.

The following key is largely based on Malavolta (1982) and Anderson and Bowen (1990).

5.1. Symptoms localized first in older leaves

Without chlorosis

Leaf blades initially dark green or bluegreen, with length and width reduced. Tips dry. Stalks thin with shorter internodes. Tillering and root growth poor. *Phosphorus.*

With chlorosis

- Uniform yellowing:

Leaves pale green and yellow gradually in the whole stool. Tips and margins of the blade dry prematurely. Growth stops. Stalks slender. Less tillering. *Nitrogen.*

- Non uniform yellowing:

Spots: Gradual loss of the green colour of the blade; small, numerous yellow spots later on with brown, dead center preferentially in borders and tips. Bottom (older) leaves may be entirely brown, rusty or "fired". Upper surface of the midrib with reddish discoloration. Less growth and tillering, stalks slender with shorter internodes. *Potassium.*

Small yellow spots which turn reddish-brown and dry in their center; dead areas coalesce giving the leaf a "rusty" appearance. Leaves dry prematurely. Poor root development. Stalks thinner and soft. *Calcium.*

Leaf blades pale green, next with small yellow spots which become brownish, uniformly distributed giving a rusty appearance similar to the symptoms of calcium deficiency. Drying of the leaves may cause death of the stool. Stalks slender. Reduced growth. *Magnesium.*

Minute circular white spots (freckles) less severe in younger leaves. Premature senescence of older leaves. Poor tillering. *Silicon.*

Streaks: Yellowish streaks 1-3 mm wide and up to 1 cm (or more) long between veins and more concentrated in the tips. With time the central part of the streaks may become purplish. Older leaves dry prematurely from middle to top. *Molybdenum.*

5.2. Symptoms localized first in young leaves

With non uniform chlorosis

Spots: Leaf tips curl under giving a hooked appearance, and sometimes stick together. Spindles often necrotic at tip and along margins. Minute chlorotic lesions with necrotic centers, later turning dark reddish-brown. Slender stalks tapering rapidly toward the growing point. *Calcium*.

Small, long watery spots parallel to the vein. Later may increase in size and the tissue is torn.

Younger leaves whitish, and dry prematurely. Apical meristem may die as well. *Fusarium moniloforme* which causes the "Pokkah Boeng" disease and some herbicides give similar symptoms.

Young plants bunched with many tillers. *Boron*.

Numerous small, pale green and retangular splotches interrupt the continuity of the uniform green of the leaf, with an aspect like mosaic. Leaves usually wider and thinner. The top of the stool with reduced tillering bents towards the ground (droopy top). Young leaves sometimes fail to unroll and the apical meristem dies. *Copper*.

Streaks: Interveinal chlorosis from tip towards the base of the leaf. With time entire stool may become yellow or whitish. *Iron*.

Interveinal chlorosis which extendes from tip to the middle of the leaf blade. Leaves narrower. Necrotic spots which coalesce in long streaks may develop in acute cases. *Manganese*.

Chlorotic streaks in the entire length of the blade, particularly in the tips. Growing upper parts may become whitish and are thinner. Growth is delayed, internodes shorter. Older leaves dry prematurely. Reduced tillering. Slender stalks with less turgor. *Zinc*.

Uniform chlorosis

Sometimes veins remain pale green. Blades shorter and narrower. With time leaves may develop a purplish tint. Stalks slender. *Sulphur*.

Young leaves wilt during hot sunny day, but usually recover overnight. *Chlorine*.

Roots shorter with thickened tips, resembling damage caused by nematodes. Leaves may show symptoms of phosphorus and potassium deficiency. *Aluminium* (excess).

Short roots, increased number of lateral roots. *Chlorine*.

Symptoms of deficiency in narrow leaf plants, such as sugarcane, are more difficult to identify than when broad leaf species are concerned. Visual diagnosis of the deficiency is further complicated due to the similarity of symptoms caused by different elements, particularly in later stages. In cases of doubt leaf analysis may help. In order to make a correct diagnosis leaves with symptoms and apparently healthy ones, within the same plantation, and of the same physiological age, should be analysed. Table 12 gives the range of concentrations of macro- and micronutrients which usually indicate deficiency.

Table 12. Range of levels of elements in the leaves usually associated with deficiency symptoms.

Element	Concentration
	% dry weight
N	1.0 - 1.25
P	0.05 - 0.1
K	0.5 - 0.01
Ca	< 0.25
Mg	< 0.15
S	< 0.1
Si	< 0.5
	ppm
B	1 - 5
Cu	1 - 5
Fe	< 50
Mn	< 20
Mo	0.05 - 0.1
Zn	10 - 15

6. Leaf analysis

Tissue analysis may be considered a method which evaluates the soil supply of available elements using the plant itself as an extracting agent. In the case of sugarcane several different tissues are analysed: leaves, internodes, juice from millable stalk.

General: Leaf, or foliar, diagnosis can be used with two main objectives, namely:

(1) evaluation of the nutritional status of the crop as illustrated in the previous section; the principle supporting this use is the following - a "normal" or healthy plant, capable of high yields has all nutrients in their

leaves in concentrations and ratios which have to be considered as adequate; on the other hand a plant suffering from malnutrition and with growth and production restricted should have one or more nutrients in lower or excessive levels in its leaves.

(2) determination of the fertilizer requirement or of adjustments in the fertilization program: three premises or conditions should be fulfilled; within limits there is a direct relationship between soil supply or fertilizer rate and yield and leaf level of the element, and between leaf level and yield. Figures 7 and 8, prepared with data from 14 field trials carried out by Malavolta *et al.* (1963), show how the three conditions are met.

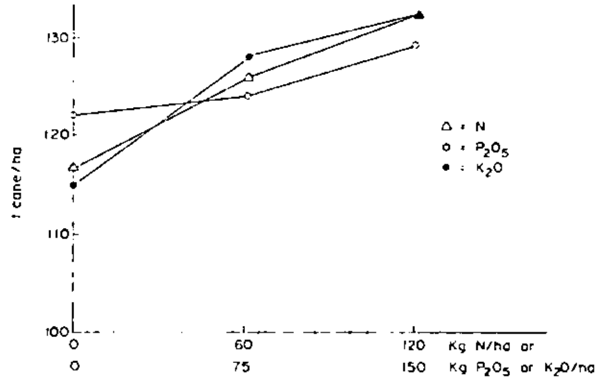

Fig. 7. Relationship between rate of N, P_2O_5 or K_2O and cane plant yield.

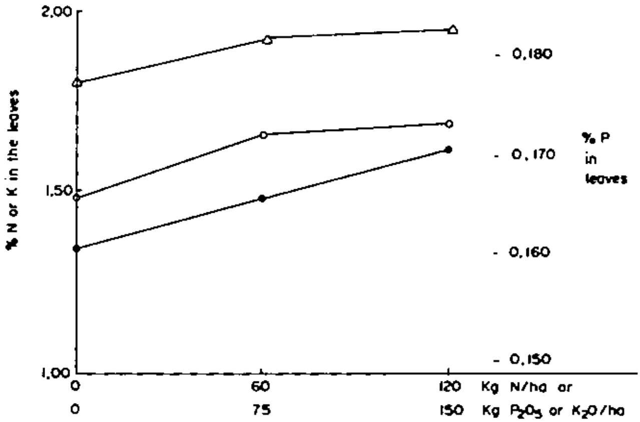

Fig. 8. Relationship between fertilizer rate and level of element in the leaves.

The third premise - relationship betwen leaf level and growth or yield - is actually more complicated. Figure 9, taken from Malavolta *et al.* (1989), is a modification of the curve presented by Prevot and Ollagnier (1956) describing the several situations which may occur.

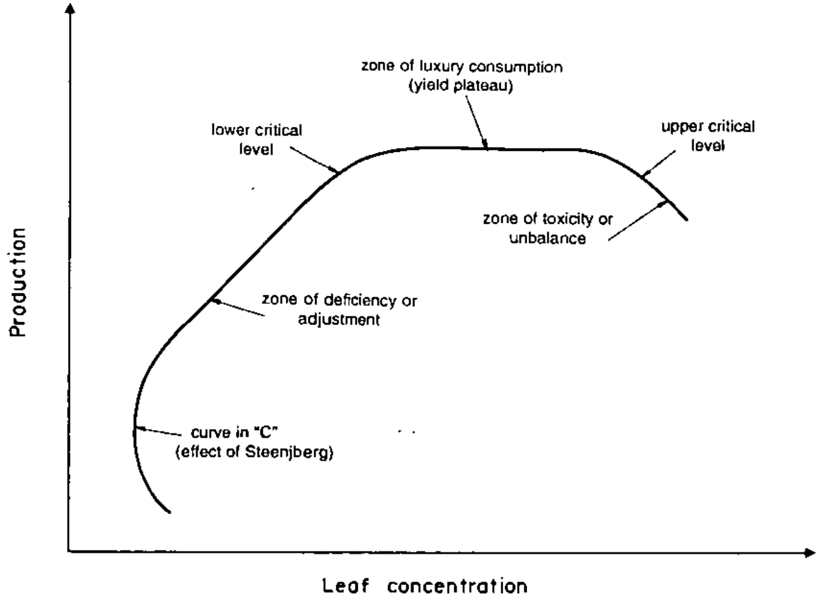

Fig. 9. A general representation of the relationship between leaf concentration and yield.

Clockwise the following segments are shown:

(a) curve in "C-" yield is increased but leaf level is reduced; this happens when the rate of dry matter production is higher than the velocity of uptake or transport of the element into the leaf tissue which causes its dilution.

(b) zone of deficiency or adjustment - only in this section is the third premise observed, and very often there is a linear relationship between increase in leaf concentration and yield;

(c) lower critical level - usually a narrow band below which yield is reduced due to a shortage of the element.

(d) zone of luxury consumption - it is wider in the case of macronutrients like K, and much shorter in other cases such as that of B; leaf level increases whereas production remains constant, there is therefore, a waste of fertility or fertilizer;

(e) upper critical level - a zone which separates the yield plateau from the toxicity zone;

(f) zone of toxicity - leaf content increases even further and yield drops, either as consequence of a toxic effect of the element, or as a result of unbalance among nutrients.

Usually the literature makes reference to just one of the two critical levels, the lower. This range of values corresponds to the maximum intensity of given physiological processes such as photosynthetic activity as measured by the absorption of labelled CO_2 (Malavolta *et al.*, 1989). In the agricultural practice, however, the goal is not the maximum physical production but rather the realization of the maximum economic yield (MEY). For this reason the concept of critical level or lower critical level was redefined with the introduction of an economical component: it is the range of an element in the leaf below which production is restricted and above which fertilizer application is no longer economical (Malavolta and Pimentel Gomes, 1961). This means that above this physiological-economical critical level, both yield and leaf content of the element could rise in response to the fertilization. The increase in yield, however, does not pay the additional fertilizer and the cost of its transport and distribution. Malavolta and Cruz (1971) have shown that the well known equation of Mitscherlich fits the experimental data describing the relationship between rate of fertilizer and yield, that is:

$$y = A\,[1 - 10^{-c(x+b)}] \qquad (1)$$

where y is the yield due to x - amount of element supplied plus b - the soil supply; c is the coefficient of carrier efficiency and A is the maximum yield. The dosage of element capable of producing the maximum economical yield is calculated using the equation.

$$x^* = 1/2x \;\; x^* = 1/2x_u + (1/c)\log\frac{wu}{tx_u} \qquad (2)$$

where x^* is the dosage of the element giving the maximum economical yield; x_u is the dosage of the element which caused u = the increase in yield relative to the treatment without the element; w is the unit price of the agricultural product (ton of sugarcane, for instance) and t = unit price of the fertilizer element. The relationship between rate of fertilizer x and leaf level of the element, Y, is described usually by one of the following equations:

$$Y = a + dx,\; Y = a + dx + ex^2 \text{ or } Y = a + dx - ex^2 \qquad (3)$$

The critical level as defined, is then calculated by setting $x - x^*$ in the regression equations (3).

The mineral composition of the leaf reflects the action and interactions of several factors which played their roles until the moment the sample was taken for analysis, that is:

$$Y = f\,(S, V, A, Cl, Cp, Pd) \tag{4}$$

wherein Y = leaf concentration of the element
S = soil, fertilizer, amendment
V = plant, variety, part
A = age
Cl = climate (light, temperature, rainfall)
Cp = cultural practices
Pd = pests and diseases.

Sampling: It seems that in most regions leaf +3 according the numbering proposed by Kuijper, is taken for analysis (see p. 8 and Figures 1 and 2). For the mineral analysis commonly the middle third, midrib excluded, is the only part used. The number of leaves sampled varies from 2 to 20 per hectare (Malavolta *et al.*, 1972; Orlando and Campos, 1975). This, however, seems too large a number in the case of plantations with thousands of hectares. Jones Jr. *et al.* (1991) suggest that 15 leaves per uniform plot should constitute the composite sample. The plot in question could have from less than I up to 50 hectares. Samples are collected by crossing the field along two diagonals or in zig-zag. Leaf samples collected should be analysed as early as possible to allow for the correction of an eventual deficiency disclosed by the data. In the case of plant cane this is usually done when plants are between 3 and 5 months of age: it can be seen in Table 13 that in 4 months old plants there is the largest difference in leaf K content between potash-fed and control plants. In the case of ratoons sampling should be done also when plants are about 4 months old. Different procedures are followed when the crop log system designed by Clements and his coworkers is used (see Clements, 1961; 1980). The evolution of the nutritional status and the need for fertilization is monitored by analysis made at regular intervals. Sheaths from leaves 3, 4, 5 and 6 (the spindle leaf is number 1) are used for determination of moisture, sugar, P and K. Leaf blades are analysed for N. Phosphorus is also determined in the fifth internode. The sheath tissue serves also for the analysis of Ca, Mg and micronutrients.

Table 13. Difference in leaf K percentage of dry matter of plants fertilized with K and control.

Age, months	Difference (% K)
04	1,00
06	0,75
08	0,50
10	0,25
12	< 0,25

Factors: As mentioned earlier the mineral composition of the leaf tissue is influenced by various factors. For this reason it is necessary to change the general equation (4) to: $Y = f(S)$ (5)

In other words, the only independent variable should be soil fertility (S), either natural or modified by fertilizers and amendments. All the other factors have to be made constant. The extent of modification in leaf composition brought about by several factors can be assessed by the following examples.

Orlando *et al.* (1978) conducted leaf analysis of the variety CB 41-76 grown in five different soil types receiving adequate rates of fertilizer. Table 14 gives the range of variation and average composition of the leaves. This type of finding, of course, is to be expected due to the differences in soil fertility.

Table 14. Variation in mineral composition of leaf +3 due to soil type.

Element	Range %	Average %	Element	Range ppm	Average ppm
N	1.76-1.99	1.82	B	14- 17	15
P	0.15-0.17	0.16	Cu	5- 6	5
K	1.37-1.58	1.45	Fe	192-383	248
Ca	0.45-0.59	0.46	Mn	137-171	156
Mg	0.18-0.25	0.21	Mo	0.06-0.11	0.09
S (*)	0.04-0.06	0.05	Zn	15- 18	16

(*) Sulfate - S.

Capó *et al.* (1953) observed differences in leaf composition among 13 varieties grown in the same soil. Nevertheless, for practical purpose, they found that the same levels of N, P and K could be used to interpret their nutritional status.

Marked differences among varieties were also recorded by Evans (1967). In Brazil, Orlando Filho (1976) analysed the macronutrients in the leaf +3 of 16 varieties grown in the same soil. As Table 15 shows, significant differences were found in the case of all elements.

Table 15. Variation in the composition of leaf +3 of 16 varieties.

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

As far as the effect of climate is concerned, the influence of rainfall has been more frequently considered. With data obtained by Samuels and Landrau Jr. (1952) the following regression equations were calculated:

(1) $Y = 0.96 + 0.0008\ x_1$

(2) $Y = 0.90 + 0.0132\ x_2$

wherein $Y = \%$ N in the leaf

x_1 = quantity of rain in mm which fell in the period between cutting and sampling

x_2 = quantity of rain in mm which fell in the week before sampling

It follows from equation (1) that a rainfall of 250 mm leads to an increase of 0.20% in leaf N; according to equation (2) a rainfall of 25 mm in the week before sampling causes a rise of 0.33% in the level of nitrogen. In the case of N, Evans (1961) estimates that 4 weeks before sampling 150-250 mm of well distributed rains lead to an adequate level, whereas an excess caused a decrease in leaf nitrogen.

Figures 10 and 11, prepared with data obtained by Orlando (1978), show the variation in the content of N, P and K of leaf +3, respectively in plant cane and in the first ratoon, as influenced both by age of the crop and by rainfall. Using regression analysis Malavolta and Carvalho (1984), who worked also with the Ca, Mg and S data, were able to define the effect of 200 mm of rain which fell 2 months before sampling on leaf composition. In plant cane the following values representing actual increases were calculated: P = 0.016 to 0.034%, depending upon soil type, K = 0.071%; Mg = 0.019 to 0.388%.

For the first ratoon crop, the increases were estimated to be: N = 0.17%, P = 0.02%, Mg = 0.027%, S = 0.055%. Variations not given were not significant.

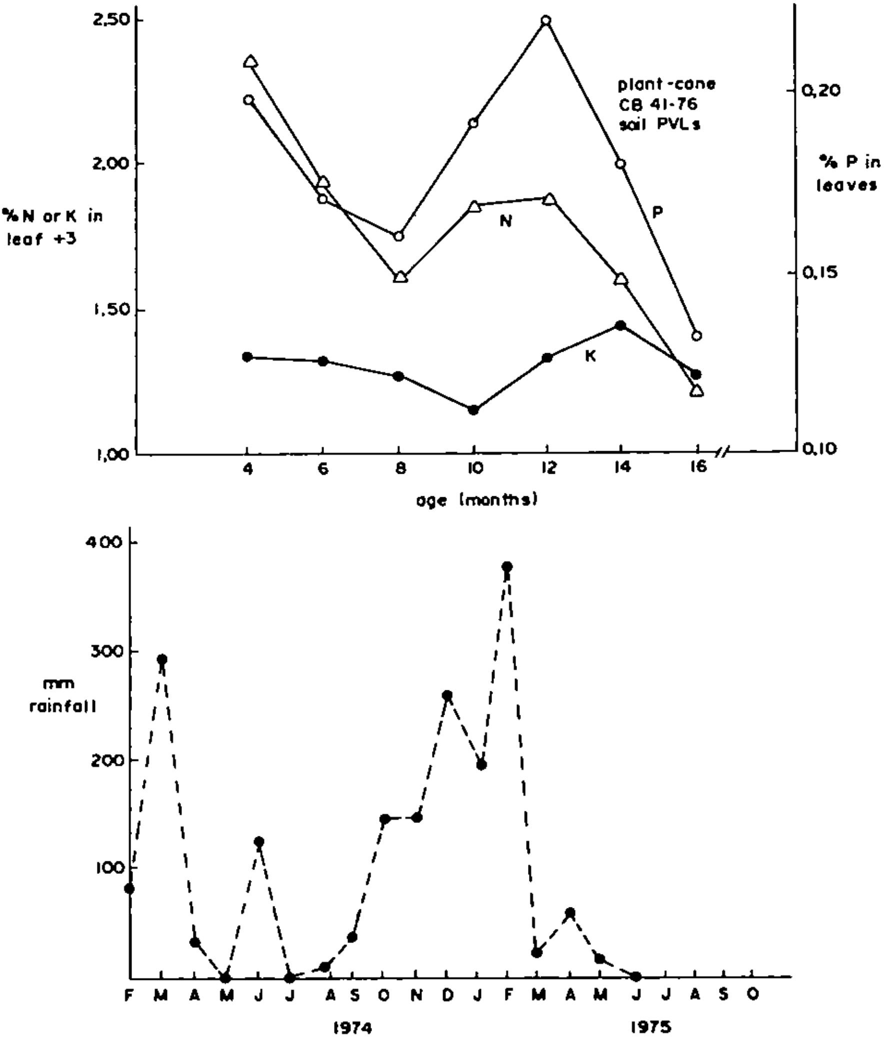

Fig. 10. Variation in leaf N, P and K in relation to age and rainfall (plant-cane).

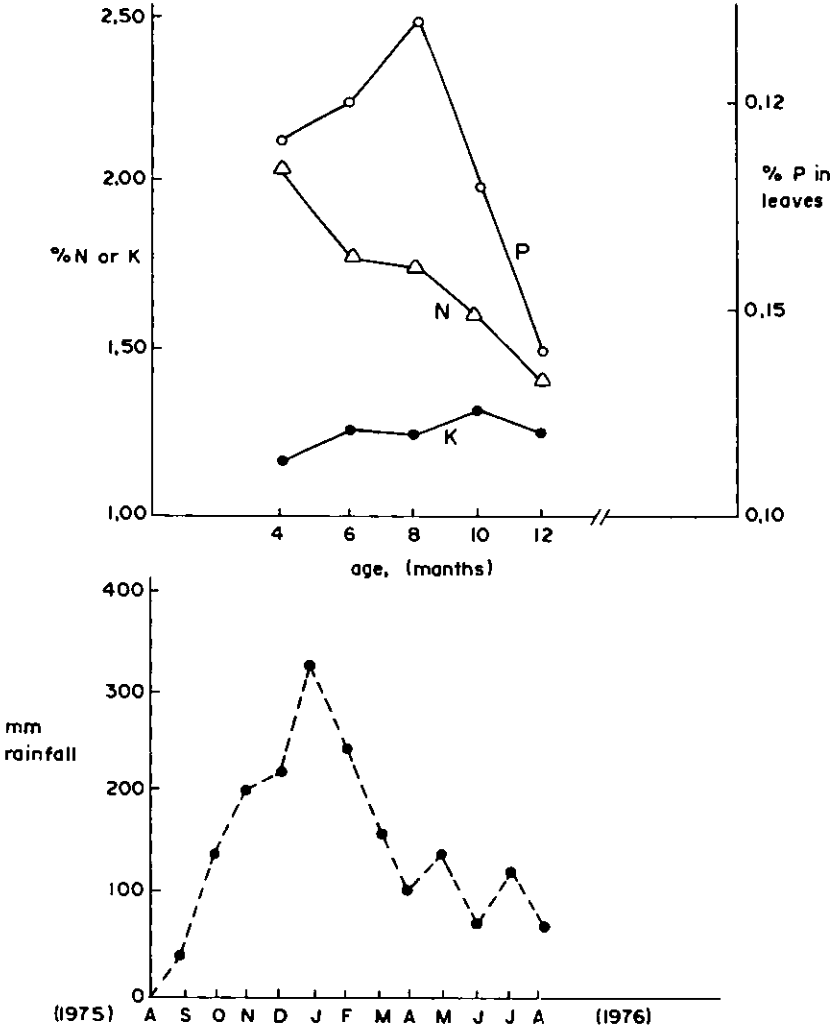

Fig. 11. Variation in leaf N, P and K in relation to age (ratoon).

Interpretation: Due to the number of factors which influence leaf composition (the book by Samuels, 1969, gives more detail) there is variation in the literature in the interpretation of the levels found in the analysis. For this reason it is necessary to pay attention to the sampling procedure: cane, variety, leafpart analysed and age. Usually, total contents are analysed; soluble forms of N, not considered in the routine, could, however, provide better information than total N.

Figure 12, prepared with data obtained by Teixeira (1980) shows a better correlation between NH_4-N and yield of the first ratoon than between either nitrate-N or total N and production.

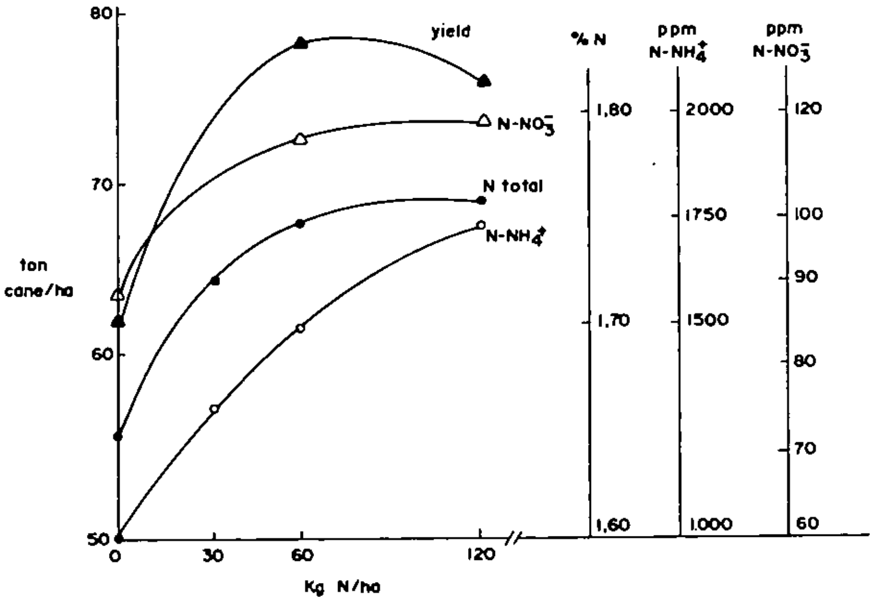

Fig. 12. Relationship between rates of N, yield and nitrogen forms in the leaves.

Usually the individual values of the concentration of macro- and micronutrients are used to evaluate the nutritional status of the sugarcane plant and to make recommendations for fertilization. As shown in Table 16, despite all causes of variation involved there is a good deal of agreement among countries and regions as far as adequate levels are concerned.

The same could be said with respect to the concentration of micronutrients in the leaf tissue (Table 17).

Table 16. Levels of macronutrients considered adequate in several countries or regions.

Country or region	Crop	N	P	K	Ca %	Mg	S	Ref.
Australia	Plant	1.9-2.5	0.21-0.30	1.30-2.00	0.20-0.60	0.10-0.30	-	(1)
	Ratoon	1.9-2.5	0.21-0.30	1.30-2.00	-	-	-	
Brazil	Plant	1.9-2.1	0.20-0.24	1.10-1.30	0.80-1.00	0.20-0.30	0.25-0.30	(2)
	Ratoon	2.0-2.2	0.18-0.20	1.30-1.50	0.50-0.70	0.20-0.25	0.08-0.35	
British Guyana	Plant	2.1	0.21-0.35	1.25-2.00	0.15-0.20	0.12-0.18	0.08-0.35	(3)
	Ratoon	1.9	0.21-0.35	1.25-2.00	0.20-0.24	0.12-0.18	-	
Colombia	-	1.8-2.0	0.25-0.35	1.60-1.80	>0.25	>0.20	-	(4)
India	-	1.96	0.086	1.99	-	-	-	(5)
Puerto Rico	-	1.6-2.0	0.18-0.24	1.55-2.00	-	-	0.13	(6)
South Africa	-	1.7-1.9	1.10-0.20	1.05-1.10	0.15-0.18	0.08	0.12-0.13	(7), (8)
USA	-	1.5-1.75	0.18-0.22	1.25-1.75	0.28-0.47	0.14-0.33	0.13-0.18	(9)

(1) Reuter (1986). Blade leaf + 3. 10 month old plant, 7 months ratoon

(2) Malavolta (1982). Blade leaf + 3. 4 months old plant and ratoon

(3) Evans (1967). Blade leaf top visible dewlap (+1). 3-5 month old plant-cane and ratoon

(4) Garcia Ocampo (1991). Blade leaf + 1

(5) Srivastava (1992). Blades leaves 3-6, 4 months for N. P and K sheath, sugar free dry weight basis

(6) Samuels (1959). Leaves general, 3 month

(7) Gosnell and Long (1971). Blade leaf + 1, 5 month old

(8) Schroeder *et al.* (1993)

(9) Anderson and Bowen (1990). Blade leaf + 2, 3-4 month. Data from Louisiana.

Table 17. Levels of micronutrients considered adequate in several countries and regions.

Country or region	Crop	B	Cl	Cu	Fe	Mn ppm	Mo	Si	Zn	Ref.
Australia	-	-	-	2	50	-	-	-	10	(1)
Brazil	Plant	9 -30	-	8- 10	200-500	100-250	0.15-0.30	-	25-50	
	Ratoon	9 -30	-	8- 10	80-150	50-125	-	-	25-30	(2)
British Guyana	-	2 -10	<0.5(5)	5-100	4- 15	20-200	0.08-1.00	-	15-50	(3)
South Africa	-	1.6-10	-	49-915	3- 12	15		-	12-25	(4), (6)
USA	-	3 - 8	<0.068(5)	7-600	20- 21	14-235	0.05-4	1.5-4(5)	19-38	(1)

(1) Anderson and Bowen (1990). Blade leaf top visible dewlap, 4-6 months
(2) Malavolta (1982). Blade leaf + 3, 4 months
(3) Evans (1967). Blade leaf top visible dewlap, 4-6 months
(4) Wood (1987). Blade leaf top visible dewlap, 4 months
(5) Percentage dry matter, sheaths leaves + 1 to + 4 for Cl, blade leaf top visible dewlap for Si
(6) Schroeder *et al.* (1993).

Most of the data found in the literature deal only with plant cane. Table 18 could, therefore, be useful, since it presents adequate values for plant cane and two ratoons.

Instead of absolute values, ratios of concentrations of elements can be used for the various applications of leaf analysis. This is the approach of the Diagnosis and Recommendation Integrated System (DRIS) developed by Beaufils (1971, 1973) and first used in sugarcane by Beaufils and Sumner (1976). Summaries of the DRIS are presented by Orlando and Zambello Jr. (1983), Malavolta *et al.* (1989) and by Jones Jr. *et al.* (1991).

Table 18. Nutrient concentrations observed in Brazilian plantations with a yield of 100 t ha^{-1} (1).

Nutrient	Plant cane	1st ratoon	2nd ratoon
		%	
N	1.47	1.64	1.86
P	0.16	0.15	0.21
K	1.49	1.08	0.87
Ca	0.39	0.28	0.68
Mg	0.35	0.20	0.35
S	0.17	0.10	0.12
		ppm	
B	20	11	9
Cu	19	6	6
Fe	271	66	62
Mn	256	52	99
Zn	12	5	16

(1) Blade leaf + 3, plants 4 months old (Yamada, 1992).

In order to use the DRIS it is necessary to have a large number of data (nutrient levels and corresponding yields) which allow the calculation of means and variances of ratios of elements which discriminate between high and low yielding subpopulations. A calibration formula is fed both means and coefficient of variations of DRIS parameters of the high yielding subpopulation in order to make the diagnosis. The formula calculates the relative indices for elements which could be higher (positive), lower (negative) or equal to zero: the more negative the value the more deficient the nutrient and higher the need in the fertilization program. The more positive the index the less needed are the nutrients; close to that found in the high yielding subpopulation the DRIS index for each element is zero (Elwakli and Gascho, 1984). When all the DRIS indices are added irrespective of sign the Nutritional Balance Index (NBI) is obtained. It is a measure of balance of nutrients. The larger the value, the greater the imbalances among elements.

Table 19 shows the DRIS indices and the NBIs for 8 sugarcane fields analysed by Elwakli and Gascho (1984). Field number 3 extremely deficient in K had the highest NBI value. The DRIS approach can also be used in the interpretation of the results of fertilizer trials.

Table 20, due to Orlando Filho and Zambello Jr. (1983) gives an example: in the control plot (0-0-0) P was limiting. When P and K were added N became the limiting element followed by P. The negative index with respect to K appeared only when N and P were applied.

Table 19. Concentrations of elements and DRIS indices of leaf nutrients in eight sugarcane fields of Florida, USA.

Field No.	N	P	K	Ca	Mg	N	P	K	Ca	Mg	NBI*
			%					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

Table 20. Utilization of DRIS indices in an experiment in Brazil.

	Treatment		Yield	N	P	K	N	P	K	NBI*
N	P_2O_5	K_2O								
	kg ha^{-1}		t/ha		%			DRIS indices		
0	0	0	81	1.66	0.13	1.30	21	-32	32	85
0	300	300	97	1.71	0.16	1.42	-41	-12	14	67
180	300	300	168	1.86	0.17	1.42	3	-3	3	9
160	0	300	106	1.73	0.11	1.32	74	-74	72	220
160	300	0	126	1.90	0.18	1.32	9	19	-19	47

* Nutritional Balance Index.

Utilization: It has already been pointed out that the two chief uses of leaf analysis are the evaluation of the nutritional status and the establishment of fertilizer rates, the second of course being a consequence of the first. Surveys of the nutritional status of the sugarcane plantations in a given region can be useful for a preliminary evaluation of limiting factors from the point of view of soil fertility, and for the assessment of fertilizer needs in broad terms. An example of this utilization was given in the item just discussed, in the case of the plantations from Florida, USA. Gallo *et al.* (1968) in Brazil conducted a detailed evaluation of 202 plantations, 133 of them with plant-cane. In representative plots larger than 1 ha, 30-40 stools were chosen at random. From each stool having 3 stalks or more, 3 leaves + 3 were collected. Therefore each plantation was represented by 90 to 120 leaves. The results obtained are summarized in Table 21. The decreasing orders of frequency of deficiencies are as follows:

macronutrients - K > Mg > N = P = S > Ca
micronutrients - Fe > B > Cu > Mn > Mo = Zn

Table 21. Results of a survey of the nutritional status of sugarcane plantations, variety CB 41-76 (*).

Element	Average		Higher frequency		Deficiency likely	
	plc	rat	plc	rat	range	plantations
N %	1.89	1.76	1.60-1.80	1.60-1.80	1.08-1.60	12
P	0.152	0.184	0.12-0.14	0.16-0.18	0.07-0.12	12
K	1.32	1.26	1.20-1.40	1.20-1.40	0.34-1.20	22
Ca	0.73	0.50	0.70-0.80	0.30-0.40	0.23-0.30	7
Mg	0.25	0.22	0.20-0.25	0.20-0.25	0.04-0.15	15
S	0.035	0.055	0.02-0.03	0.05-0.06	0.006-0.20	11
B ppm	13	20	10- 15	15- 20	3- 10	9
Cu	6	5	6- 8	4- 6	3- 4	7
Fe	426	249	300-400	100-200	70-100	11
Mn	238	107	100-150	50-100	22- 50	3
Mo	0.06	0.14	0.03-0.06	0.05-0.08	0.02-0.03	2
Zn	16	16	12- 14	10- 12	7- 10	2

(*) plc = plant cane, 4 months old
rat = ratoon, 4 months old
Sampling - leaf + 3, middle part, mid rib excluded
S (sulphur) - soluble sulfates.

Recently this utilization of leaf analysis in South Africa was reported by Schroeder *et al.* (1993).

The rationale of using leaf analysis as a means for making fertilizer recommendations or adjustments thereof is illustrated in Figure 13 which was made with data obtained by Zambello Jr. (1979).

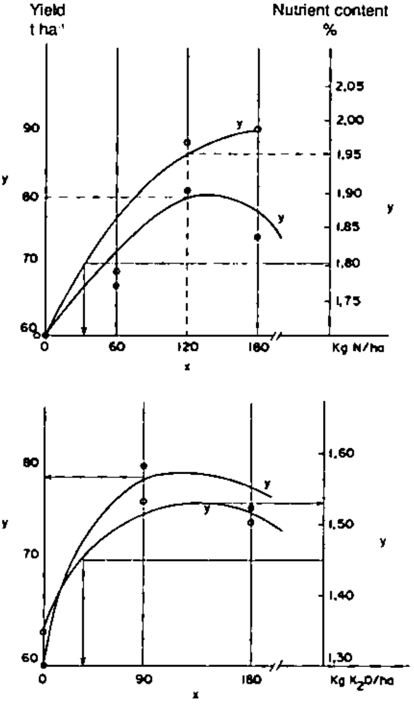

Fig. 13. The principle for the determination of rates of fertilizer N and K_2O.

The three premises or conditions to use leaf analysis for such a purpose are met:

120 kg N gave a 2.00% N content in leaf +3 and a yield of 80 t ha^{-1};
90 kg K_2O led to a 1.55% K in leaf +3 associated with a production of 77 t ha^{-1};

1.80% N found in the leaf +3 of a sample corresponds to a soil supply of 30 kg ha^{-1} N, and to a yield of 70 t ha^{-1}; in order to raise leaf N to 2.00% and yield to 80 t ha^{-1}, it would be necessary to apply 120-30 = 90 kg ha^{-1} N; by the same reasoning to reach 1.55% K in leaf +3 and a production of 90 t ha^{-1}, the rate of K_2O to apply would be 90-45 = 45 kg ha^{-1} K_2O.

Table 22 gives recommendations for fertilization of plant cane in Puerto Rico based on leaf analysis (Samuels *et al.*, 1956). The middle part of leaves + 2, + 3 and + 4 collected when plants are 3 month old was analysed.

Table 22. Recommendations for fertilization in Puerto Rico.

Nutritional status	% N	kg ha^{-1} N	% P	kg ha^{-1} P_2O_5	% K	kg ha^{-1} K_2O
Very low	<1.00	300-200	<0.10	300-150	<1.00	300-200
Low	1.00-1.40	300-100	0.10-0.15	150- 50	1.00-1.50	300-100
Slightly low	1.40-1.50	100- 0	0.15-0.18	75- 0	1.50-1.65	100- 0
Normal	1.50-2.00	0-100	0.18-0.25	0	1.65-2.00	0- 60
High	2.00-2.50	0	0.25-0.30	0	2.00-3.00	0
Very high	>2.50	0	>0.30	0	+3.00	0

Table 23 shows the recommendations for British Guyana according to Poidevin and Robinson (1964) and Poidevin (1964): the middle portion of the leaf with top visible dewlap, midrib excluded, is analysed.

Table 23. Recommendations of fertilization for Br. Guyana based on leaf analysis (according to Poidevin and Robinson, 1964 & Poidevin, 1964).

Element	Level %	kg ha^{-1}	Element	Level %	kg ha^{-1}
		Plant cane			
	17 weeks			24 weeks	
	>2.0	0		>1.7	0
N	1.8-2.0	25	N	<1.7	25
	<1.8	50		-	-
	>0.18	0 (P_2O_5)		>0.15	0 (P_2O_5)
P	0.15-0.18	50 (P_2O_5)	P	<0.15	50 (P_2O_5)
	<0.15	75 (P_2O_5)		-	-
	>1.2	0 (K_2O)		>1.0	0 (K_2O)
K	1.0-1.2	75 (K_2O)	K	<1.0	75 (K_2O)
	<1.0	100 (K_2O)		-	-
		Ratoon			
	12 weeks			20 weeks	
	>2.0	0		>1.8	0
N	1.8-2.0	25	N	1.6-1.8	25
	<1.8	50		<1.6	50
	>0.20	0 (P_2O_5)		>0.17	0 (P_2O_5)
P	0.16-0.20	50 (P_2O_5)	P	<0.17	50 (P_2O_5)
	<0.16	75 (P_2O_5)		-	-
	>1.20	0 (K_2O)		>1.1	0 (K_2O)
K	1.00-1.20	75 (K_2O)	K	<1.1	75 (K_2O)
	<1.00	150 (K_2O)		-	-

Other tissues and other tests: Burr *et al.* (1957) proposed the stalk as a much more sensitive indicator of the nitrogen nutrition than the leaf. This has been confirmed in Brazil by Santos *et al.* (1977): as shown in Figure 14, there is a closer correlation between N content in the 8-10 internode with nitrogenous fertilization than with leaf + 3 N %. With respect to K, however both tissues are adequate (Humbert, 1968). Figure 15 shows details of the stalk sampling.

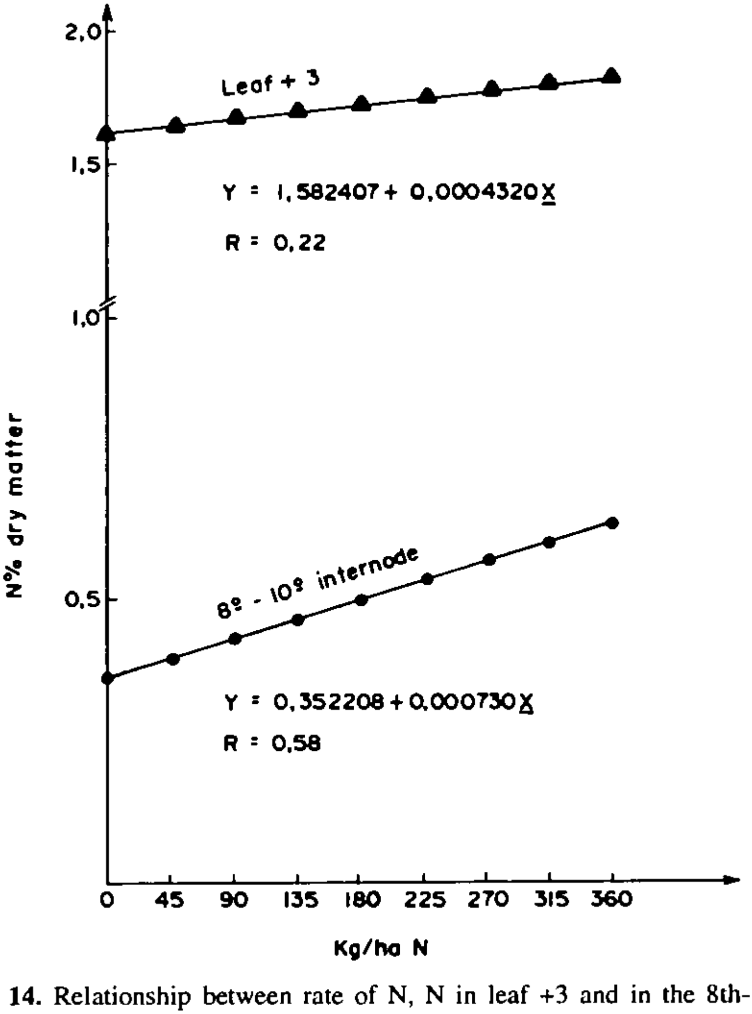

Fig. 14. Relationship between rate of N, N in leaf +3 and in the 8th-10th internodes (according to Santos *et al.*, 1977).

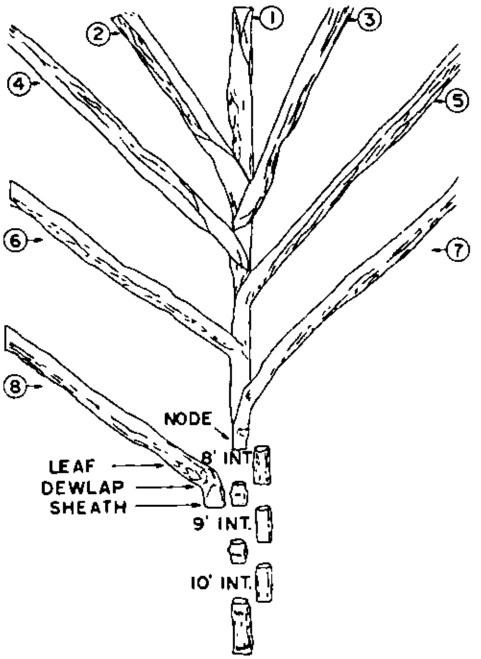

Fig. 15. Scheme showing the internodes used for analysis (8-10 stalk) (according to Santos *et al.*, 1977).

A new approach to determine the nutritional status was suggested by Bittencourt *et al.* (1992). It consists in the direct chemical analysis of the diluted juice in which P, K, Ca and Mg are determined.

Silva and Basso (1993) determined the activity of the acid phosphatase enzyme (which hydrolyses organic phosphates releasing inorganic P) in leaves of plants grown under varying levels of phosphorus in the substrate. As expected there was a negative correlation between enzyme activity and growth and P accumulated by the plants. Since the "de novo" synthesis of the enzyme is inhibited by the phosphate ion, its activity is inversely proportional to the P level in the tissue. It seems therefore that an early diagnosis of the P status of the plant can be achieved through the in vivo assay of the acid phosphatase enzyme as proposed by Besford (1980).

7. Fertilization

The aim of the fertilization program is to cover the difference between requirement and supply, that is:

(M) fertilizer = [M (requirement - supply)] f

wherein M = a macro or micronutrient, f is a factor higher than 1 destined to compensate for losses due to volatization, leaching, fixation and immobilization (see Fig. 4). Whenever the soil supply is lower than the crop requirement, fertilizers have to be added in order to increase and to keep M (soil solution) at a level compatible with the plant needs. In order to make practical fertilizer recommendations, we have to answer several questions, namely: What? Which element(s) is (are) limiting growth and production; How much? What quantity has to be added; When? In what epoch or epochs has fertilization to be done; How? What is the most efficient placement; With what? Which fertilizers are to be used; Effect on quality? Not only total tonnage of millable stalks are to be considered, the effect of the fertilizer on sugar yield has also to be taken into account; What are the effects of fertilizer use on the environment? Neither mineral or organic fertilizers, such as the by-products filter cake and vinasse should be used in such a way as to cause pollution of the soil, the water or the air; Does it pay? The increase in sugar yield per ha has to cover all the expenses involved with the fertilization, from its purchase to its storage and distribution in the sugarcane field.

7.1. What and how much ?

The capacity of the soil to supply nutrients can be evaluated through leaf analysis already dealt with, and more frequently via soil chemical analysis. It seems that no method of soil analysis is being routinely used in order to assess the need for nitrogen. Under Brazilian conditions, however, Alvarez *et al.* (1991) have found a significant and negative correlation between response of plant cane to nitrogenous fertilizers and soil organic matter content, according to the regression equation: $y = 99.6 - 26.81\ x + 1.620\ x^2$ wherein y = increase in yield, in tons/ha, due to N and x = percent of organic matter. Zero response would occur when x = 5.6%. In the case of plant cane, Weng and Li (1992) verified that the amount of N mineralized in the laboratory under incubation of soil samples is a parameter for the assessment of soil fertility. The quantities of N mineralized in one year varied, according to the estimates, between 260 and 330 kg N per ha. No net mineralized N was found in cane plant residues.

Available phosphorus is extracted by various solutions:
1) acidic - 0.05 N HCl + 0.025 N H_2SO_4 (Mehlich); 0.025 N HCl + 0.03 N NH_4F or 0.1 N HCl + 0.03 N NH_4F (Bray I and II, respectively); 2) alkaline - 0.5 M $NaHCO_3$ (Olsen); 3) buffer solutions of weak acids - 0.54 N HOAC - 0.7 N Na OAC pH 4.8 (Morgan). More recently Raij *et al.* (1986) in Brazil introduced a mixture of anion and cation exchange resins for the simultaneous extraction of P, K, Ca and Mg from the soil sample. Figure 16 shows the calibration curve obtained using Mehlich's extracting solution (also called North Carolina) (Orlando Filho and Rodella, 1983): A Relative Yield of 90% is achieved when soil P is equal to 30 ppm.

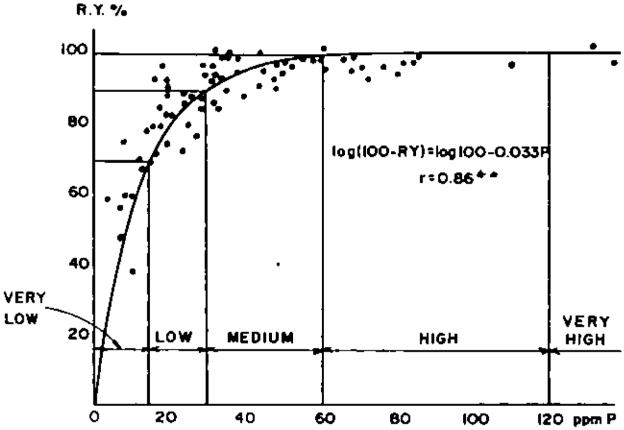

Fig. 16. Calibration curve for the relative yield of sugarcane as a function of soil P (Relative yield (R.Y.%) = $\frac{\text{yield without P}}{\text{yield with P}} \times 100$).

Routinely, available K, which comprises both solution and exchangeable potassium, predominantly the latter, is extracted by diluted acids, e.g. Mehlich's solution, or by salts of organic acids such as ammonium acetate. Figure 17 is a calibration curve for soil K extracted by the North Carolina solution: 90% Relative Yield is obtained with 80 ppm or 0.23 cmol kg^{-1}.

Sulfate sulphur is extracted by the solution of Morgan, by phosphate solutions containing acetic acid and others.

Several extractants are used for micronutrients: B - hot water, dilute HCl; Cu, Fe, Mn and Zn - Mehlich, in the case of acid soils and the chelating agent DTPA (diethylene triamine penta acetic acid) when the pH is 7 or above. Mo is extracted by an acidic solution of ammonium oxalate.

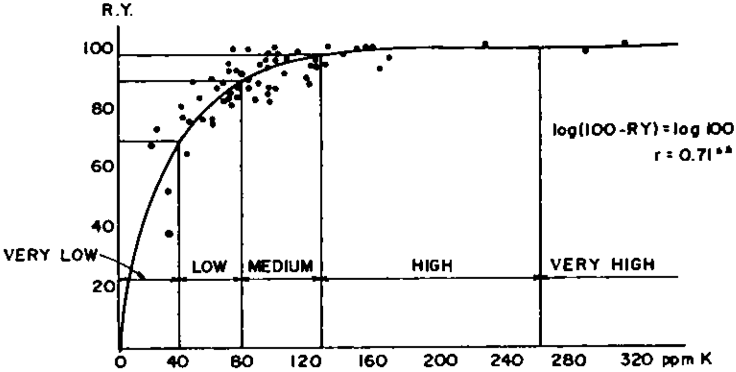

Fig. 17. Calibration curve for the relative yield of sugarcane as a function of soil K.

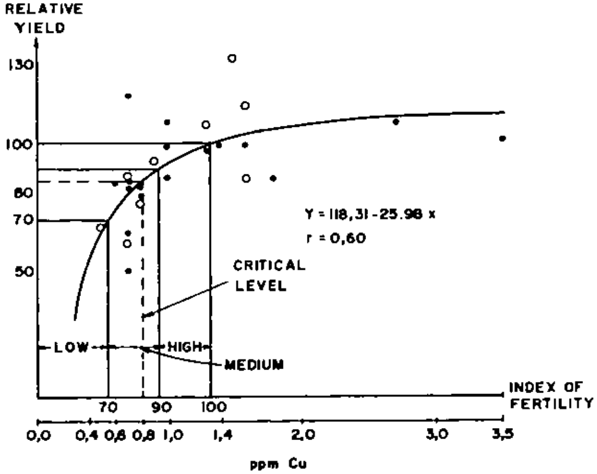

Fig. 18. The correlation between soil Cu and the relative yield.

The calibration for Cu extracted by Mehlich presented in Fig. 18 shows that a Relative Yield of 90% occurs when the soil supplies 0.8 ppm (Santos and Sobral, 1980).

Table 24 summarizes the rates of the primary macronutrients recommended in various countries and regions. The data were assembled by Srivastava *et al.* (1992) except in the following cases; Brazil-Malavolta (1982); Colombia-Garcia Ocampo (1991); Costa Rica-Chaves & Alvarado (1994); Cuba-Villegas (1994); Ecuador-Amores (1992); Mexico-Palacios (1990) quoted by Villegas (1994).

Table 24. Fertilizer recommendations.

Country or region	Crop	kg ha^{-1}			Notes
		N	P_2O_5	K_2O	
Argentina	-	100	Adapt. to requirem.		-
Australia	Plant cane	56	25- 80	75-150	In addition to Bureau mixture
	Ratoon	78	-	-	
Bangladesh	-	120	85	110	-
Brazil:					
North East	Plant cane	60- 80	80-180	30-120	N - 2/3 sidedressed P_2O_5 & K_2O - according to soil analysis
	Ratoon	60- 80	20-100	40-140	P_2O_5 & K_2O - same
South East	Plant cane	50- 90	50-110	20-120	See North East
	Ratoon	50- 90	25- 50	10- 80	
Cent. West	Plant cane	30- 40	30-120	30-120	See North East
	Ratoon	40- 60	15- 60	20- 90	
South	Plant cane	40-100	0-120	30-120	See North East
	Ratoon	20- 40	20- 60	0- 60	
British Guyana	-	65- 90	50-100	60-150	-
Colombia	Plant cane	50- 70	50-100	60-150	N-same doses sidedressed according to leaf analysis P_2O_5 & K_2O - rates depending upon soil analysis
	Ratoon	50-100	60-120	60-150	
Costa Rica	Plant cane	80-200	60-200	80-200	-
	Ratoon	100-250	50-200	80-250	-
Cuba	Plant cane	0	0- 50	0-120	P_2O_5 & K_2O - rates depend upon soil analysis and yield level
	Ratoon	35-150	0- 50	0-150	
Ecuador	Plant cane	120	75-135	75-195	N-1/3 sidedressed P_2O_5 & K_2O according to soil analysis
	Ratoon	90	-	-	
India:					
Subtropics	-	100-250	60	80	N: several dressings
Tropics	-	150-300	80-120		

Table 24. Continued.

Country or region	Crop	$kg\ ha^{-1}$			Notes
		N	P_2O_5	K_2O	
Indonesia	-	120	According to soil analysis		
Jamaica	-	80-160	According to soil analysis		
Mauritius	-	100-125	(2-1-1 mixture)		
Mexico	-	120-180	0-150	0-150	Most frequent rates: N-120; P_2O_5-60; K_2O-60
Pakistan	-	90-160	-	-	-
Philippines					
VMC District	-	125	120	180	-
Luzon	-	120-140	-	-	-
Puerto Rico	-	135-200	62	112	-
South Africa					
Coastal lowland	Plant cane	100-120	40	100	N & K_2O for plant cane in 2 applications
	Ratoon	140	20	150	
Natal midland	Plant cane	80	60	125	-
	Ratoon	120	40	175	-
Lowveld	Plant cane	120	30	125	-
	Ratoon	100	10	175	-
USA:					
Hawaii:					
irrigated	Plant cane	400	280	400-450	N split into 2 applications
rainfed	Plant cane	300	280	400-450	

Two examples explain how soil analysis is used to estimate the rate of P fertilizer. Table 25 shows the recommendations used in India according to Srivastava *et al.* (1992). In the Ferralsols of Cuba, P fertilization is estimated by taking into consideration the phosphate adsorption capacity which could be related to the concentration of the element in the soil solution as shown in Table 26 (Cabrera, 1994).

Table 25. Recommended rates of P_2O_5 based on soil analysis (India).

Method	Level of available P	Likelehood of response	Recommended rate kg ha^{-1} P_2O_5
Modified Truog	<25 kg ha^{-1}	certain	200-500
	25-45 kg ha^{-1}	uncertain	50-100
	>45 kg ha^{-1}	none	none
Modified Olsen	0- 6 ppm	certain	100-170
	7-14 ppm	uncertain	60-100
	>15 ppm	none	none

Table 26. Recommended rates of P_2O_5 for Cuban ferralsols according to P in soil solution.

Category	P in soil solution ppm	Recommended rate kg ha^{-1} P_2O_5
High fixer	<0.016	100
Medium fixer	<0.016-0.025	50
Low fixer	0.025-0.038	25
Very low fixer	>0.038	0

7.2. When ? (timing of application)

As shown in Figure 6, initially the quantities of N, P and K taken up and accumulated are very low. A period of rapid production of biomass is associated with increased rate of absorption of nutrients. Timing of application of NPK has to take into consideration the following points: period(s) of higher requirement; behaviour of the element in the soil. In practice, a compromise based on experimental results has to be made. However, such results are site specific and care must be used in extrapolating to other conditions. Both nitrogen and potash fertilizers tend to increase the osmotic pressure of the soil solution which when too high could damage the seed pieces or the roots. Nitrogen in mineral forms can be leached from the rhizosphere. The same is true for K in the case of soils with low CEC.

These facts seem to point out the need to apply only part of the N requirement at planting and of doing the same for potash in sandy soils. Phosphatic fertilizers may be applied in the planting furrow. The remaining N and K can be sidedressed at various intervals after germination. In the case of irrigated sugarcane the total amounts of N and K could be split into several applications.

The Risaralda sugar mill (Ingenio Risaralda) in the Department of Risaralda, Colombia, has one of the highest average yields of rainfed cane in the whole world: 128 tons per hectare as an average of 15 cuts. At planting 110 kg of P_2O_5 are usually applied; three months later 70-90 kg N and 30-60 kg K_2O (depending up on soil analysis) are distributed. Each ratoon, one month after cutting the previous crop, receives 120-140 kg N and 60 kg of K_2O; 3 and 4 months later 50-60 kg N are applied, each 3-4 ratoons 60 kg P_2O_5 (Ing. Agr. Jairo Cuellar, private communication, 1994).

The benefits of splitting the rates of N and K are frequently demonstrated by the experimental results. Table 27 shows the effect of split applications of N to an 18 month old crop (Toledo and Novaes, 1962); Table 28 gives results in 24 month old plant cane (Geus, 1973).

Table 27. Effects of split applications of N in 18 months crop (1).

Treatment	t ha^{-1}
Without fertilizer	44
P K	49
P K + 1/2 N at planting and 1/2 N beginning rainy season	62
P K + 1/3 N at planting, 1/3 N beginning rainy season, 1/3 N 3 months later	65
P K + 1/4 N at planting, 1/4 N beginning rainy season, 1/4 N 3 months, 1/4 N 5 months later	61

(1) N - 120 kg ha^{-1}; P_2O_5 - 120; K_2O - 80.

Table 28. Effects of split applications of N in 24 months crop (1).

Treatment	t ha^{-1}	
	Cane	Sugar
P K	135	22.5
P K + 56 kg N at planting	139	23.0
P K + 56 kg N sidedressed 3 months after planting	172	29.1
P K + 56 kg N sidedressed 12 months after planting	147	23.6

(1) Geus (1973).

It should be kept in mind, however, that late applications of N, particularly of high rates, should be avoided since although increases in millable stalk yield may occur, sucrose content could decrease due to the promotion of vegetative growth. In the experiment carried out by Alvarez and Freire (1962) in a light textured soil low in K (0.04 cmol kg^{-1}) when the total rate of K was divided into two applications, half at plant and half 2 months later (end of the rainy season), a significant increase in yield was obtained; splitting the total rate into 3 equal parts (planting, 2 and 9 months later) was less efficient (Fig. 19).

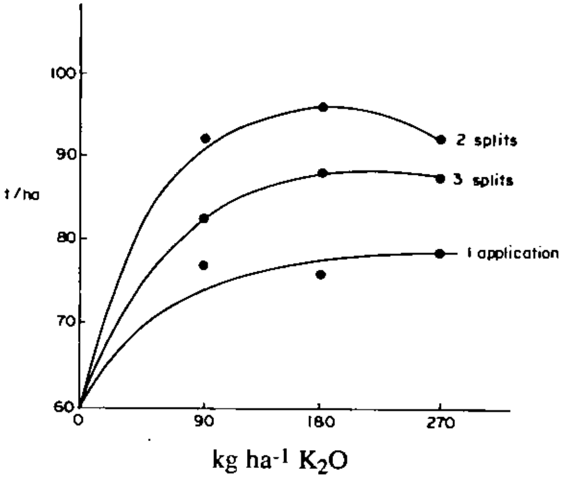

Fig. 19. Effect of rates and split applications of K_2O in plant cane.

7.3. How ? (placement)

The efficacy of placing fertilizer depends on several factors, such as: process of contact between the element and the root, distribution of the root system; type of crop (cane-plant, ratoon) and spacing, type of fertilizer and rate of application.

Barber (1966) and Barber & Olson (1968) have shown that root interception, mass flow and diffusion make the following percent contributions to the total of the element which reaches the root surface: N-1, 99, 0; P-2, 4, 94; K-2, 20, 78. While in the case of nitrogen mass flow plays an almost exclusive role for the contact, diffusion is the chief mechanism (94%) for P and for K (78%). It follows therefore that as long as P is placed adequately, both N and K will be taken up equally well.

Golden (1967) verified that vertical roots in the growing season develop in greater number and activity than the lateral ones. The ratoons have a shallower root system than plant cane, the old root system gradually dies and is replaced by a new one from the developing shoots. Placement studies with radioactive P showed that the optimum placement was in the planting furrow beneath the seed piece where the highest percentage of roots have access to the fertilizers (Humbert, 1968). For the ratoon crop the fertilizer (usually N and K, less frequently N P K) is placed in furrows on one side and as near to the cane row as possible or, when planting is closer, in the middle of the rows (Nelson, 1980) shortly after harvesting (Tables 29 and 30).

Table 29. Effect of method of P application on plant cane in Brazil (1).

Treatment	t ha^{-1}
Deep placement	103
Surface application	90

(1) Orlando Filho *et al.* (1979).

Table 30. Response of the ratoon crop to the method of P application and to residual P as superphosphate in South Africa (Geus, 1973).

Treatment	Cane yield t ha^{-1}
1. No P	37.5
2. Broadcast	81.0
3. Band 10-15 cm wide, one side of the cane row	75.0
4. Deep placement (22.5 cm and in band 10-15 cm as before)	73.0
5. Application in furrow at plant cane	109.2

When anhydrous ammonia or acqua ammonia is the nitrogen source, it has to be applied in furrows and immediately covered to avoid loss of N by volatilization. Depending upon climatic conditions, urea N applied to the soil surface, particularly when urease-rich crop residues are present, could be lost to the atmosphere in large proportions. Denmead *et al.* (1990) in Australia reported that 30-40% of urea N could be lost when applied to the trash blanketed surface of cane plots. When the rainfall, immediately after urea use, was greater than 13 mm, however, the applied urea was leached from the trash into the soil and volatization virtually ceased.

High rates of N and K should not be applied close to the seed piece in the planting furrow due to the risk of increasing too much the osmotic pressure of the soil solution. In such conditions, part of the fertilizer should be sidedressed. On the other hand, the association between broadcast (before planting) and furrow applied P could be profitable, as demonstrated by Morelli *et al.* (1991) who used magnesium thermo-phosphate as a source of phosphorus: the treatment with 200 kg P_2O_5 ha^{-1} broadcast plus 100 kg P_2O_5 ha^{-1} furrow applied was the most economical for cane production: this resulted in yield increase of 27.3 t ha^{-1} in plant cane and 35 t ha^{-1} in the first ratoon.

N and K fertilizers can also be applied in irrigation water (for details see Humbert, 1968).

When N and K are applied in split dressings, it is almost impossible to apply fertilizers on the soil surface after the crop has developed a close canopy. The fertilizer can then be spread from the air. According to Samuels (1969) when urea is applied on closed in cane, nearly 95% falls on leaves and stalks and only 5% reaches the soil directly. Urea on the leaf surface is dissolved by the transpired or dew water and is promptly absorbed: 75-80% enters the plant within 24-48 h. In terms of change in leaf N, soil applied urea is slower-acting. There is no leaf burn provided the leaf sheaths have a minimum of 80% moisture at the time of application. Aerial application of KCl (100-200 kg/ha) is also used in several sugarcane growing regions; urea and muriate of potash may be applied together to avoid nutritional unbalance. In poorly drained Hawaiian soils, it was found that 19 kg K_2O leaf applied gave better results than 200 kg to the soil surface.

7.4. Which fertilizer?

Table 31 lists the main fertilizers used in the sugarcane world. Main products containing micronutrients are shown in Table 32. At planting N, P and K are commonly applied, whereas as sidedressing only N or N and K are used. The use of fluid fertilizer seems to be expanding due to the lower cost of both products and application. Frequently the blends are made at the sugar mill which buys in the raw materials: anhydrous ammonia, phosphoric acid or monoammonium phosphate and muriate of potash. Sometimes rock phosphate plus sulfuric or phosphoric acid is used to obtain a suspension with partial acidulation. Typical formulations (suspensions) used in Brazil are: 3-15-10, 12-4-12, 12-6-18, 10-0-18, 15-0-15. Further details can be found in Palgrave (1991) and in Malavolta (1993).

All mineral sources of N are considered equally effective according to Srivastava *et al.* (1992). Samuels and Capó (1956) mention that experiments were carried out in Puerto Rico since the year 1910 in order to compare N sources (Table 33). As shown in Table 33, with the exception of tankage (a slaughterhoue residue) which has lower availability, the results are equally effective. The method of application of nitrogenous fertilizers depends upon their solubility, which influences the relative efficiency: Alvarez *et al.* (1957, 1958) demonstrated that when the full dose was applied in the planting furrow, both castorseed meal and, hornmeal, sources which gradually release N, gave higher yields than other mineral sources: when split applications were made, however, the results were equivalent (Table 34), except for calcium cyanamide which was distributed in the furrow.

Brinholi *et al.* (1980) applied anhydrous ammonia and ammonium nitrate to ratoons and found both to give the same increases in yield, but a higher profit was obtained with the first source due to lower unit cost of N. Malavolta (1980) has summarized the results of many experiments designed to compare sources of N. The data indicated that the yield response of different N-fertilizers was practically the same, although some slight deviation may occur: ammonium sulfate could produce more on a S deficient soil, for instance.

Water-soluble forms of P (superphosphates, ammonium phosphates) are preferred on soils of high pH such as those rich in calcareous silt. Less soluble forms are beneficial on acidic or lateritic soils. In Australia, for example, large dressings of finely ground, soft rock phosphate are used to build up soil reserves, followed by smaller annual applications of soluble forms (Srivastava *et al.*, 1992).

Table 31. Fertilizers commonly used on sugarcane (1).

Fertilizer	Nutrient content %						$CaCO_3$ equivalent	Salinity
	N	P_2O_5	K_2O	Ca	Mg	S		
Anhydrous ammonia	82	-	-	-	-	-	1.5	47
Acqua ammonia	16-25	-	-	-	-	-	-0.3 -0.5	?
Ammonium nitrate	33	-	-	-	-	-	-0.6	105
Nitrochalk	27	-	-	3	2	-	-0.3	61
Ammonium sulfate	21	-	-	-	-	24	-1.1	69
Calcium nitrate	15	-	-	26	-	-	+0.2	65
N solutions	21-49	-	-	-	-	-	-0.4 -0.9	78
Urea	45	-	-	-	-	-	-0.8	75
Sodium nitrate (Chilean)	16	-	-	-	-	-	+0.3	100
Diammonium phosphate	16	48	-	-	-	-	-0.7	34
Monoammonium phosphate	10	50	-	-	-	-	-0.6	30
Nitrophosphates	14-22	10-22	-	6- 8	-	-	-0.1 -0.3	?
Sodium and potassium nitrate	15	-	14	-	-	-	+275	92
Simple superphosphate	-	20	-	18	-	12	0	8
Triple superphosphate		45	-	10	-	1	0	10
Thermophosphate	-	19	-	20	9	-	+500	-
Rock phosphate	-	26-37	-	25-28	-	-	+100	-
Potassium chloride	-	-	60	-	-	-	0	116
Potassium sulfate	-	-	50	-	-	18	0	46
Potassium nitrate	14	-	44	-	-	-	+260	74

(1) $CaCO_3$ equivalent: + alcalinity, tons carbonate/ton product; salinity: relative to sodium nitrate.

Table 31. Fertilizers commonly used on sugarcane (1).

Fertilizer	Nutrient content %						$CaCO_3$ equivalent	Salinity
	N	P_2O_5	K_2O	Ca	Mg	S		
Anhydrous ammonia	82	-	-	-	-	-	1.5	47
Acqua ammonia	16-25	-	-	-	-	-	-0.3 -0.5	?
Ammonium nitrate	33	-	-	-	-	-	-0.6	105
Nitrochalk	27	-	-	3	2	-	-0.3	61
Ammonium sulfate	21	-	-	-	-	24	-1.1	69
Calcium nitrate	15	-	-	26	-	-	+0.2	65
N solutions	21-49	-	-	-	-	-	-0.4 -0.9	78
Urea	45	-	-	-	-	-	-0.8	75
Sodium nitrate (Chilean)	16	-	-	-	-	-	+0.3	100
Diammonium phosphate	16	48	-	-	-	-	-0.7	34
Monoammonium phosphate	10	50	-	-	-	-	-0.6	30
Nitrophosphates	14-22	10-22	-	6- 8	-	-	-0.1 -0.3	?
Sodium and potassium nitrate	15	-	14	-	-	-	+0.3	92
Simple superphosphate	-	20	-	18	-	12	0	8
Triple superphosphate		45	-	10	-	1	0	10
Thermophosphate	-	19	-	20	9	-	+0.5	-
Rock phosphate	-	26-37	-	25-28	-	-	+0.1	-
Potassium chloride	-	-	60	-	-	-	0	116
Potassium sulfate	-	-	50	-	-	18	0	46
Potassium nitrate	14	-	44	-	-	-	+0.3	74

(1) $CaCO_3$ equivalent: + alcalinity, tons carbonate/ton product; salinity: relative to sodium nitrate.

Table 32. Main sources of micronutrients.

Product	Micronutrient	Content %
Borax ($Na_2B_4O_7.10H_2O$)	B	11
Solubor ($Na_2B_4O7.5H_2O + Na_2B_{10}O_{16}.10H_2O$)	B	20
Boric acid (H_3BO_3)	B	17
Cupric sulfate ($CuSO_4.5H_2O$)	Cu	25
Cupric oxide (CuO)	Cu	75
Cu-chelates	Cu	5-13
Ferrous sulfate ($FeSO_4.7H_2O$)	Fe	25
Fe-chelates	Fe	5-14
Manganous sulfate ($MnSO_4.H_2O$)	Mu	26-28
Oxide (MnO)	Mu	41-68
Mn-chelates	Mu	8-12
Sodium molybdate ($Na_2MoO_4.2H_2O$)	Mo	39
Ammonium moly. (NH_4) $6Mo_7O_{24}4H_2O$	Mo	54
Molybdenum oxide	Mo	66
Zinc sulfate ($ZnSO_4.7H_2O$)	Zn	23
Oxide (ZnO)	Zn	30-78
Zn-chelates	Zn	5-13

Table 33. Relative efficiency of nitrogenous fertilizers in Puerto Rico.

Source	Relative yield
Ammonium sulfate	100
Ammonium nitrate	94
Calcium cyanamide	98
"Nugreen"	104
Sodium nitrate	100
Tankage	99
Uramon	96
Urea formaldehyde	94

Table 34. Effect of nitrogenous fertilizers applied to plant cane in Brazil.

Treatment	Yield (t/ha)
Control (no N)	81
Castorseed meal	91
Chilean nitrate of sode	89
Ammonium sulfate	91
Nitrochalk	91
Calcium cyanamide	82
Urea	88

Figure 20 taken from Malavolta (1982) shows the results of experiments carried out in Brazil to compare different phosphates: except for rock phosphates of low reactivity (apatites), the different P sources are equally effective.

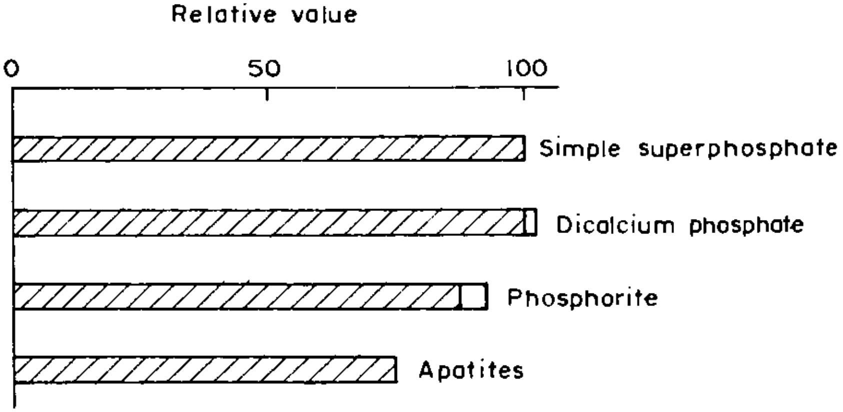

Fig. 20. Relative value of several phosphates.

Table 35 gives data from 17 experiments analyzed by Freire *et al.* (1968). Dicalcium phosphate and magnesium thermo-phosphate, in which a large proportion of the total P is soluble in neutral ammonium citrate, gave results equivalent to water soluble superphosphate.

Table 35. Relative efficiency of simple superphosphate (=100) and other phosphatic fertilizers applied to cane plant at the rate of 100 kg ha^{-1} P_2O_5.

Fertilizer	Number of cents	Relative efficiency
Dicalcium phosphate	4	105
Thermophosphate	3	107
Bonemeal	5	91
Olinda phosphorite	4	63
Alvorada apatite	6	61
Araxa apatite	2	57
Phosphorus bauxite	3	40

A rise in soil pH could reduce the efficiency of less soluble phosphate, particularly that of rock phosphates (Table 36).

Table 36. Influence of soil pH on the efficiency of various phosphates (single superphosphate = 100).

Fertilizer	pH	
	5.0	5.5
Thermophosphate	112	102
Dicalcium phosphate	116	97
Bonemeal	93	88
Apatite	76	49

As in the case of nitrogenous fertilizer which may contain other elements besides N (S, ammonium sulfate) the response to phosphate fertilizers could be in part due to other elements: in the experiment conducted by Ferreira *et al.* (1989) yields from magnesium multiphosphate were higher than those obtained with triple superphosphate thanks to the presence of S (multiphosphate is a modified form of single superphosphate). In all cases it should be kept in mind that the effect of P applied to cane plant usually lasts for several ratoons which frequently obviates the need for other applications until the cycle starts all over again.

Potassium chloride and potassium sulfate are equally effective except, of course, in soils which are deficient in S.

7.5. Effect on quality

It is well known that "sugar is made in the field, not in the factory". Sugar formation and accumulation is a function of several variables: variety and age or duration of the crop cycle, climate conditions (moisture, light, temperature), soil fertility and fertilization. The effect of fertilization of course, reflects to a large extent the role played by the nutrient in the physiological process within the plant, particularly photosynthesis, transport and accumulation of sucrose (the sink source relationship) as already discussed.

Nitrogen: According to Geus (1973), an increase in the rate of N raises yields of stalk and sugar until yield reaches a maximum. If nitrogen is applied in excess of the optimum, sugar production may drop. Hodnett (1956) reviewed 767 experimental results obtained since 1930 in the former British Empire, and estimated that each 56 kg ha^{-1} of N applied caused a decreased in the range of 0.04 to 0.33% in the concentration of sucrose. This decrease, however, is not an invariable rule.

Valdivia *et al.* (1978) in Peru, where N is usually applied at the beginning of vegetative growth, report no negative effect of high rates of nitrogen: the use of 300 kg ha^{-1} N or more causes no damage to the quality. Late applications of N, about 2 months before harvesting, associated with plenty rainfall (75-150 mm) reduce both sugar concentration and purity. As time of cutting approaches, N levels in the plant should be sufficiently low to restrict vegetation and to promote an increase in sucrose content. The effect of timing of N application on the sugar yield was demonstrated by Chwan-Chau (1976) among others: late application at 10 months caused a decrease in the sugar yield of 14 g per stalk when compared to the application at 7 months. There are, however, varietal differences. Marinho *et al.* (1975) in Brazil verified that in some varieties the use of rates as low as 50 kg ha^{-1} N decreased pol % and purity. In other varieties no unfavourable effect was observed.

Phosphorus: Humbert (1968) has analysed the results of 354 experiments conducted during 1940-1954: in no case did P fertilizer impair cane quality while it was improved in 7-13% of cases. Hodnett (1956) found both positive and negative results as a consequence of the applications of 56 kg ha^{-1} P_2O_5. Marinho *et al.* (1975) in their turn found that, when used at rates higher than 100 kg ha^{-1} P_2O_5, the element can reduce yield, sugar concentration, pol % and purity, particularly in ratoons and in soils not deficient in phosphorus. On the other hand, in P deficient soils there was an increase in pol % and purity when the rates varied between 50-100 kg ha^{-1} P_2O_5.

The amount of P in cane juice has an effect on clarification and should be in the range of 132 to 264 ppm P when lime is used for clarification. Other methods of clarification may need lower values. Serra *et al.* (1974) mentioned that P - poor juices give more turbid clarified juices which is due to lower amounts of precipitates being formed in the process. It is cheaper, however, to add P in the clarification directly than to try to make the juice richer through the use of phosphatic fertilizers in cases where there is no gain in yield of stalks.

Potassium: Potassium applications seem to influence both millable stalk yield and sucrose content in the same direction as pointed out by Samuels and Landrau Jr. (1956). In other words: as the supply of K is increased there are raises in yield and sugar % of cane and in Brix % juice also. This trend was also observed by Hodnett (1956) in his review paper: K deficiency or less than adequate supply reduces stalk yield and juice quality. Both photosynthetic rate and sucrose transport from the leaf into the stalk are impaired.

There is close partnership (or positive interaction) between N and K: the reduction in sugar content caused by high rates of N is ameliorated by an adequate supply of K as shown in Table 37 taken from Geus (1973): the applications of nitrogen in the absence of K led to a lowering in sugar concentration, whereas the addition of the latter to a large extent restores the sucrose content.

Table 37. Effects of N and K on percentage of sucrose.

K_2O	N kg ha^{-1}					
kg ha^{-1}	0	100	200	300	400	Average
0	17.3	16.6	16.2	15.8	15.7	16.3
100	16.9	18.3	17.3	16.3	16.4	17.0
200	17.3	17.2	17.6	17.2	17.6	17.4
300	18.1	17.4	17.7	17.7	17.1	17.6
400	17.4	17.6	17.1	17.0	17.4	17.3
Average	17.4	17.4	17.2	16.8	16.8	17.1

No detrimental effect of K on quality was observed in the experiments carried out by Marinho *et al.* (1975). In 15% of the trials, there was a positive effect. According to Orlando Filho (1985), increasing dosages of K may exert a negative effect on apparent sucrose percent in cane (pol % cane) and may promote an increase in the ash content of juice.

Increased ash content in cane juice has a negative influence on sugar quality since K is the main constituent of juice ashes. Potassium passes through the clarification process affecting the exhaustion of the final syrup, keeping a certain amount of sucrose in solution. K is a mellassigenic substance because one mol of K holds one molecule of sucrose. The unfavourable effects of K however, should be anticipated only when excessive rates are used: in low potassium soils improvement in cane quality are to be expected, as shown in Figure 21 (Malavolta, 1982).

Other elements: Silva (1983) has summarized the effect of other elements on the quality of sugarcane according to the world literature. Calcium supply raises sucrose content and helps to reduce the negative effect of the excessive N/K ratio. Sugar concentration is reduced when Mg is deficient. The increase in sugar yield per hectare due to the addition of S observed by Malavolta *et al.* (1989) was due both to higher production and higher sucrose concentration.

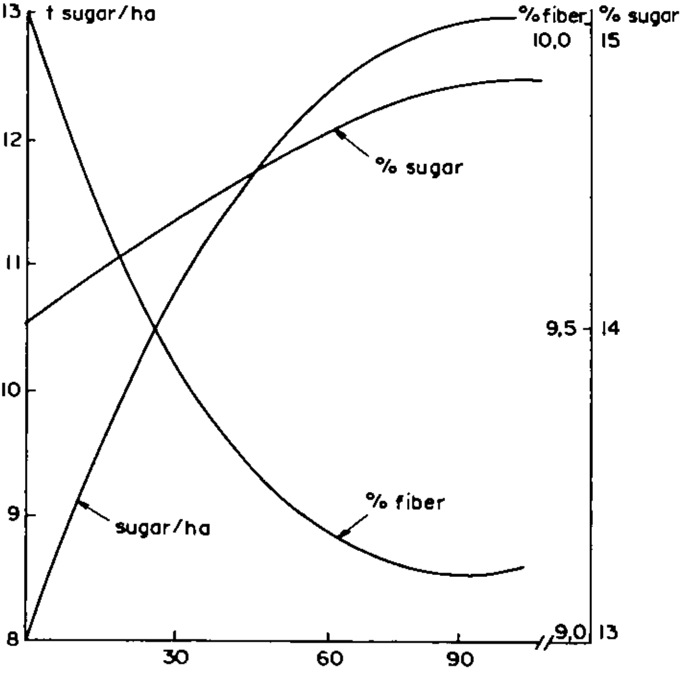

Fig. 21. Effect of applying K on sucrose yield, sucrose and fiber contents.

7.6. Effect on the environment

Proper management of sugarcane plantations should aim for high yields and economic returns, while avoiding detrimental impacts on the environment -air, water, soil. This subject has been covered by Rosseto (1987) and more recently by Cabrera (1994) and Orlando Filho (1994).

Ripoli *et al.* (1991) estimated that a production of 78 tons of millable stalk per hectare leaves a mass of residue of 22 tons which represents an energy potential of 29 barrels of oil or the equivalent of 9066 liters of ethanol. The usual practice of burning trash before harvesting, therefore, causes a loss of a large proportion of the energy stored in the biomass. Nevertheless the practice continues since it makes the cutting more efficient and cheaper whether it is done by hand or by machine. The pressure of the environmentalists, however, is leading sugar mills to use raw cane harvesters at least when plantations are close to towns. There is no evidence that soil properties, either physical or chemical, are damaged by burning of the trash. Particulates released in the atmosphere constitute a nuisance rather than a health risk. Carbon released in the atmosphere in all sugarcane regions correspond to 37 $\times 10^6$ tons per year, which represents 10% of the total world output.

The efficiency of recovery of the applied N can be as high as 52.9% depending upon the timing of applications (Weng *et al.*, 1993) in the case of plant cane, and it could be even higher in the ratoons. There is unlikely to be any danger of increasing the nitrate content of drinking water which might result in a health risk. In fact, no case of contamination of reservoirs in sugarcane areas has been reported in the literature. Neither is there been any mention of eutrophication of lakes or ponds due to phosphorus originating from cane fields. Most of the applied P not used by the plant remains fixed in the soil, the quantities leached and carried by run off being negligible (CEA, IFA and IPI, 1983).

Erosion, besides decreasing soil fertility by carrying away part of the topsoil, contributes to the pollution of rivers and lakes due to the pesticide residues it may transport. Because sugarcane provides a good soil cover and is usually planted on terraces on slopes, it is less susceptible to erosion than other crops. Minimum or zero tillage is increasingly used and this minimizes erosion damage.

Each ton of millable cane generates: 100-150 kg of sugar, 85 kg of alcohol, 250-280 kg of bagasse, 25-40 kg of filter press cake and about 7 kg of ash (from bagasse burning in the boilers). When alcohol is produced, each liter generates about 12 liters of distillery slops or vinasse. The three residues or by-products, ash, filter cake and vinasse are recycled back to the field. For this reason, rather than polluting, they contribute for the maintenance or improvement of soil physical, chemical and biological conditions.

7.7. Does it pay?

Liming: When sugarcane is grown continuously, and soil acidity is not corrected, production tends to decline. Liming can bring about considerable increase in yield as shown in Table 38 prepared with data obtained by Wutke *et al.* (1960) and Wutke and Alvarez (1968).

In the first period, 5 t ha^{-1} of dolomitic limestone were applied; in the second period only the residual effect was observed, and in the third 3 tons of limestone were distributed.

Table 38. Effect of liming in sugarcane production.

Treatment	1st period 1954-56	2nd period 1956-58	3rd period, 1958-61 Plant cane	3rd period, 1958-61 Ratoon
	t ha^{-1}			
Control	52	31	36	26
NPK	79	69	84	64
NPK + lime	88	94	128	73

The effect of the treatments on soil characteristics can be seen in Table 39. In South Africa, according to Wood (1993), marked responses in cane yield were obtained on midland soils, in most cases without any significant influence on cane quality. One trial, however, indicated that liming depressed sucrose percent in cane, and this decline was accompanied by a general increase in leaf N. It is probable that liming increased release of N by mineralisation of the organic matter under these conditions. Therefore, N rates may be reduced. In Brazil no increase in yield due to lime is likely when the soil has more than 2.2 meq of Ca + Mg per 100 ml. In Puerto Rico responses to lime were not observed when pH was above 5.5 (Samuels and Capó, 1956). Calcium and Mg fertilizers are recommended in South Africa based on soil threshold values of 150 ppm Ca and 25 ppm Mg (0.75 and 0.20 meq, respectively): compare these values with data in Table 39.

Table 39. Results of soil analysis after cutting plant cane.

Period	NPK	NPK + lime
<u>First</u>		
pH	4.7	5.8
Ca, cmol kg^{-1}	0.33	-
Mg, cmol kg^{-1}	0.02	-
<u>Second</u>		
pH	4.5	5.9
Ca, cmol kg^{-1}	0.26	2.66
Mg, cmol kg^{-1}	0.12	1.59

Gypsum: Gypsum ($CaSO_4.2H_2O$) plays several roles in crop production: source of S and Ca; ameliorant for aluminum toxicity and subsoil acidity; ameliorant for sodic soils; ameliorant for non-sodic dispersive soils, subsoil hardpans and hardsetting clay soils.

Two recent reviews should be read for details - Shainberg *et al.* (1989) and Alcordo and Recheigl (1993). The experiment carried out by Morelli *et al.* (1992) on a medium textured Latosol was designed to study the effects of both limestone and gypsum on yield and chemical soil properties. Before the treatments, the soil in question had an Al saturation of 75% and Ca saturation of the effective cation exchange capacity as low as 14%. Base saturation increased consistently according to the rates of lime applied (0, 2, 4 and 6 tons per ha) down to 25 cm only. Gypsum, however, increased base saturation regardless of depth and sampling time but induced leaching of Mg below the depth of 50 cm, giving a better distribution of Ca and Mg in all soil layers (0-125 cm), an increase in base saturation and a reduction in exchangeable aluminum, and giving the largest gain in yield (Table 40). The highest yield increase (sum of 4 cuts: 77 tons of millable stalk) and economic return were obtained with the use of 4 tons of lime and 2 tons gypsum.

Table 40. Sugarcane production in response to the use of limestone and phosphogypsum average of plant cane and 3 ratoons.

Limestone	Gypsum ($t\ ha^{-1}$)			
($t\ ha^{-1}$)	0	2	4	6
0	99	106	111	111
2	110	113	117	114
4	112	121	117	118
6	110	117	113	118

Nitrogen: According to Orlando Filho (1994), under Brazilian conditions plant cane responds to N application much less frequently than ratoons. Responses have occurred under three conditions: when first planted in a particular place; when minimum tillage is used; in eutrophic soils.

As shown in Figure 22, however, under Colombian conditions the effect of N applications appears from the first to the tenth crop. It is likely that the absence of response to N shown by plant cane is due to the sufficient supply represented by the mineralization of both soil organic matter and crop residues which is enhanced by the operations which improve soil aeration. On the other hand, it has been shown (Malavolta, 1991, unpublished) in Podzolic soils that the response to N applied to plant cane shows up in the first ratoon: this is because part of the element is stored in the roots (Trivelin *et al.*, 1988) and used for the growth of the next crop in addition to the nitrogen applied to the latter. Actually studies conducted in South Africa in sugarcane soils have shown a capacity of mineralization of N in the range of 44 to 143 kg/ha (Geus, 1973).

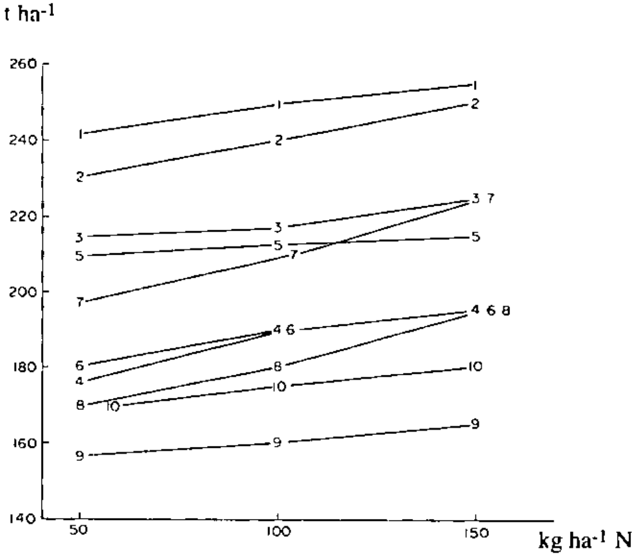

Fig. 22. Production of the variety CP 57-603 in a Mollisol of the Ingenio Manuelita in the valley of the Cauca River, Colombia, in 10 successive cuts (Quintero, 1994).

Phosphorus: According to Nelson (1980) responses obtained to an average P_2O_5 applications of 85 kg ha^{-1} on responsive soils in various parts of the world average 9 ± 1 kg of sugar per kg of P_2O_5 applied. As with other crops, responses vary with soils and decrease with successive increments. Responses are usually greater with plant cane than with ratoons. Table 41 shows the responses obtained in Brazil in 392 experiments studied by Malavolta (1980). It can be seen that responses to P in the range of 4 (not significant) to 89 tons per hectare were obtained, being more frequent in the case of plant cane. Considering both plant cane and ratoon there were slightly more responses to K than to P.

Sulphur: Malavolta *et al.* (1989) conducted 5 experiments with an average of 4 cuts each (1 plant cane + 3 ratoons). Irrespective of soil and variety, 30 kg of S per hectare was enough to reach maximum sugar yields in the case of cane plant. For ratoon crops, 15 kg of S per hectare was sufficient. In the case of plant cane the rates correspond roughly to 1/5 of the rate of P_2O_5 whereas for ratoons 15 kg S translates into 1/5 of the applied N. As a general rule 1 kg of S used either on cane plant or ratoon yielded an average of about 100 kg of sugar.

Table 41. Experimental results obtained in Brazil.

Experiments	Plant	Ratoon	Total
Total number	268	124	392
Nitrogen			
Responses	170	71	241
Percent of total	63	57	61
Effect (+ ton/ha)	6-35	5-36	-
Phosphorus			
Responses	202	73	275
Percent of total	75	59	70
Effect (+ ton/ha)	4-86	8-89	-
Potassium			
Responses	206	86	292
Percent of total	77	69	74
Effect (+ ton/ha)	1-38	3-31	-

Good correlations were found between available SO_4-S in the surface soil and sugarcane production. Responses to S were observed when the SO_4-S content in the topsoil was below 5 ppm of SO_4-S. In South Africa, Wood (1993) in soil testing less than 15 ppm SO_4-S obtained an average increase of 7 tons of cane per ha when 20-25 kg ha^{-1} S were applied.

Micronutrients: Samuels and Capó (1956) explained the lack of effect of the addition of micronutrients in Puerto Rico as a consequence of the large root system which explores a soil volume big enough to supply the elements needed. However, in other regions, beneficial effects of micronutrients are observed. Argentina. Mogilner *et al.* (1960) observed that two sprays of copper sulfate and zinc sulfate, at a concentration of 0.005%, the first at tillering and the second one month before the harvest gave satisfactory results in terms of increase in sugar yield. Australia. Zinc deficiency has been identified in Queensland. Extraction of soil Zn with 0.1 M HCl, a procedure suitable for commercial laboratories, has confirmed the deficiency (Anon., 1990). Bolivia. In soils with pH between 6.8 and 7.4, Cochrane (1979) could correct Mn deficiency thanks to applications of acid forming ammonium sulfate which, by lowering pH increases the availability; same result was achieved by applying in the fertilizer blend 8 kg of Mn in the sulfate form; leaf Mn in the +1 leaf was raised from 23 to 43 ppm.

In the same soil, Zn deficiency was corrected by the use of 6 kg of the element per ha, in the form of sulfate, which raised leaf Zn to 12 ppm. Interesting is the fact that Zn application also promoted an increase in the Mn content.

Brazil. Table 42 shows that the utilization of B, Cu, Fe and Mo increased yield in a Podzolic soil with no effect, however, on a Latosol, both under sugarcane for many years (Alvarez and Wutke, 1963).

Table 42. Yield response of cane variety Co 419 to micronutrient application.

Treatment	Yield t ha^{-1}	
Soil:	Podzolic	Latosol (1)
NPK	124	109
+ B	146	111
+ Cu	132	107
+ Fe	136	111
+ Mn	127	110
+ Mo	136	115
+ Zn	128	110

(1) Average of 2 experiments.

Figure 23, prepared with data obtained by Marinho and Albuquerque (1981) in the Northeast region, shows a remarkable effect of Cu.

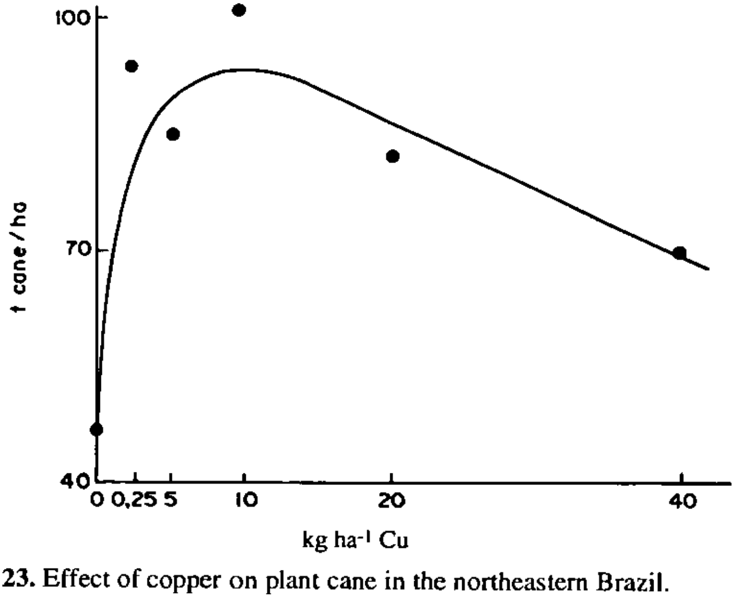

Fig. 23. Effect of copper on plant cane in the northeastern Brazil.

The rate of 5.0 kg Cu (as copper sulfate) used in the planting furrow was also capable of increasing the first ratoon yield by 19 tons of stalk. Available Cu in the soil extracted by Mehlich 1 (0.05 N HCl + 0.025 N H_2SO_4) was 0.25 ppm; 5.0 kg ha^{-1} Cu raised the level to 0.63 ppm. The most economical rate of Cu was estimated to be 7.0 kg Cu per hectare.

Responses to Zn were observed when level in the soil was lower than 0.5 ppm. In one experiment the following increases in yield due to 10 kg ha^{-1} Zn (as sulfate) applied in the planting furrow, were obtained respectively in plant cane, first and second ratoon: 9.8 and 20 t ha^{-1}. Most economical rate was 7 kg ha^{-1} Zn. As a consequence of the application of 10 kg ha^{-1} Zn, available (Mehlich) zinc in the soil increased from 0.45 to 3.0 ppm. As in the case of the experiment with Cu, soil samples were taken for analysis between the three central rows (3 subsamples) and in the central planted row, at a depth of 20 cm. Responses to Mn (5.0 kg per hectare as sulfate in the planting furrow in the NPK mixture plus 2.0% manganese sulfate as spray 90-120 days after planting) were obtained by Azeredo and Bolsanello (1981) both in Central West and South East: yields of plant cane were increased respectively, by 28 and 10 tons per hectare. A significant increase in yield of about 10 tons per ha was obtained in a sandy clay Oxisol when 10 kg of Zn ha^{-1} (as sulfate) were applied in the planting furrow. Soil Zn was raised from 0.29 to 3.5 ppm whereas leaf zinc was raised from 11 to 44 ppm (leaf + 3 sampled months after germination). The response curve was $y = 118.01 + 1.77\,x - 0.07\,x^2$ wherein x = kg ha^{-1} Zn and y = tons of cane ha^{-1}. The most economical rate of Zn application, 11 kg ha^{-1}, was calculated by making the derivative $dx/dy = 1.77 - 0.14\,x$ equal to the ratio price kg Zn:price ton of cane (Cambraia *et al.*, 1989). As a rule in Brazil in areas of known Zn deficiency 5 kg of the element per ha should be used at planting.

India. Lime induced chlorosis was corrected by 2 foliar sprays of 2% ferrous sulphate at an interval of 15 days. In another trial foliar sprays of 0.5% ferrous sulphate or iron chelate (1 kg ha^{-1}) restored the green colour in the chlorotic leaves within a fortnight. Application of sulphitation press mud, a by-product of the sugar factory, at 5 t ha^{-1}, gave about 58% more cane yield over control affected by chlorosis (Yadau and Singh, 1988). Acute deficiency and toxicity of Cu reduced concentration of chlorophyll, nucleic acids, sugar and the activity of ascorbic acid oxidase, polyphenoloxidase and cytochrome oxidase. Cu deficiency threshold could be indicated by the activities of ascorbic acid and cytochrome oxidase. Deficiency, threshold of deficiency and toxicity values of Cu in young leaves 9 months after sowing were, respectively 4, 8 and 19 ppm Cu in dry matter (Agarwala *et al.*, 1993).

Pakistan. According to Saleem *et al.* (1992), foliar sprays of Zn, Mn and B, as well as other practices (hot water treated progeny seed, fungicide, applications of NPK) are necessary to obtain maximum sugarcane yields.

Taiwan. Juang *et al.* (1978) carried out several experiments using Zn rates varying from 25 to 50 kg ha^{-1} in the sulfate form. Calculations of the marginal economic yield showed the benefit of using 25 kg ha^{-1} Zn which caused yield increases as high as 23 tons per hectare. Figure 24 demonstrates that maximum yield occurred when soil Zn (extracted by 0.1 N HCl) was about 12 ppm; leaf zinc was about 60 ppm.

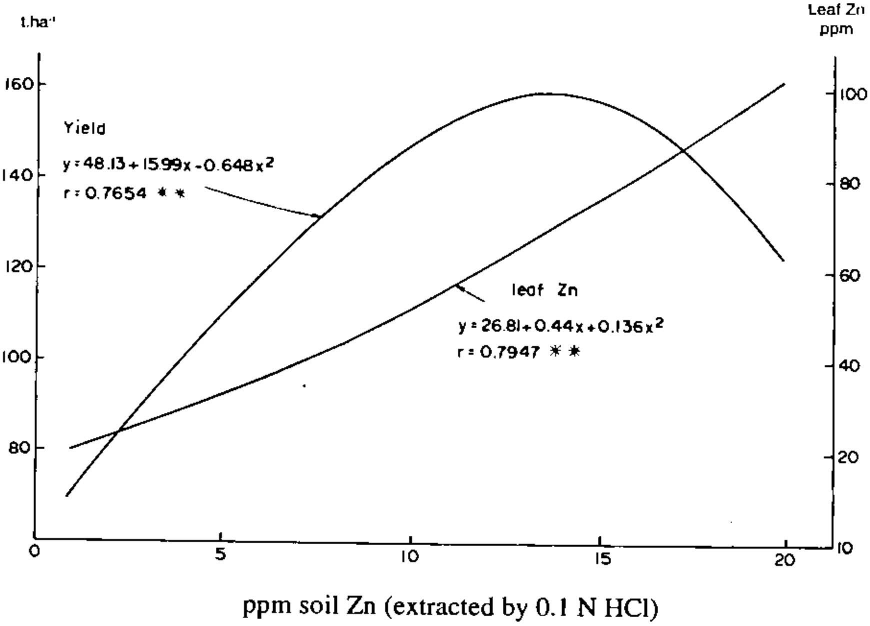

Fig. 24. Cane yield and leaf Zn, ppm in relation to soil zinc content after harvest of autumn planted cane.

USA. Anderson (1978) reported that in the Everglades of Florida (usually organic soils) sugarcane shows symptoms of Fe deficiency at the beginning of the growth period. After 3-4 months there is a recovery of the green colour. There are, however, significant losses in tillering and final yield. Deficiencies of B, Cu and Zn also occur. They are prevented by the application in the planting furrows of 1 kg B, 2 kg of Cu or 2 kg ha^{-1} Zn. Deficiencies of silicon (Si) have also been found usually in soil with less than 100 ppm of soluble Si (extracted by 0.5 M ammonium acetate at pH 4.85).

Calcium silicate slags are used for the control. In Hawaii, interest in soil silicon goes back to the end of last century, and it was believed that silica was a factor on phosphorus assimilation. Clements (1965) noted decreases in the Mn/SiO_2 and B/SiO_2 ratios in plants associated with silicate applications which were proposed as a means to correct "freckling" disease. Fox *et al.* (1967) observed that Ca silicate slag at the rate of 4.5 t ha^{-1} increased sugar yields by 12 t ha^{-1} in a field where both soil soluble (phosphate extractable) and leaf Si (extracted with trichloroacetic acid) were about 20 ppm. Deren *et al.* (1993) found differences in Si accumulation by genotypes which may be an economic advantage since silicon fertilization is costly.

7.8. Most economic rates of N, P_2O_5 and K_2O

The main objective of the sugarcane grower is not to obtain maximum physical yields, that is the highest tonnages of millable cane and sugar per hectare, but to obtain the maximum economic yield (MEY). And this, of course is a function both of the cost of the fertilizer and of the price paid for the cane and its sucrose content. Therefore the lower the price and higher the cost of the fertilizer, lower will be the rates used in order to obtain maximum profit. As an example, Tables 43, 44 and 45 give the rates of N, P_2O_5 and K_2O used in Brazil taking into account both soil analysis (for P and K) and the ratio price of one ton of cane (P) to cost of one kg of the element (C) = P/C ratio (Orlando *et al.*, 1981; Marinho and Albuquerque, 1978).

Table 43. Recommendations for the fertilization of ratoons with nitrogen related to P/C ratio.

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

Table 44. Recommendations for the fertilization of plant cane with potassium related to P/C ratio and soil test data.

P/C ratio	Soil test(1): cmol l^{-1} K		kg ha^{-1} K_2O		
	<0.12	0.12-0.23	0.24-0.40	0.41-0.8	>0.8
30	160	140	100	70	50-0
40	170	150	110	80	50-0
50	180	160	120	90	50-0

(1) Extracted by 0.5 N H_2SO_4.

Table 45. Recommendations for the fertilization of plant cane with phosphorus related to P/C ratio and P-soil test data.

Soil test ppm (1)	kg ha^{-1} P_2O_5				
	P/C: 8 ratio	14	20	26	32
> 5	120	150	170	180	190
6- 9	50	80	100	120	140
10-16	10	40	60	80	100
17-34	-	10	30	50	70
>34	-	-	10	30	40

(1) Extracted by Mehlich 1.

8. Organic manuring

Sugarcane leaves in the soil a considerable amount of organic residues - roots and trash - despite the fact that burning is done in order to make harvesting easier. It, therefore, raises somewhat the organic matter in the soil. Nevertheless organic fertilizers are frequently used to improve soil physical conditions - compacting is a common problem due to intensive mechanization - and to help to build or to maintain fertility. The organic fertilizers more commonly used are green manures and two waste products: filter press or mud cake and distillery slops or vinasse. The latter, instead of an environmental hazard, becomes a useful input in well managed sugar plantations.

8.1. Green manures

Green manures produce fresh plant material which is turned in the soil with the purpose of adding nutrients and organic matter which in part will be transformed into humic substances. According to Pimentel Gomes and Cardoso (1958) the chief desirable characteristics of the plants used as green manures are the following: (1) they should belong to the *Leguminosae* family in order to fix atmospheric nitrogen through the symbiotic association with *Rhizobium* bacteria; (2) growth has to be fast in order to overcome the competition of weeds; (3) dry matter production must be large, having low C/N ratio so as to decompose easily when plowed under; (4) the root system should be abundant and deep in order to promote biological subsoiling and mobilisation of nutrients from layers poorly explored by the sugarcane plant.

Table 46 gives the average fresh matter production of a few green manures. It should be mentioned that the green manure should be resistant to the residual effect of weed killers previously used.

Table 46. Production of fresh matter by a few green manures.

Green manure	tons/ha
Crotalaria juncea	28-54
C. spectabilis	16
C. paulina	37-42
C. grantiana	22
Dolichos lab-lab	10-40
Styzolobium deurigamum	17-35
S. aterrimum	16-43
Cajanus cajan	15-35
Canavalia ensiformis	23-33
Glycine max	15-19
Sesbania egyptiaea	24
S. aculeata	5
Vigna sinensis	18
Lupinus sp	6
Tephrosia candida	20

Green manures can be used without leaving the soil unoccupied by sugarcane for a year or during a cycle. In Brazil, it is common to sow *Crotalaria juncea*, a rapid growing legume, after the stubble is destroyed at the end of the cycle, and the beginning of the rainy season. Seeds should be inoculated and in poor soils, lime and phosphorus should be applied. The distance between rows is 120 cm and 25-50 kg of seeds per ha are used. In large plantations sowing is done by airplanes. When the plants begin to bloom they are plowed in. About two weeks later, the land is ready for planting (Souza, 1953; Cardoso, 1956; Malavolta *et al.*, 1959). Soybeans, beans and peanuts to be used as a cash crop can also be sown as a green manure: the pods are harvested and the residues are turned in.

Table 47 shows the effect of *Crotalaria juncea* on the yield in a soil deteriorated by years of inadequate management especially lack of lime and fertilization (Wutke *et al.*, 1960).

Table 47. Sugarcane yield response to mineral fertilizers, liming and green manure.

Treatment	Cane yield: t ha^{-1} 1st*	2nd*	3rd*	Average
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

* 1st-3rd harvest.

As shown in Table 48 large amounts of nutrients are added to the topsoil when the green manure is turned in. This, of course, does not represent (except partially in the case of N) a net addition but rather a cycling of elements from other soil layers.

Table 48. Quantities of nutrients accumulated by green manures (1).

Element	*Crotalaria* (2)			*Lab lab* (3)		
	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	13	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	8650	24807	33457	6944	1635	8579
Mn	487	982	1469	764	299	1063
Zn	38	97	135	48	36	84

(1) Malavolta, Kronka and Caceres (unpublished, 1994).
(2) Fresh weight in tons: roots 6; tops 32;
(3) Fresh weight in tons: roots 4; tops 13.

8.2. Filter press cake or filter mud

Filter press cake, filter mud or press cake, is a by-product of the process of clarifying the juice and may contain about one third of the P originally present in the stalk (Halliday, 1956). More detailed analyses are given in Table 49. In comparison with other macronutrients, it is relatively low in K. Since it is a bulky product and with high moisture content it is usually applied on the sugar mill land or close by.

Table 49. Composition of press cake (1).

Component	Content
	% dry matter
N	1.4
P inorganic	0.9
P organic	0.4
K	0.3
Ca	3.0
Mg	0.4
S	1.3
C	40.0
Si	3.0
Ash	18.0
Organic matter	81.0
	ppm
Co	1.4
Cu	65
Fe	2500
Mn	624
Mo	0.6
Zn	89

(1) Moisture: 78%. Data from Brasil Sobr. (1958) and Gloria *et al.* (1974).

The material usually already fermented is used in various ways:

(1) broadcast before planting at rates from 50 to 100 t ha^{-1};

(2) in the planting furrow, rates from 5-20 tons per ha.

Due to the fact that it is low in K (which appears in the distillery slops or vinasse) it is convenient, when it is going to be used exclusively, to add potassium chloride to correct its composition. An interesting solution is to mix the two by-products (press cake and vinasse), add water and pump the slurry into furrows in the field (Gloria *et al.*, 1973). The composition of such a mixture is given in Table 50.

(3) in between the rows of ratoons (rates 5-20 tons/ha).

Table 50. Composition of the residue resulting from the mixture of vinasse with filter cake.

Component	Content, kg m^{-3}
N	0.4
P_2O_5	0.09
K_2O	0.35
Ca	0.42
Mg	0.05
S	0.11
Organic matter	0.63
C/N	19.0
pH	5.3

Filter mud can also be used to prepare compost after mixing with bagasse and vinasse. Ashes from the boiler are sometimes added to the press cake in order to make a more complete fertilizer.

Yield increases due to the application of filter cake have been registered in various regions such as Brazil (Rodella *et al.*, 1990), Colombia (Quintero, 1986), Costa Rica (Berrocal, 1988). The effects are explained by improvement in soil physical conditions (porosity, water and air storage and circulation), reduction in acidity (increasing Ca and decreasing Al levels) and supply of nutrients, particularly P and S.

In the Risaraldo sugar mill area in Colombia, there is a small percentage of sodic soils (18% Na in the CEC). As shown in Figures 26 and 27, such soils can be successfully reclaimed by broadcasting and turning in about 80 t ha^{-1} of filter mud.

8.3. Distillery slops, vinasse, stillage, dunder

In the factory process for extracting raw sugar, more than three quarters of the potassium in the millable stalks is concentrated in the molasses. When the molasses are used to make rum (or similar beverages) or industrial alcohol the potash is left in the distillery slops or vinasse (Halliday, 1956). According to Orlando Filho (1994), two situations may occur as far as the sugar and alcohol industries are concerned: (1) when the main product is sugar, 1 ton of cane will give 100 kg of sugar and 35 kg of filter cake, plus 40 kg molasses or 12 l of alcohol and 156 l vinasse; (2) when only alcohol is produced, 1 ton of cane will generate 80 l of alcohol and 1,040 l of vinasse.

The composition of vinasse may vary depending on the substrate for fermentation as can be seen in Table 51 (Gloria *et al.*, 1973). This residue is relatively low in P (which apppear in the press mud) and rich in K.
There are three main ways for using vinasse in the field.

Table 51. 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

Distribution in furrows

This is the system first used by Almeida (1952), the pioneer research worker who demonstrated the feasibility of using vinasse as a fertilizer. In areas near the distillery, undiluted vinasse is applied usually in nurseries. More frequently the stillage is diluted in the proportion 1:8 or 1:10 using waste water or other sources. The vinasse is led to large tanks from where it is distributed by gravity or pumped into furrows in the field.

Distribution by trucks

Vinasse supplemented with other nutrients (N, P) or not is carried by trucks to places not too far from which it is discharged on the surface to be planted or on the field which has the stubble of the previous crop (Lima, 1953).

Distribution by sprinklers

The vinasse is brought into the field and, after dilution, it is sprayed with the aid of hydraulic guns (Leme *et al.*, 1979). The rate of application varies between 50 and 100 m^3 ha^{-1}.

For some years, sugarcane growers were afraid of applying vinasse in the field due to the acid reaction of this by-product (see Table 51) which would be harmful to the plants. Vinasse was then an environmental problem since part of it was dumped into the rivers or would contaminate water sources by seepage or overflow of the reservoirs. It was shown, however, that instead of lowering the soil pH vinasse either previously neutralized with lime water or not, caused a reduction in soil acidity a few weeks after application. The rise in pH was roughly proportional to the dosage employed. Other favourable effects were observed, clearly disclosing the potential of vinasse as a fertilizer. Ranzani (1956) verified a considerable increase in the water holding capacity in the treated soils, a likely consequence of the finely divided organic matter contained in the stillage; there was also an increase in the cation exchange capacity and in the quantity of exchangeable cations, particularly K. Similar findings were observed by Nunes *et al.* (1981). Cesar and Manfrinato (1954) showed that vinasse reduced by a factor of 50% soil losses due to erosion. Camargo *et al.* (1983) reported that vinasse increases soil aggregation (which would reduce erosion losses) due to the transformation by microorganisms of its organic matter. Actually a marked increase in the number of microorganisms had been described by Camargo (1954).

Field experiments with sugarcane and other crops (Table 52) demonstrate the favourable effect on yield of vinasse applications.

Table 52. Yield response to vinasse application of various crops.

Crop	Average yield, t ha^{-1}	
	Control	Vinasse treated
Sugarcane	44	117
Maize	0.8	3.0
Beans	0.4	0.9
Cotton (seed)	0.3	1.4

Since this by-product is low in P, the addition of this element can increase yields dramatically as shown in Table 53. High doses of stillage, however can delay maturation, increase ash in the juice and lower sucrose content (Stupiello *et al.*, 1977; Magro *et al.*, 1980).

Table 53. Combined effects of P (120 kg ha^{-1} P_2O_5) and vinasse on sugarcane yield.

Vinasse m^3/ha	Without P	With P
	t ha^{-1}	
0	31	33
250	55	149
500	105	144

It is necessary therefore not to apply excessive volumes of vinasse (usually more than 100 m^3) since the benefit on the yield of millable stalk could be jeopardized by a lowering of the quality. Vinasse has been used to ameliorate sodic soils in the Cauca Valley of Colombia (Alvaro Garcia Ocampo, 1994, private communication).

Other uses of vinasse have been studied: Horowitz *et al.* (1985a, b) developed an industrial process designed to prepare a complete fertilizer. The waste is enriched by adding N, P, soluble and sparingly soluble silicate, Mg, and micronutrients. It can also be used as substrate for the production of biogas (60% methane + 20% CO_2) by anaerobic digestion: 150 m^3 of vinasse/day would yield 18.000 m^3 of biogas/day; the effluent, which retains the nutrients, can still be used as a fertilizer (Rocha, 1988).

9. References

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10. Appendix

Visual symptoms of nutrient deficiency

Plate No. 1.
Nitrogen deficient stools
Poor plant growth and tillering, slender stalks, leaves are pale green, old leaves are stronger affected and die back
(Source: Dr. J. Orlando F°, UFSCAR, Araras, SP, Brazil).

Plate No. 2.
In the foreground -a nil P plot; stunted cane growth, reduced tillering, discolouration of the older leaves to reddish, reddish violet-purple (Source: Dr. G.A.C. Albuquerque, Planalsucar, Maceió, AL, Brazil).

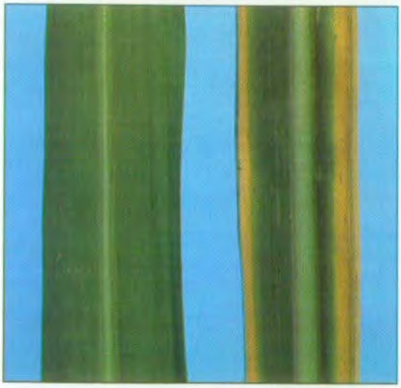

Plate No. 3.
Potassium deficient leaf at right, older leaves are affected; chlorosis and necrotic lesions at the tip and along the margins (Source: Dr. J. Orlando F°).

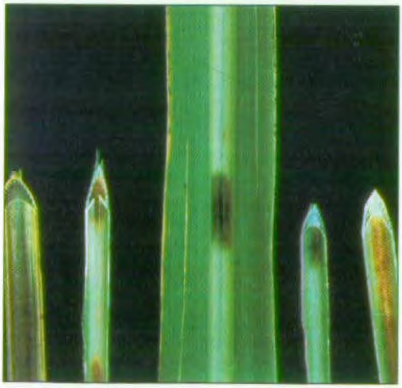

Plate No. 4.
Red discoloration of the upper surface of the midrib due to K deficiency. (Source: Dr. J. Orlando F°)

Plate No. 5.
Magnesium deficient stool, older leaves are affected, chlorotic blotches between the nerves, yellow stripes turning to red necrotic lesions starting at the tip and margins resulting in "rusty" appearance of old leaves
(Source: Dr. M.A.C. Santos, Planalsucar, Recife, Pernambuco, Brazil).

Plate No. 6.
Sulphur deficient leaf (down), young leaves uniformly chlorotic
(Source: The Sulphur Institute,Washington, DC, USA).

Plate No. 7.
Severe zinc deficiency in a plant cane field crop; reduced growth and tillering, thin stalks and short internodes, young and immature leaves are affected having degrees of chlorosis, but no wilting and die back
(Source: Dr. W. Maibaum, International Potash Institute).

Plate No. 8.
Severe copper deficiency in a sugarcane field crop, strong growth inhibition, leaves (young) are chlorotic, wilted and die back (Source: Dr. C.S. Fernandes, UF Pernambuco, Recife, PE, Brazil).

Plate No. 9.
Iron deficiency (right) in a plant cane crop, left: variety less sensitive to low iron supply, young leaves affected first, varying degrees of chlorosis, entire plant may become chlorotic (Source: Dr. W. Maibaum, International Potash Institute).

Plate No. 10.
Boron deficient cane plant, young leaves are affected, chlorosis of tips quickly becoming necrotic